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CAPTURE-CONCENTRATE-CLEAN

CAIRE™ Technology

# Advanced Industrial Air Pollution Control Capture Concentrator Systems

## Technology, Performance, Awards, and case studies of the Fluidized Bed Concentrator

**Advanced Industrial Air Pollution Control**
**Capture Concentrator Systems**

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# Advanced Industrial Air Pollution Control
# Capture Concentrator Systems

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## I. INTRODUCTION:

In manufacturing, process exhaust gas (air) streams may contain volatile organic compounds (VOCs), Hazardous Air Pollutants (HAPs), particulate, etc. These are considered pollutants/emissions and must be removed from the air prior to release to avoid air pollution emissions into our communities. Add-on controls either collect the pollutants for recovery and reuse or destroy the pollutants. A number of control options are available including thermal oxidizers, catalytic oxidizers, and biofiltration which destroy pollutants. Other control systems including condensation, scrubbing, and adsorption systems may recover pollutants. Regardless of what control technology being used, if the process exhaust is a high volume, dilute exhaust stream, a capture concentrator system upstream of the control device to reduce exhaust gas volume to process should be considered. Capture concentration is typically done via adsorption of the VOCs on carbon or zeolite, followed by desorption into a much lower volume of exhaust. Capture concentrators can reduce the volume of solvent-laden air to be processed by a factor of 10 to 20:1 or even greater than 1000:1. The resulting concentrated smaller volume exhaust stream may be heated, cooled, or otherwise treated by a smaller control device with less energy.

This paper provides an overview of capture concentrator systems for advanced air pollution control including an introduction to the Fluidized Bed Concentrator (FBC), with Bead Activated Carbon (BAC). Paper includes a description of the 1) FBC technology, 2) BAC media used, 3) performance characteristics, 3) typical applications, 4) FBC environmental awards, and 5) a case study review of the demonstration of the FBC technology for use in controlling emissions from wood drying.

## II. BACKGROUND: CAPTURE CONCENTRATOR SYSTEMS[1]

The first thought source owners face with requirements to lowering VOC emissions is likely to be (and should be) pollution prevention. In fact, pollution prevention, e.g., reformulation of inks and coatings and modification of equipment and work practices, can provide low-cost emissions reductions. On the other hand, reformulated materials often have very different properties from their conventional parents, leading to changes in product quality, compounded by the effects of different work practices and equipment configurations. Further, pollution prevention may not be able to provide the necessary emissions reductions at an acceptable cost.

Particularly where time is limited, such as for compliance with the printing and publishing MACT rule, implementing pollution prevention approaches may be difficult. In light of these concerns, add-on VOC controls offer an excellent alternative or adjunct to pollution prevention.

Add-on controls include all technologies which remove VOCs from exhaust gas streams. Add-on controls either collect the VOCs for recovery and reuse, or destroy the VOCs.

If the VOCs have recovery value, which typically implies single-VOC exhaust streams, and if the cost of recovery is less than the cost of purchasing new material, which typically implies concentrated exhaust streams, then recovery makes sense. Carbon or zeolite adsorption, scrubbing, and condensation are typical recovery techniques. Note that the installation and operation of a recovery technology may more than pay for itself if the recovery value of the VOCs is high enough.

If the VOC has no recovery value, as for example, when it is a mixture, or if it poses disposal concerns, such as for toxic compounds, then destruction probably makes the most sense. Thermal and catalytic oxidation and biofiltration would be useful in this case.

Regardless of what control technology you use, if you have a high volume, dilute exhaust stream you probably want to consider using a capture concentrator (concentration) system upstream of the control device to reduce exhaust gas volume to process. Capture concentrator systems are useful in front of control devices for treating very high volumes of very dilute exhaust gas. Capture concentration is typically based on adsorption of the VOC on carbon or zeolite, followed by desorption with a much lower volume of hot gas.

Adsorption on activated carbon or zeolite is useful for recovery of VOCs with intermediate molecular weights (typically about 45-130). Smaller compounds do not adsorb well, and larger compounds may not be removed during regeneration, which typically is by steam or hot gas stripping. Activated carbon can be used in a variety of applications including removing contaminants in wastewater treatment and removing mercury from exhausts from coal-fired power generators[2]. Adsorption is most effective at lower temperatures,

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[1] "Using VOC Control Technologies to Go Beyond MACT Requirements…and Help your Bottom Line". Institute of Clean Air Companies (ICAC) website. https://www.icac.com/page/Publications#VOC_Bottom_Line (Accessed January 20, 2022.

[2] "Products and Services". Advanced Emissions Solutions (ADES) website. https://www.advancedemissionssolutions.com/ADES-Investors/ada-products-and-services/default.aspx (Accessed January 22, 2022).

so that cooling of hot exhaust gas streams may be necessary. Further, in some adsorption systems, dehumidification of very humid streams may be necessary for the carbon to have the greatest capacity. Activated carbon may be used to remove compounds in a once-through process with off-site regeneration or in continuous processes with on-site continuous reactivation. The Fluidized Bed Concentrator (FBC) uses specialized synthetic activated carbon beads as the adsorbent media to remove compounds.

Capture concentrators may be configured as vessels, equipment with trays, or wheels containing activated carbon or zeolite. If configured as a wheel with sections, most of the space on the wheel functions in adsorption mode, with one small sector being regenerated at any given time. Rotary wheel concentrators can reduce the volume of solvent-laden air to be processed by a factor of 10 to 20:1, while Fluidized Bed Concentrators (FBCs) can reduce the volume by factors greater than 1000:1. This allows the use of smaller control devices. As a result, operating costs tend to be lower.

## III. DESCRIPTION OF FLUIDIZED BED CONCENTRATOR (FBC) TECHNOLOGY:

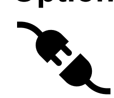
- **FOUR PRIMARY PARTS**

**1. Adsorber:** The adsorber section has trays filled with very adsorbent BAC. Contaminated process exhaust enters from the bottom, passing upward through the adsorption trays, fluidizing the Bead Activated Carbon (BAC) adsorbent. When the process air interacts with the BAC, it adsorbs (captures) the Volatile Organic Compounds (VOCs) in its pores. VOC saturated BAC flows to the bottom of the adsorber vessel and is transferred using fans to pneumatically transfer it to the desorber. Cleaned (reusable) BAC from the desorber feeds continuously into the top of the adsorber, providing counter-current VOC removal.

**2. Desorber:** In the desorber, the BAC is heated (regenerated), causing it to release the VOC vapors into a low volume, gas stream. This gas stream is then circulated continuously to the next stage in the process. The regenerated (cleaned) BAC is then returned continuously to top of the adsorber for reuse. Returning this regenerated BAC to the top of the adsorber provides a final "polishing" of emissions to remove residual emissions prior to release of the process exhaust air.

