2024 ChemE Cube^{TM} Problem Statement

Document Revision History

Version (Date)	Comment
1.0 (January 2024)	Initial release of 2024 competition rules
2.0 (March 2024)	Updated Criteria Table with points. Included a duel calculator. Explanation of scoring breakdown.
3.0 (September 2024)	Added link for required quick connect adapters for cubes.

ChemE Cube™ Competition 2024

Problem Statement: Modular Direct Air Capture

Business Objective

The carbon cycle is nature's way of recycling carbon atoms from the atmosphere to the terrestrial organisms, ocean, land, and then back into the atmosphere. With the introduction of human carbon emissions, there has been a net positive increase of carbon dioxide in the air. Carbon dioxide emissions are the largest greenhouse gas (GHG) emissions globally, accounting for 76% of all GHG emissions annually[1] and reaching 34.8 billion tons in 2020.[2]

The rising CO_2 emissions leads to increasing global temperatures, rise in ocean acidification, and disruption of ecosystems. The effects of climate change can directly and indirectly impact human health. In order to take into account this global issue, the 2015 Paris Climate Change Agreement was enacted in order to combat the rise of global CO_2 emissions. Its goal is to limit global warming to preferably 1.5°C.[3]

There are different ways to reduce the amount of CO_2 emitted. Conserving energy, efficient energy use, switching fuel type, and changes in use of land and land management practices help reduce the amount of CO_2 emitted. Carbon capture and storage (CCS) can be used to capture CO_2 at the point where it is emitted to keep it from entering the atmosphere. However, even after employing all of these approaches, many external technology assessments[4] suggest that additional steps will be needed to meet stated climate goals. This includes the deployment of direct air capture technologies, where CO_2 in the air is removed and sequestered.[5] This is what your design will aim to achieve.

You are tasked with creating a modular direct-air capture mini-plant with both adsorption and regeneration that can fit inside a cube that is 1-foot in length, width, and height. Your mini-plant must capture CO_2 from surrounding atmospheric air. It is also important that your cube design is efficient so that the CO_2 emissions that come from the energy (used to power the mini-plant) is low. You will have a maximum budget of $1,500 for your first-of-a-kind prototype. Your design should be marketable as a modular CO_2 capture device. Ultimately, it should create an impact by demonstrating technological breakthroughs, be able to address a market, and finally, benefit humanity.

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[1] https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data
[2] https://ourworldindata.org/co2-emissions
[3] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[4] https://www.iea.org/reports/net-zero-by-2050
[5] An updated roadmap to Net Zero Emissions by 2050 – World Energy Outlook 2022 – Analysis - IEA

Related Efforts

The following related efforts may help to provide clarity and resources to you as you develop your cube:

- The United States' National Energy Technology Laboratory Direct Air Capture (DAC) Center supports rapid development and commercialization pathways for technologies that remove CO_2 from the atmosphere.[6]
- The Justice40 Initiative[7] was enacted by President Biden to ensure that 40% of the overall benefits of certain Federal investments go to communities that are underserved and overburdened by pollution. A cube such as this has the potential to address disproportionate needs of underserved communities.
- XPRIZE hosts a competition revolved around the removal of carbon dioxide.[8] They have noted three grand challenges that come with carbon dioxide removal: 1} Massive scale required for carbon dioxide removal, 2) Current DAC solutions are too expensive, and 3) Structural incentives are lacking from both the government and markets.
- The Direct Air Capture (DAC) Coalition supports the international effort to address the climate challenge by bringing together diverse, leading global innovators to educate, engage, and mobilize DAC technology.[9]
- Carbon Dioxide Removal Primer is a new online resource on the fundamentals of carbon dioxide removal and its role in addressing the climate crisis.[10]

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[6] https://netl.doe.gov/dac

[7] https://www.whitehouse.gov/environmentaljustice/justice40/#:~:text=What%20is%20the%20Justice40%20Initiative,underserved%2C%20and%20overburdened%20by%20pollution.