- **Recovery System:** In the recovery system, a low volume inert carrier (nitrogen) gas is introduced into the bottom of the desorber. Gas flows up through the desorber as the BAC flows downward. The system is heated via either hot oil or electric heating. The heat causes the VOCs to volatilize off the BAC. The VOC vapors are liberated resulting in a concentrated waste flue gas stream that moves from the desorber to the condenser. This system may eliminate the on-site use of natural gas entirely. Thus, it offers an "All Electric" control technology.

**"All Electric" Option**



- **Oxidation System:** In the oxidation system, clean hot stripping air at 100-700°F is introduced to the bottom of the desorber. It flows upward across the BAC to both volatilize the VOCs and fluidize the BAC.

**3. Condenser or Oxidizer:** The gas stream from the desorber is circulated continuously to this system.

- **Recovery System – "All Electric" option:** In the recovery system, nitrogen gas circulates from the desorber to the condenser continuously. The VOC vapors are sufficiently concentrated such that the vapors can be cooled via a tube and shell condenser converting the vapor to liquid. The liquid drains continuously into a storage system. The liquid VOCs can then be reused or sold. The nitrogen recirculates back to the desorber where it entrains the VOCs vapors again and the cycle continues.

- **Oxidation System:** In the oxidation system, the vapors are instead sent to a small thermal oxidizer to treat the VOCs. While this system does not provide recovered (collected) VOCs, it nevertheless retains FBC technology benefits including significantly reducing natural gas usage. The burner component of the thermal oxidizer is selected to provide enough energy to increase the thermal oxidizer to 1400°F operating temperature. The burner is designed to minimize the "fire rate and thus consume negligible fuel. Optionally, a "low $NO_x$" design can be selected to minimize production of NO and $NO_2$ (oxides of nitrogen). Thus, the system minimizes energy usage and GHG emissions.[3]

**4. Side Stream Reactivator (SSR)[4]:** A small portion of the BAC exiting the desorber may be transferred to an optional SSR. The SSR reactivates the BAC by heating it to >1000°F with the introduction of a small amount of water which reactivates the BAC continuously to regenerate it and thus maintain its ability to adsorb VOCs. Reactivated BAC from the SSR is transferred back to the top of the adsorber for reuse.

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[3] "VOC Removal and Destruction System and Method". U.S. Patent and Trademark Office. https://appft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearch-bool.html&r=1&f=G&l=50&co1=AND&d=PG01&s1=20190022579.PGNR.&OS=DN/20190022579&RS=DN/20190022579 (Accessed October 4, 2021).

[4] "GASTAK® Solvent Recovery and Odor Removal by Fluidized Bed Process". Kureha Ecology Management Co., LTD website. https://www.kurekan.co.jp/en/download/gastak.pdf (Accessed September 18, 2021).

## IV. FBC ADSORBENT MEDIA:

| **Bead Activated Carbon (BAC)** | **Bead Activated Carbon (BAC), the Media or Sorbent, Fluidized in Tray** |
|---|---|
|  |  |

The BAC adsorbent utilized in this system is an essential element of the FBC technology. Specialized Bead Activated Carbon (BAC) efficiently adsorbs VOCs (i.e. terpenes) from the process air. The BAC has high-fill (adsorption) capacity, is a small sphere-shaped particle that is less than 1 mm in diameter with a narrow particle size distribution, has low dust, has high purity, has high flowability, and has high strength and wear resistance as measured by ASTM D 3802 – 79 (2005) Standard Test Method for Ball-Pan Hardness of Activated Carbon.[5] The spherical shape enables the BAC to fluidize and flow.

The BAC can be reactivated and reused. This is accomplished either by either continuous or batch processes.

- **Continuous Reactivation:** In the continuous process, a small amount of BAC is diverted from the BAC exiting the desorber and sent to an in-line side stream reactivator (SSR).[6] It is then returned to the top of adsorber. Returning this reactivated BAC to the top of the adsorber provides a final “polishing” of emissions to remove residual emissions prior to release of the process air.

- **Batch Reactivation:** In the batch process, for operators that do not have an SSR, the BAC is unloaded periodically, shipped offsite for reactivation, and then reloaded once returned. In the interim, a second load of BAC is utilized. Reactivation is typically performed by California Carbon who has been providing

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[5] “ASTM D3802-79 (2005) Standard Test Method for Ball-Pan Hardness Of Activated Carbon. https://webstore.ansi.org/standards/astm/astmd3802792005 (Accessed September 18, 2021).
[6] “GASTAK® Solvent Recovery and Odor Removal by Fluidized Bed Process”. Kureha Ecology Management Co., LTD website. https://www.kurekan.co.jp/en/download/gastak.pdf (Accessed September 18, 2021).

reactivation services since 1975.[7] This service includes the following reactivation warranties: the *"Carbon will be reactivated to 95% of Virgin Activity per ASTM D 3467"* and the *"Carbon will lose no more than 10% of incoming volume of the specified mesh size in the reactivation process."* [8] BAC lifetime is site and application specific. Some operators have been reusing their BAC for years.

## V. FBC OPTIONS: RECOVERY AND OXIDATION

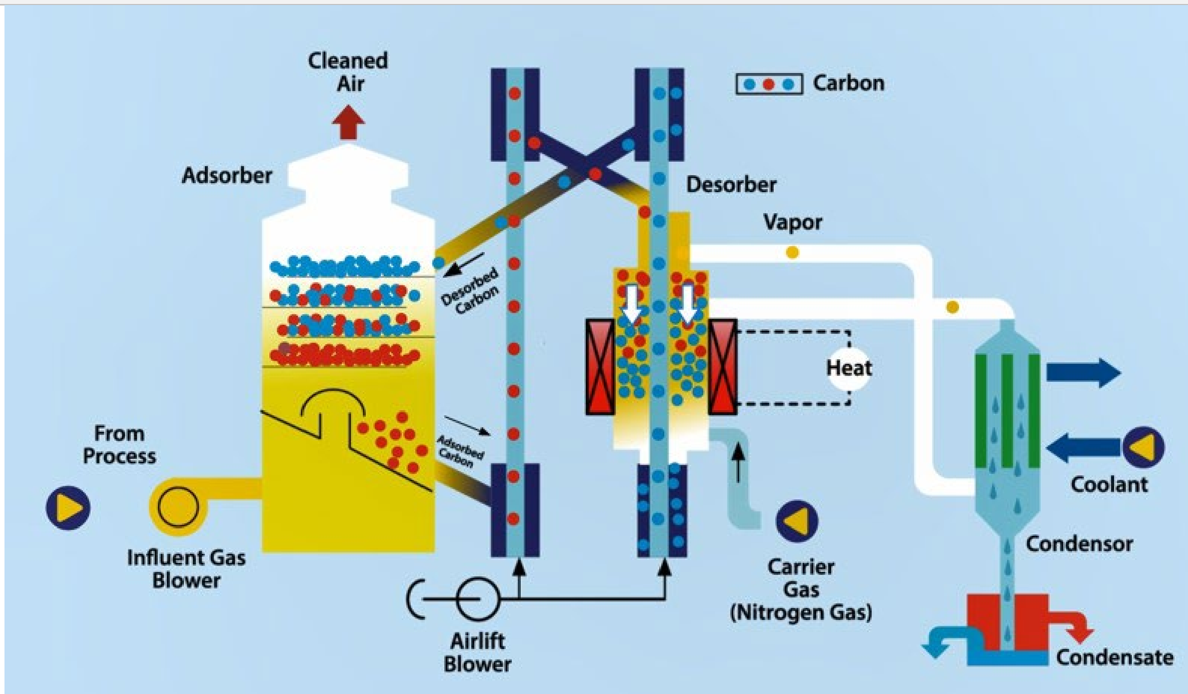
The Fluidized Bed Concentrator can be utilized to either recover the VOCs or oxidize them as shown in these figures. Operators typically select the desired option based on a number of factors especially including the anticipated value and reusability of the recovered VOCs. The value of the VOCs depends on a number of factors including the anticipated quantity recovered, purity, salability, and/or reusability.

- **Recovery:** When the value of the recovered VOCS is high and if the cost of recovery is less than the cost of purchasing new material, then recovery makes sense.

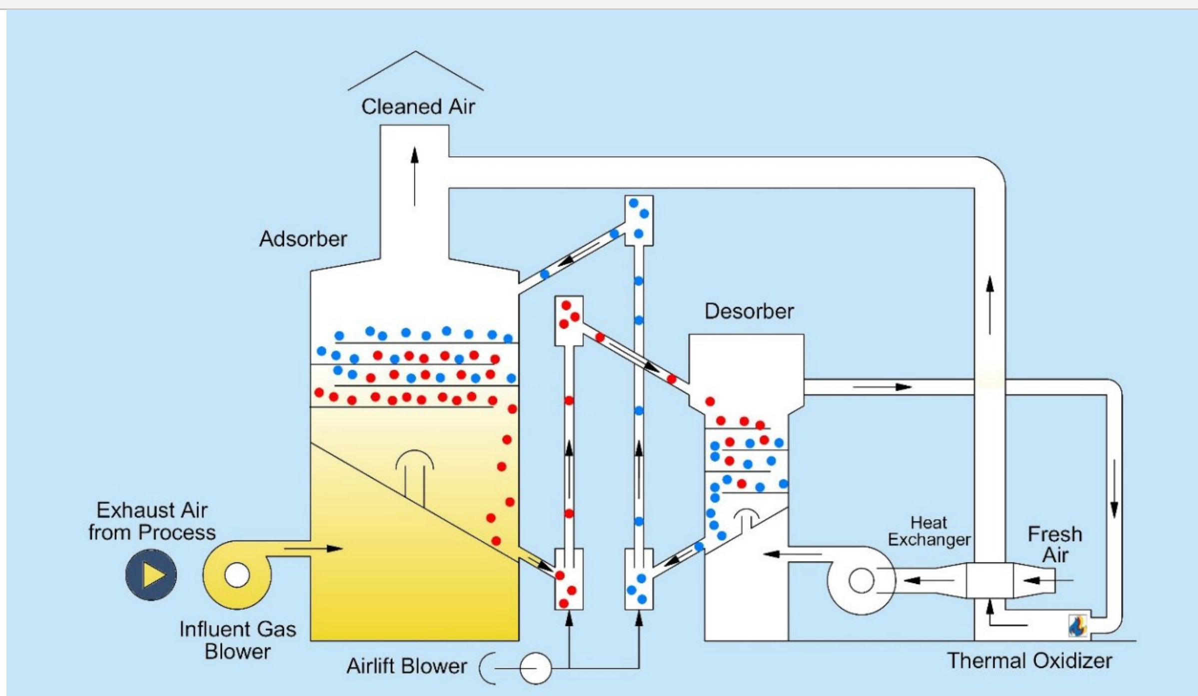
- **Oxidation:** If the VOC has low or no recovery value, as, for example, when it is a mixture, or if it poses disposal concerns, such as for toxic compounds, then destruction probably makes the most sense. Excluding value derived from VOC recovery, the oxidation option retains FBC system performance characteristics including reductions in energy usage.

[7] "California Carbon Co. Inc. Welcome". California Carbon website. http://www.californiacarbon.com/index.html (Accessed September 18, 2021).
[8] "Custom Spent Carbon Reactivation". California Carbon website. http://www.californiacarbon.com/pdfs/Custom%20Reactivation.pdf (Accessed September 18, 2021).

## FBC RECOVERY SYSTEM: Adsorbs, Desorbs, and Condenses VOCs




## FBC OXIDATION SYSTEM: Adsorbs, Desorbs, and Oxidizes VOCs



## VI. PROCESS PERFORMANCE CHARACTERISTICS:

- **<u>Reduces Energy Usage (i.e. natural gas):</u>**
  - **Baseline Systems:**
    - **Thermal Oxidizers:** Thermal oxidizers burn VOCs by heating them in enclosed combustion chambers in the presence of excess oxygen. The precise temperature and residence time needed for effective reduction of VOC emissions varies with the nature of the VOC. However, temperatures of 1400-2000°F and residence times of 0.5-2 seconds are typical. Especially in low concentration exhaust gas streams, auxiliary fuel is necessary to maintain combustion temperatures. Therefore, most thermal oxidizers incorporate some form of heat recovery to lower auxiliary fuel costs. For example, a regenerative thermal oxidizer (RTO) may be used to lower fuel costs. Even with an RTO, fuel usage may still be high when treating low concentration exhaust streams.
    - **Capture Concentrators:** Capture concentrator systems reduce the volume of the exhaust gas stream and increase the concentration of VOCs in the gas stream. These two things in combination reduce the energy required to subsequently treat the VOCs as follows:
      - For a concentrate and oxidize system, reducing the exhaust volume reduces the amount of energy required to produce heat to heat the exhaust stream and thus oxidize the VOCs. Concentration may even result in an exhaust stream that is "self-sustaining", i.e. requires little to no auxiliary fuel (natural gas).
      - For a concentrate and recover system, reducing the exhaust volume reduces the amount of energy required to provide cooling to cool the exhaust stream and thus condense the VOCs.
      - If the concentration step can be done efficiently, this then enables the use of smaller control devices that use less energy to either oxidize or recover the VOCs. As a result, operating costs tend to be lower.
  - **FBC Technology:** Unlike the RTO, the exhaust going through the adsorber media is not heated. This eliminates energy required to produce heat to heat the exhaust stream thus reducing energy usage. As a capture concentrator, the VOCs are collected in the adsorber and concentrated by heating to release them into a much smaller stream in the desorber. The reduced volume concentrated exhaust stream requires less energy to treat than the dilute exhaust stream.
    - **Recovery – "All Electric" Option:** For a recovery system, the control device can be "<u>All Electric</u>". It could eliminate the use of natural gas entirely.
    - **Oxidation:** The FBC oxidation system significantly reduces natural gas usage but does not eliminate it.