[8] $100M Prize For Carbon Removal | XPRIZE Foundation

[9] Direct Air Capture Coalition (daccoalition.org)

[10] https://cdrprimer.org/

Technical Objectives

Cubes will be supplied with DC current only to allow for the use of off-grid power sources such as solar or wind power. For safety reasons, cubes may not exceed 10A or 120 watts. Cubes operating at a higher wattage will not pass safety inspection and therefore will not be able to compete. Regulated 12 V DC power will be provided for the competition. Your plant must use exactly 12 V. Power will be provided from standard banana jacks (socket) color coded red and black to indicate polarity. Ensure that your plugs are not "bulging" out and are uniform in size to ensure a proper connection with the power supply. (See image below for reference). Cubes should provide suitably insulated, properly gauged leads not less than 12ft in length terminated in standard banana plugs to access the provided power. During the duels, total power consumption will be measured by each cube and be included in the scoring rubric.

Figure 1: Male banana plugs

<u>Cube Input</u>

- Teams will need to pull air (via suction) from the air inlet ballast tank into their system. This is to prevent large fluctuations of CO_2 concentrations during the duel. Air will NOT be pumped into your system. There will be no required inlet flowrate. Teams will choose their own inlet flowrate to hit the target concentration they wish to hit. This encourages teams to find the perfect balance when designing their cubes. (Note: the max flowrate allowed is 1.5L/min)

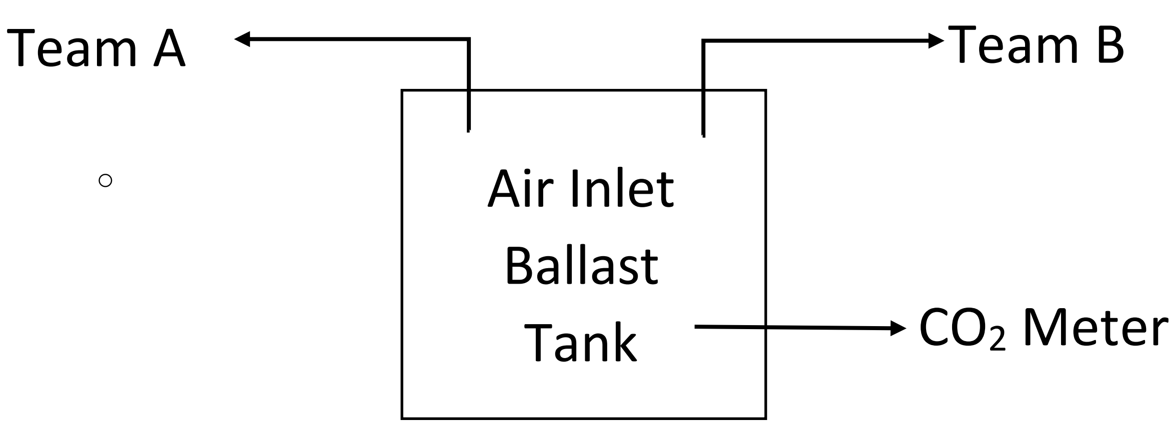

Figure 2: Duel setup

- Connection Point Requirement: You must use PVC tubing with ⅛ inch I.D. and ¼ inch O.D. (or have an adapter) to ensure proper connection with the CO_2 meter.
- Teams that do not have an inlet/outlet pipe directly incorporated into their cube must use quick connect adapters that are attached to their cubes that will connect with the scoring flowmeter and CO_2 meter. It must be compatible with PVC tubing with ⅛ inch I.D. and ¼ inch O.D. (or have an adapter).