○ **Energy Reduction Calculation:** The amount of energy that is eliminated, that would have been used by the thermal oxidizer, can be calculated utilizing one of many credible sources. One of the best sources is the Institute of Clean Air Companies' Guidance Methodology[9]. Calculators are also available on-line including those provided by the EPA[10], Cycle Therm[11], and Captis Aire[12]. With these calculators, users can input their specific data and the calculators will calculate the estimated amount of energy required to run the thermal oxidizer. All these sources rely on a single primary factor to calculate energy required to heat the air. This factor is the specific heat of air which is the number of British Thermal Units (BTUs) required to heat one pound of air by one °F. This factor along with the system specific factors including the standard cubic feet per minute (sCFM) of air, the temperature increase, the density of air, and conversion factors provide the number of BTUs required to heat the air going through the device. These factors are used together with the energy efficiency and the heat generated by the oxidation of the emissions to calculate the BTUs of energy required to heat the air going through the Regenerative Thermal Oxidizer (RTO). Users can then multiply BTUs times the forecasted long-term cost of natural gas to estimate the long-term cost of natural gas required over the 20+ year life of the thermal oxidizer. This calculation provides the value of the natural gas elimination.

- **Reduces Greenhouse Gas (GHG) emissions:**

○ **Baseline Systems:** Capture concentrator systems reduce the volume of the exhaust stream being treated and increase the concentration of the VOCs, thus move the system closer to being "self-sustaining". This means less fuel, i.e. natural gas, is burned. Thus, greenhouse gas emissions are reduced by reducing the amount of fuel, i.e. natural gas, burned to heat the exhaust stream being processed.

○ **FBC Technology:** Similar to other concentrator systems, the FBC, reduces greenhouse gas emissions due to the reduction or elimination of natural gas usage and reduction in electrical usage. In addition, in a recovery system, the VOCs being controlled are captured rather than oxidized. Thus, it reduces the amount of greenhouse gas emissions generated by oxidizing the emissions being controlled.

○ **GHG Calculations:** The greenhouse gas emissions reduction can be calculated based on the amount of carbon in natural gas eliminated and its stoichiometric conversion to carbon dioxide ($CO_2$). The Environmental Protection Agency (EPA)

[9] ICAC Guidance Method for Estimation of Gas Consumption in a RTO. Institute of Clean Air Companies website. https://cdn.ymaws.com/www.icac.com/resource/resmgr/RTO-F1.pdf (Accessed September 18, 2021)

[10] "Air Pollution Control Cost Estimation Spreadsheet". Environmental Protection Agency (EPA) website. https://www.epa.gov/sites/production/files/2018-01/oxidizers_calc_sheet_finalversion_1-16-2018.xlsm (Accessed Feb 3, 2021).

[11] "Operating Cost Calculator". Cycle Therm website. http://www.cycletherm.com/resources/operating-cost-calculator.aspx (Accessed Feb 3, 2021).

[12] "Calculate Engineering Estimate of Natural Gas Usage and Greenhouse Gas Generation". Captis Aire website. https://www.captisaire.com/Value-Calculator/ (Accessed Feb 3, 2021).

has an on-line calculator[13] that enables the user to calculate greenhouse gas emissions that are eliminated by eliminating natural gas used to heat the air in the thermal oxidizer.

- **Generates Revenue from Sales of Recovered Organics:**

  ○ **Baseline Systems:** When using a recovery system, operators have options to separate, collect, and sell or reuse the volatile organic compounds recovered. For example, the organics may be recovered by collecting them from a condenser and/or separated from water by phase separation.

  ○ **FBC Technology:** When using the FBC recovery system, operators have the option to collect and sell or reuse the volatile organic compounds recovered. The liquid VOCs are collected from the FBC condenser for reuse or sale.

  ○ **Value of Organics:** The value of the recovered VOCs will depend on the type, amount, and purity of VOCs collected.

- **Enables Sales of Carbon Offsets:**

  ○ **Baseline Systems:** If baseline concentrator systems reduce energy usage and meet the requirements for creating a new carbon offset methodology, they may be able to provide carbon offsets for reductions in greenhouse gas emissions.

  ○ **FBC Technology:** In conversations with American Carbon Registry[14] and ClimeCo[15], it may be possible to measure, register, and verify carbon offsets for a site converting to the FBC technology due to the reduction in energy usage.

  ○ **Carbon Offsets:** The quantification methodology and value of carbon offsets is evolving quickly. But these carbon offsets can be sold or traded externally. Or they may be utilized for internal credit accounting purposes. Potential values for these carbon offsets vary widely.[16] However, as of early 2021, American Carbon Registry and ClimeCo estimated the value of carbon offsets for an FBC project at $5/ton.[17]

- **Reduces Electricity Usage:**

  ○ **Baseline Systems:** If baseline capture concentrator systems reduce the differential pressure across their respective media systems, they may reduce horsepower required to run the fans and thus reduce electrical usage. For instance, if the distance through which the exhaust air must pass as it passes

[13] "Greenhouse Gases Equivalencies Calculator - Calculations and References". EPA website. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (Accessed December 28, 2020).
[14] "Harnessing the Power of the Markets to Improve the Environment". American Carbon Registry website. https://americancarbonregistry.org/ (Accessed February 3, 2021).
[15] "Scalable greenhouse gas projects to earn real financial returns for your business." ClimeCo website. https://climeco.com/ (Accessed February 3, 2021).
[16] "Allowance Price Explorer". International Carbon Action Partnership website. https://icapcarbonaction.com/en/ets-prices (Accessed Jan 20, 2021).
[17] Eric Ripley (Director Industrial Programs, American Carbon Registry), in a phone conversation with Kim Tutin November 17, 2020.

through the media (the media thickness or depth) is reduced, differential pressure (backpressure) may be reduced. This may occur in capture concentrator wheel type designs where media is separated into many smaller sections.

o **FBC Technology:** The horsepower required to run the fans to move the process exhaust air through the BAC may be reduced to ~ ¼ of that required for the RTO. due to two things:

- First, the media thickness is reduced from 16 feet for the RTO to just 1 foot for the FBC. The exhaust air in the RTO travels through two media beds, each of which is ~8 feet thick. Thus, the total media thickness in the RTO is ~16 feet. In the FBC, the adsorber has 6 trays and the media thickness in each tray is 1-2 inches. Thus, the total media thickness in the FBC is just 12 inches (1 foot).
- Second, the BAC is fluidized (moving) and flows like water rather than being packed (non-moving). This makes it much easier for the exhaust gas to pass through the media.
- The result is that the differential pressure (backpressure or pressure drop) across the system is reduced to just 3.5" for the FBC versus the typical 10-20" for the RTO. Thus, the horsepower to run the fans for the FBC is reduced versus the RTO.

o **Electrical Savings Calculation:** To estimate the electrical savings, the sum of electrical demands from the capture concentrator, i.e. the FBC, is subtracted from the sum of electrical demands of the baseline system, i.e. the RTO. Net kW·h along with site-specific electricity costs and operating hours per year are used in combination to estimate electrical savings.

- **<u>Improves Mass Transfer of VOCs into Media:</u>**

o **Baseline Systems:**

▪ **Adsorption:** In sorbent concentrator systems, process exhaust air moves across the sorbent. VOCs are removed via attraction (adsorption) of the VOCs on carbon or zeolite sorbents in packed (non-moving) beds.

• This may be accomplished by capture concentrators that have wheels with sectors containing activated carbon or zeolite. In this arrangement, most of the space on the wheel functions in adsorption mode, with one small sector being regenerated at any given time.

• Or the process exhaust air may be forced through large vessels containing sorbents. In this arrangement, the VOCs are treated via a once-through process.

▪ **Regeneration / Reactivation:** Regeneration is accomplished by heating the sorbent with heaters, heated gases, steam, etc. If using steam, water may be a byproduct. This can be accomplished either via off-site regeneration or by alternating the flow between multiple vessels where one vessel functions in adsorption mode while the other is being regenerated at any given time. In both these arrangements, the sorbent is being regenerated in batch or semi-continuous fashion. Reactivation may be accomplished by sending the sorbent off site for reactivation. Or the sorbent may be discarded when it becomes saturated.

- **Effect of water vapor:** Especially for process exhaust air heavily laden with water vapor (i.e. 10% or more by volume), the sorbent may become partially or fully saturated with water. At high moisture content, water molecules begin to compete with the hydrocarbon molecules for active adsorption sites. This reduces the capacity and the efficiency of the adsorption system. For example, per this Title V Permit application[18]: "*Carbon adsorption is not practical because of the high moisture content of the exhaust stream from the lumber drying kilns. At high moisture content, water molecules begin to compete with the hydrocarbon molecules for active adsorption sites.*"

○ **FBC Technology:** The FBC enables superior mass transfer of VOCs through counter current flow fluidized BAC that is continuously regenerated.

- **Adsorption:** The BAC in the fluidized bed concentrator adsorber is fluidized (moving) by the process air moving opposite (counter current) to the BAC as it moves downward through the trays in the adsorber. This provides excellent mixing of the BAC and contact with the air. As this occurs, VOCs or odors are transferred from the process air to the BAC. The cleaned air exits through the top of the adsorber.

- **Regeneration / Reactivation:** The BAC is regenerated continuously via continuous recirculation to and from the desorber. It is reactivated continuously if the system includes the Side Stream Reactivator (SSR). This ensures the BAC retains the capacity to maintain adsorption efficiency. Regeneration is done at temperatures well above the boiling point of water, often around 400°F or more. This minimizes or eliminates accumulation of water and/or organics on the BAC.

- **Effect of water vapor:** Continuous regeneration and reactivation at temperatures above the boiling point of water, i.e. 400°F and >1000°F respectively, volatilize the water off the BAC and prevent the BAC from becoming saturated with water. Thus, the BAC maintains adsorption efficiency even when treating process exhaust streams with high moisture contents and minimizes or eliminates need for dehumidification systems.

- **Effect of Fluidized (moving) vs Packed (non-moving) media:** BAC media fluidization prevents pockets of high concentration VOCs, provides higher dry particulate tolerance (reduced plugging of interstitial spaces between media), and enables continuous on-site regeneration and reactivation.

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[18] "West Fraser – Dudley Sawmill." Pages 5-5 and 5-6. Georgia Environmental Protection Division website. https://epd.georgia.gov/document/document/17500035applicationpdf/download (Accessed Sept 18, 2021).

## VII. FLUIDIZED BED CONCENTRATOR (FBC) AWARDS:

**CLEAN AIR**
Excellence Award
U.S. Environmental Protection Agency

**AIR CONSERVATIONIST**
of the Year
Alabama Wildlife Federation

**GREEN CHEMISTRY**
Challenge Award
U.S. Environmental Protection Agency

**INNOVATION CROSSROADS**
Entrepreneurial Award
Oak Ridge National Lab

**DEPARTMENT OF ENERGY**
Bioenergy Technologies Office
Renewable Blending Components to
Enable 100% Sustainable Aviation Fuel

The FBC has been recognized for excellence in environmental performance. Honda Motors of Alabama was recognized as air conservationist of the year when they implemented the FBC to control emissions when they increased production.[19] Ford's "Fumes to Fuels" work was awarded the EPA's Clean Air Excellence award.[20] In this work, they utilized the FBC to capture solvent-laden air, strip the solvent from the air, concentrate the solvent up to 2,000 times, and send it to a fuel reformer. The fuel reformer used the concentrate to generate hydrogen-rich fuel, which was directed into a fuel cell to generate electricity. The Capture Adsorption Innovation Reduces Emissions (CAIRE™) technology won the EPA's Green Chemistry Challenge award.[21] Captis Aire's owner, Kim Tutin, was selected for the Innovation Crossroads Entrepreneurial Fellowship Award from Oak Ridge National Lab for the CAIRE™ technology.[22] Department of Energy and Boeing awarded Captis Aire $2.5 Million for the project entitled *"Renewable Blending Components to Enable 100% Sustainable Aviation Fuel (SAF)"*.[23]

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[19] "HMA Honored as Air Conservationist of the Year". Honda website. https://www.hondaalabama.com/article/hma-honored-as-air-conservationist-of-the-year (Accessed September 21, 2021).

[20] "Clean Air Excellence Award Recipients". Environmental Protection Agency (EPA) website. https://www.epa.gov/sites/default/files/2015-06/documents/clean_air_excellence_award_recipients_year_2003.pdf (Accessed September 21, 2021).