Cube Output

- There is no required outlet flowrate. Teams do not need to install their own flowmeter at the outlet. RAPID will attach the "scoring" flowmeter at the outlet of the cubes. The maximum measurable outlet flowrate on the scoring flowmeter is 1.5 L/min.
- Connection Point Requirement: You must use PVC tubing with ⅛ inch I.D. and ¼ inch O.D. (or have an adapter) to ensure proper connection with the CO_2 meter.
- Teams that do not have an inlet/outlet pipe directly incorporated into their cube must use quick connect adapters that are attached to their cubes that will connect with the scoring flowmeter and CO_2 meter. It must be compatible with PVC tubing with ⅛ inch I.D. and ¼ inch O.D. (or have an adapter).
    - Link to buy PVC tubing with ⅛ inch I.D. and ¼ inch O.D.: DERNORD PVC Tubing 1/8"ID X 1/4"OD Flexible Clear Vinyl Hose 50 Feet for Food Grade: Amazon.com: Industrial & Scientific
    - Link to buy quick connect adapter: Amazon.com: TAILONZ PNEUMATIC Male Straight 6mm Tube OD x 1/4 Inch NPT Thread Push to Connect Fittings PC6-N2 (Pack of 10) : Industrial & Scientific

Regeneration Paper Study

Due to the difficulties of incorporating a regeneration step in your cubes for the competition (safely in a conference center environment), we are introducing a unique approach this year. There will be a paper study of various regeneration methods. Each regeneration method will have its own price and will be taken into account in the "Total Cost to Capture" criteria. The price of the regeneration will be calculated based on the energy/heat required to bring the specific adsorbent to its regeneration temperature, and to overcome the desorption/reaction energies necessary to evolve CO_2. Regenerations for systems with stronger CO_2 binding energies will be more energy intensive, and some proposed methods will have added complexity accounted for in the cost to regenerate. The amount of material subject to this regeneration calculation will be based on your total sorbent weights, regardless of actual CO_2 loading in the duel. As such, it behooves you to minimize excess sorbent in your cube. You will provide justification for the method chosen in the Engineering Design Package (EDP) to match your cube's capture technology. Below are the possible categories you may choose for regeneration:

- Strong aqueous base
- Strong aqueous base with causticization step (cube must precipitate a calcite during the duel in order to claim this regen benefit)

- Strong aqueous base with a Bi-Polar Membrane Electrodialysis system (cube must include a BPMED membrane use in the duel to claim this regen benefit)
- Liquid amine (i.e. MEA)
- Amino Acid based capture system (i.e. PyBIG)
- Ion exchange resin with TSA
- Ion exchange resin with TVSA (applicants must provide supplemental assessment why TVSA is more economical or feasible than TSA)
- Supported MOF with TSA
- Supported MOF with TVSA (applicants must provide supplemental assessment why TVSA is more economical or feasible than TSA)
- Supported amine (i.e. PEI) with TSA
- Supported amine (i.e. PEI) with TVSA (applicants must provide supplemental assessment why TVSA is more economical or feasible than TSA)
- Algae/Bio base assuming some form of bio-sequestration (i.e. BECCS)
- Moisture Swing (i.e. ion exchange resin)

In addition to the score-contributing regeneration cost calculation based on the qualifying methodology, teams must provide calculations explaining the expected regeneration costs for their DAC systems. These calculations should use literature citations or commercial product specifications to define the sorbent specific regeneration temperatures, heat capacities, heats of reaction, sorbent loadings, type of energy inputs, energy prices, a description of the process flow required to perform the regeneration, and a calculation showing what you would expect your regeneration costs would be on a $/tonne of sorbent, and $/tonne CO_2 basis.

Weight regulations

Your cube will be measured twice during the competition, in order to correctly measure the total amount of adsorbent in your cube. The first weigh-in will take place during the safety inspection. Here, cubes will have no adsorbent loaded. The second weigh-in will take place during the duel. Here, cubes will be loaded with adsorbent. Major physical modifications are not allowed in between the two weigh-ins. If a small modification is needed, your cube will be weighed again.