[21] "Green Chemistry Challenge: 2023 Greener Reaction Conditions Award". EPA website https://www.epa.gov/greenchemistry/green-chemistry-challenge-2023-greener-reaction-conditions-award (Accessed April 18, 2024).

[22] "ORNL welcomes sixth cohort of Innovation Crossroads clean energy entrepreneurs". Oak Ridge National Lab website. https://www.ornl.gov/news/ornl-welcomes-sixth-cohort-innovation-crossroads-clean-energy-entrepreneurs (Accessed April 18, 2024).

[23] Renewable Blending Components to Enable 100% Sustainable Aviation Fuel (SAF). Department of Energy website. https://www.energy.gov/sites/default/files/2023-01/2638-1508_Captis_Aire_LLC_Subtopic_Area_1_SummaryAbstract.pdf (Accessed May 10, 2024).

## VIII. FLUIDIZED BED CONCENTRATOR (FBC) APPLICATIONS:

Concentrator systems, including the FBC, are advantageously used in front of control devices when treating very high volumes of very dilute exhaust gas to reduce energy usage. Recovery systems are beneficial when the value of the recovered VOCs is high.

The following are a few examples where the FBC has been utilized historically.

| FBC Application | Chemistry |
|---|---|
| Adhesive Tape Mfg | Toluene |
| Agricultural Products | Organic Acid & Ammonia Odor |
| Aluminum Casting | Phenol, Formaldehyde, Ammonia |
| Animal Lab | Odor Control |
| Atomic Power Plant | Styrene |
| Auto Parts Degreasing | Trichloroethylene |
| Bakery | Odor Control |
| Brewery | Odor Control |
| Car Wash | Kerosene |
| Cellophane Coating | Toluene, Ethyl Acetate, Butyl Acetate |
| Ceramic Condenser | Terpineol |
| Confectionery | Odor control |
| Chemical Production | Toluene, Higher Molecular Weight Alcohols, Carbon Tetrachloride |
| Dye Production | Perchloroethylene |
| Electronics Mfg Plant | DMF, MEK, etc. |
| Electronics Parts Cleaning | Trichloroethylene, Toluene, 1,1,1-Trichloroethane |
| Fabric Washing | Perchloroethylene |
| Feed Processing | Odor Control |
| Film Coating | MEK, Methyl Cellosolve, Toluene, Tetrahydrofuran |
| Film Laminating | Toluene, Ethyl Acetate, n-Hexane |
| Gravure Printing | Toluene, Xylene, n-Propanol, n-Propyl Acetate, mixed |
| Iron Casting | Phenol, Formaldehyde, Ammonia |
| Lacquering of Film | Toluene, Ethyl Acetate, MEK |
| Landfill | Odor Control |
| LSI Mfg Plant | Phenol, Acetone, Methanol, Mixed Solvents |
| Lubrication Mfg | Mixed Solvent Odor Control Magnetic Tape, Chlorinated Hydrocarbon |
| Medicine Mfg Plant | Butanol, Methylene Chloride |
| Paint Booth | Thinner |
| Printing Ink Mfg | Mixed Solvents |
| PVC Resin Mfg Plant | Vinyl Chloride |
| Resin Mfg | N-Hexane, Methylene Chloride |
| Rubber Coating | Toluene |

| | |
|---|---|
| Rubber Vulcanizing | Odor Control |
| Sandpaper Mfg | Toluene, Xylene, Ethyl Acetate |
| Semiconductor Mfg | IPA, HMDS, NMP, Ethanol, Methanol, Ethyl lactate |
| Silk Screen Printing | Xylene, Mixed Solvents |
| Teflon Tubing Mfg | Perchloroethylene |
| Wastewater Aeration | Odor Control |

## IX. FLUIDIZED BED CONCENTRATOR (FBC) CASE STUDIES: [24]

| FLUIDIZED BED CONCENTRATOR: | |
|---|---|
| **Industry**<br>**Location**<br>**Inlet Stream**<br>**VOCs**<br>**Performance Achieved**<br>**Notes** | Semiconductor Chip Manufacturing<br>Israel<br>20,000 CFM<br>Semiconductor solvents, 50 ppmv<br>95% Reduction Efficiency<br>System located in populated area of a major city has eliminated nuisance odor |
| **Industry**<br>**Location**<br>**Inlet Stream**<br>**VOCs**<br>**Performance Achieved**<br>**Notes** | Semiconductor Chip Manufacturing<br>Arizona<br>36,000 CFM<br>Semiconductor solvents, 25-100 ppmv<br>90%+ Reduction Efficiency<br>System met strict local compliance requirements while achieving Zero Unscheduled Downtime (ZUD) |
| **Industry**<br>**Location**<br>**Inlet Stream**<br>**VOCs**<br>**Performance Achieved**<br>**Notes** | Teflon Tubing Manufacturing<br>Massachusetts<br>1,800 CFM<br>Perchloroethylene, 1500 ppmv<br>98% Reduction Efficiency<br>Recovered solvent re-used in process. System payback in 1 year. |
| **Industry**<br>**Location**<br>**Inlet Stream**<br>**VOCs**<br>**Performance Achieved**<br>**Notes** | Furniture Painting<br>California<br>50,000 CFM<br>Paint Solvents, 25-50 ppmv<br>90%+ Reduction Efficiency<br>Recovered solvent and reformulated with paint |
| **Industry**<br>**Location**<br>**Inlet Stream**<br>**VOCs**<br>**Performance Achieved**<br>**Notes** | Military Vehicles<br>Michigan<br>150,000 CFM<br>Paint Solvents<br>95% Reduction Efficiency<br>Controlled multiple different interchangeable VOC sources. |

[24] "Environmental C&C Inc". Environmental C&C website. https://www.environmentalcc.com/ (Accessed September 18, 2021).

| **Automotive Site, Alabama, 100,000 CFM**<br>**Paint Solvents, >90% Reduction Efficiency**<br>**Two adsorbers and one desorber** |
|---|
|  |

| **Military Vehicles, Michigan, 150,000 CFM**<br>**Paint Solvents, 95% Reduction Efficiency**<br>**System provided control of multiple different interchangeable VOC sources** | |
|---|---|
| **Image shows**<br>**three adsorbers**<br>**one desorber** |  |
| **Image shows ductwork that enabled control of any of the 3 sources to any of the 3 adsorbers.**<br><br>**Each adsorber has its own process fan.** |  |

## X. APPLICATION OF THE FBC TECHNOLOGY SPECIFIC TO WOOD DRYING:

- **FBC DEMONSTRATION DESCRIPTION:**

Captis Aire founder and Environmental C&C worked on a project together from 2015-2021 with a commercial oriented strand board (OSB) manufacturer to demonstrate the ability to utilize the FBC to control emissions from wood drying.

In wood products manufacturing, process gas exhaust streams released from drying wood contain VOCs, including turpentine (terpenes). These VOCs are considered pollutants/emissions and must be removed from the air prior to release to avoid air pollution emissions into our communities. Wood drying operations utilized in the manufacture of oriented strand board (OSB), lumber, wood pellets, wood to liquid biofuels, plywood, particleboard, etc. are few examples of these processes that have process exhaust streams containing VOCs including terpenes.

Work on this patent[25] pending[26] technology was executed in three phases:

1. In the first phase, laboratory screening work was done to explore whether emissions from wood drying, primarily terpenes, could be adsorbed by Bead Activated Carbon (BAC) at the expected operating temperatures. Success was demonstrated via terpenes adsorption at expected operating temperatures.
2. In the second phase, a small-scale pilot adsorber was installed at a commercial oriented strand board (OSB) manufacturing site to demonstrate ability to adsorb emissions from wood drying under commercial manufacturing conditions. Success in this demonstration enabled funding for a much longer, much more comprehensive demonstration.
3. In the third phase, the pilot unit capabilities were expanded to include the adsorber, desorber, and condenser. The SSR performance was simulated by semi-continuous additions of virgin BAC during air emissions compliance testing. The pilot unit ran for 6 months with over 1700 hours on-line. Ability to meet air emissions control compliance, per the Plywood and Composite Wood Products Maximum Achievable Control Technology (PCWP MACT) requirements, was determined by two independent certified air emissions[27] stack testing companies[28] during two separate testing events. The FBC system successfully met the PCWP MACT requirement of >90% Reduction Efficiency in

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[25] "Methods and Systems for Recovering Terpene Compositions from Wood Drying Exhaust". World International Patent Office (WIPO) Website. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019148208 (Accessed Sept 18, 2021).

[26] "Methods and Systems for Controlling Emissions from Wood Drying Processes". WIPO Website. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019148207 (Accessed September 18, 2021).

[27] "AIR Advanced Industrial Resources". AIR website. https://airtest1.com/ (Accessed April 16, 2020).

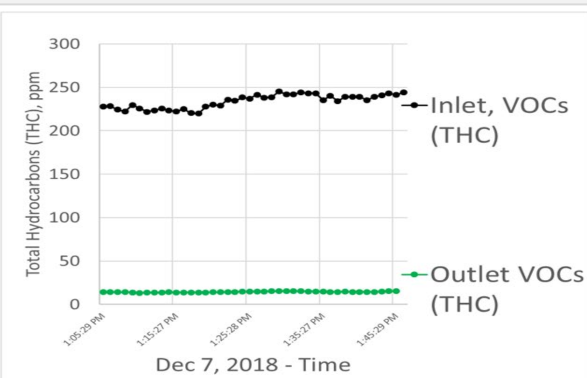
[28] "Testing and Modeling". John Zink Hamworthy Combustion website. https://www.johnzinkhamworthy.com/testing-modeling/ (Accessed Feb 3, 2021).

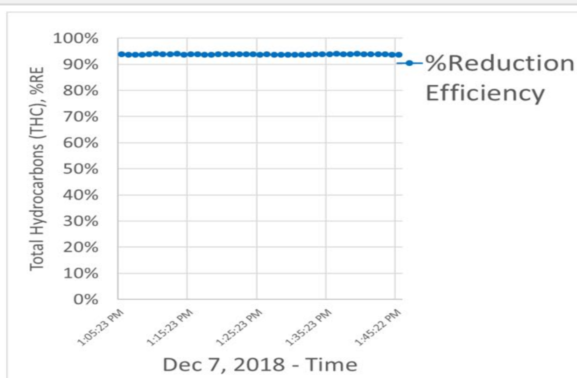
both tests.  In the second test, the system successfully met the compliance requirements three times in a row, over each of the three one-hour testing intervals.

- **RESULTS OF FBC AIR POLLUTION CONTROL COMPLIANCE TESTING:**

| **Emissions Measured:** | **FBC %Reduction Efficiency** |
|---|---|
| Total Hydrocarbons (THC), as carbon including Methane | 92% |
| Volatile Organic Compounds (VOCs), as carbon.<br>(Total non-methane hydrocarbons – THC minus Methane) | 92% |
| Formaldehyde | 83% |
| Methanol | 75% |
| GHC - Nitrogen Oxides (NOx) | 55% |
| Particulate Matter (PM), total filterable | 50% |
| Condensable Particulate Matter | 59% |
| Total Particulate Matter, Filterable + Condensable | 51% |
| Total PM2.5, Particle Size Analyses (PSA) Filterable + Condensable | 60% |
| Total PM10, Particle Size Analyses (PSA) Filterable + Condensable | 64% |
| Carbon Monoxide (CO) | 7% |
| Sulfur Dioxide (SO2) | 99% |

- **RESULTS OF VOC REDUCTION EFFICIENCY PERFORMANCE MEASURED BY FLAME IONIZATION DETECTOR (FID):** [29]
  - >90% Reduction Efficiency




[29] Advanced Industrial Resources, Inc. emissions testing results from the FBC at commercial wood drying site in 2018.  Results were demonstrated during three 1-hour testing intervals. https://airtest1.com/ .  (Accessed September 18, 2021)

- **RESULTS OF FBC VOLATILE ORGANIC COMPOUNDS CAPTURE:**

Terpenes were collected from the pilot unit. These terpenes are a mixture of terpene hydrocarbons, primarily Alpha and Beta pinenes. These terpenes are responsibly-recovered, biobased materials. Potential applications for these terpenes include use in fuels, fragrances, solvents, adjuvants, cleaners, polyterpene resins, etc.

**Terpenes Collected from Pilot FBC**


- **VALUE OF TERPENES:**

The Pine Chemicals Association has documented gallons of terpenes per oven dry ton of wood in a variety of tree species. Typically, there is ~1 gallon of turpentine (terpenes)[30] per oven dry ton of wood product produced from green pine wood from the SE part of the United States, i.e. Loblolly Pine, Jack Pine, Slash Pine, Shortleaf Pine, Ponderosa Pine, Pitch Pine, Pond Pine, Red Pine, and Spruce Pine. If 75% of this is evaporated and captured from the drying process, the value of the terpenes per year can be calculated by multiplying this yield by the oven dry tons (ODT) of wood produced and the typical price per gallon[31] for terpenes.