CO_2 Capture Wager

Duels will also include an aspect to allow teams to demonstrate their control of the DAC reactions in their cube systems. At the beginning of each duel, teams will be told what the current CO_2 concentration is within the Air Inlet Ballast Tank and they will need to submit a wager on the total amount of CO_2 their cube will capture during the duel. Wagers should be made as standard volumes of CO_2 in mL. Your total duel score will be impacted based on how close your team gets to capturing your wagered volume of CO_2.

Score Calculator

A duel/score calculator can be found here under competition materials. Teams will be able to input their own values and freely choose the different regeneration methods as listed above. There are two tabs in the calculator; Regeneration Costs and Duel Calculator. Under the "Regeneration Costs" tab, you will find a list of the different regeneration methods and their associated costs. Under the "Duel Calculator" tab you will find a mock duel setup of two different teams and their respective collected data over a duel.

Duel Timing

Format: Each team will compete in two head-to-head duels; each takes place over 20 minutes.

- The first 5 minutes will be setup/startup of the cube.
  - Note that any CO_2 capture capacity consumed during this setup period will NOT count towards your total CO_2 captured, so make sure that your set-up/start-up procedure is appropriate to maintain the viability of your capture device during the duel
- The next 10 minutes, the cube will run autonomously.
  - This will be the recorded period during which the duel will be scored. Outlet air concentration, flow rate, temperatures, and cube power consumption will be measured and recorded continuously during this period.
- Final 5 minutes will be the shutdown and disconnection of the cube.

Scoring Breakdown:

A total of 1000 points can be scored across the competition:

- Duel: Maximum 600 points
  - Maximum 250 points per duel
  - Bonus points ranging from 5-100 are awarded to the top 8 teams with the lowest total cost to capture
    - 1st Lowest: 100 Points
    - 2nd Lowest: 90 Points
    - 3rd Lowest: 75 Points
    - 4th Lowest: 60 Points
    - 5th Lowest: 45 Points
    - 6th Lowest: 30 Points
    - 7th Lowest: 15 Points
    - 8th Lowest: 5 Points
- Pitch: Maximum 200 Points
- Ad: Maximum 100 Points
- Poster: Maximum 100 Points

Refer to the rubric for each element of the competition for a comprehensive scoring breakdown.

- Cube Criteria

Table 1. ChemE Cube: Direct Air Capture Criteria

Criteria	Lower Limit Upper Limit	Point Values	How the criteria are measured
Total CO_2 Captured Weighted by Cube Cost (mL/$)	Head-to-head scoring. The team with the higher value after adjustment from the CO_2 wager will receive full points.	30	Taking the average CO_2 captured across 10 minutes, dividing it over the cost of the cube.
Total CO_2 Captured Weighted by Power Consumption (mL/Wh)	Head-to-head scoring. The team with the higher value after adjustment from the CO_2 wager will receive full points.	30	Taking the average CO_2 captured across 10 minutes, dividing it over the total power consumption.
Total CO_2 Captured Weighted by Cube Mass (mL/kg)	Head-to-head scoring. The team with the higher value after adjustment from the CO_2 wager will receive full points.	30	Taking the average CO_2 captured across 10 minutes, dividing it over the weight of the cube (measured before the duel).
Total Cost to Capture ($/g CO_2)	Head-to-head scoring. The team with the lower value will receive full points.	120	This criteria incorporates team's power consumption, cost of materials, and the regeneration step chosen.
CO_2 Wager	Teams wager how much CO_2 they think their cube can capture. The closer a team is to their wager, the higher the score multiplier is that will be applied to the three weighted CO_2 capture criteria. No direct points are given to the team with the closest wager.		
The following criteria are associated with the safety of operating your team's cube. By applying for the competition, you are indicating that your team has fully reviewed and agrees to follow the ChemE Cube Safety Program, documents can be found on the ChemE Cube website.			
Temperature of Exhaust Stream	Points are given to teams if criteria is met. No head-to-head scoring.	20	Temperature must not exceed 75F due to safety considerations.