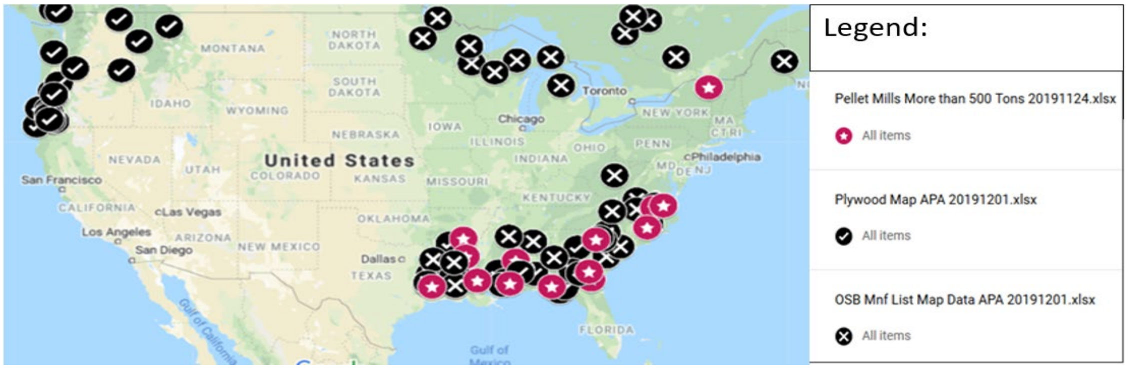
$$\left(\frac{1\ Gallon\ Terpenes}{ODT\ Wood}\right) * \left(\frac{ODT\ Wood}{Year}\right) * (\%Yield) * \left(\frac{\$\ Dollars}{Gallon\ Terpenes}\right) = \$\ /\ Year$$

- **TERPENES TYPICAL PROPERTIES:**

| | |
|---|---|
| **Appearance** | **Clear Liquid** |
| **Moisture** | <0.1% |
| **Weight per Gallon** | 7.2 pounds per gallon |
| **Specific Gravity** | 0.86 |
| **Sulfur Content** | < 10 ppm |

[30] "Sulfate Turpentine Recovery". Pulp Chemicals Association. Pages 9-12 and 127. https://www.pinechemicals.org/store/viewproduct.aspx?id=1579188 (Accessed Jan 2, 2022).
[31] "Price Chart for Gum Turpentine". PineChem website. http://www.pinechem.net/images/gall/ChartGNE.GIF Accessed Jan 3, 2022).

- **MAP OF POTENTIAL WOOD DRYING SITES FOR FBC USE:**




This map shows potential sites where various wood products are produced where the FBC may be used to control emissions. Potential sites include but are not limited to oriented strand board (OSB), lumber[32], plywood[33], wood pellets[34], wood to liquid biofuels[35], particleboard, medium density fiberboard (MDF), etc.

- **RESULTS OF DISCUSSIONS WITH ENVIRONMENTAL AGENCIES:**

Official stack testing results were discussed with two state environmental agencies and two federal environmental protection agency (EPA) personnel. In all discussions, environmental agency personnel were supportive of providing a permit for full size commercial FBC system.

- **FINAL RESULTS FROM WOOD DRYING DEMONSTRATION:**

  - The FBC system demonstrated good operational reliability.
  - Salable terpenes, composed primarily of Alpha and Beta Pinenes, were collected.
  - The FBC pilot met the PCWP MACT requirement of >90% Reduction Efficiency[36] in both tests. In the second test, the system met the compliance requirements three times in a row, over each of the three one-hour testing intervals.
  - No natural gas was used and thus greenhouse gas emissions were reduced.
  - State and Federal environmental personnel reviewed these results and were supportive of permitting for a full commercial FBC system.

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[32] "The mill map allows you to visually locate and drill down to find the mill you're interested in." Primary Forest Products Network website. https://primary.forestproductslocator.org/mill-map (Accessed September 18, 2021).

[33] "Manufacturer Directory". Engineered Wood Association website. https://www.apawood.org/manufacturer-directory (Accessed September 18, 2021).

[34] "Biomass Magazine". Biomass Magazine website. See http://biomassmagazine.com/plants/map/pellet/ (Accessed September 18, 2021).

[35] "We Create Renewable Fuel from Wood Waste". USA BioEnergy website. https://usabioenergy.com/ (Accessed January 22, 2022).

[36] "Electronic Code of Federal Regulations (eCFR)". eCFR website. See Table 1B https://www.ecfr.gov/cgi-bin/text-idx?node=sp40.13.63.dddd#ap40.14.63_12292.1 (Accessed April 16, 2020).

## XI. CONCLUSIONS:

Regardless of what control technology you use, if you have a high volume, dilute exhaust stream you probably want to consider using a capture concentrator system upstream of the control device to reduce the exhaust gas volume to process. Capture concentrator systems utilize an adsorbent media such as activated carbon or zeolite to first capture (adsorb) the VOCs. The VOCs are subsequently released typically via heating with hot gases or steam into a much smaller exhaust stream. Capture concentrators may be configured as vessels, equipment with trays, or wheels containing activated carbon or zeolite. With an efficient concentration step, a smaller control device may be used to treat the resulting concentrated exhaust. As a result, total operating costs may be reduced.

The Fluidized Bed Concentrator (FBC) provides an affordable, reliable, and accessible clean technology for control of VOCS, HAPS, and even particulate control in some applications. This technology is well established in many applications including electronics and lead parts manufacturing processes where it has been used successfully for many years. It is an emerging technology for use in wood drying applications.

Especially for process exhaust streams with low VOC concentrations, the FBC technology is a patent[37] pending[38], cost competitive, industrial air pollution control technology that enables operators to advantageously:

1. Generate revenue via sales of recovered organic products, including biobased products in biomass applications, and sales of carbon offsets
2. Improve sustainability by reducing energy usage and reducing greenhouse gas (GHG) emissions
3. Reduce operational costs by reducing energy usage (natural gas and electricity) and maintenance costs
4. Enhance VOC mass transfer to BAC to maximize capture efficiency
5. Provide continuous in-situ BAC regeneration and reactivation to enable BAC reuse
6. Minimize water content of BAC thus maintaining its ability to adsorb VOCs even in high moisture content process exhaust streams

Like any air pollution control technology retrofit, careful consideration of many design parameters and the unit's specific operating profile and goals need to be considered during the design, installation and startup/optimization processes. There are excellent resources to assist with evaluating, implementing, and optimizing capture concentrator air pollution control systems.

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[37] "METHODS AND SYSTEMS FOR RECOVERING TERPENE COMPOSITIONS FROM WOOD DRYING EXHAUST". World International Patent Office (WIPO) Website. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019148208 (Accessed September 18, 2021).

[38] "METHODS AND SYSTEMS FOR CONTROLLING EMISSIONS FROM WOOD DRYING PROCESSES". WIPO Website. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019148207 (Accessed September 18, 2021).

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