Reduction of Jet Engine Testing Emissions Through Adsorption of Carbon Dioxide

A Collaboration with General Electric Aerospace

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Process Scope

This project aims to develop a system to capture the carbon dioxide released during jet engine testing at General Electric Aerospace. To achieve the sustainability goals set by GE, the CO_2 emissions released from the combustion of jet fuel must be captured before it is released into the atmosphere.

The design basis of this facility was extracted from engine testing data of the largest engine, the GE9X, to determine the maximum air flow and composition of the air based on fuel consumption. The carbon capture facility is projected to capture 80-95% of the carbon emitted from the exhaust resulting in a maximum of 97,000 lbs/hr and 110 million pounds of CO_2 yearly.

Process Synthesis

Adsorption using activated carbon was selected due to cost-effectiveness, feasibility, sorbent regeneration, and separation efficiency. Adsorption of CO_2 in a fluidized bed was chosen as this design is capable of handling large gas volumes at high velocities to increase the contact between the gas and the solid sorbent. As opposed to a fixed bed, a fluidized bed's adsorption ability is dictated by the cross-sectional area of the reactor. Because of this, the bed height is significantly reduced when using a fluidized bed. The residence time to bed height ratio was optimized to reach an adequate theoretical adsorption of CO_2 and tower height. Each tower contains 23, 2-meter fluidization sections that contain four fluidized beds. The sections each have a flue gas outlet and vane axial fan to overcome the pressure drop during fluidization without disrupting the test cell pressure.

The design of the processing facility was based on the maximum exhaust flow rate of the largest engine in GE Aerospace's fleet, GE9X, during acceptance testing. This provides an overestimate of AC handling, production capabilities, and CO_2 production. Only a fraction of the acceptance test operates at maximum capacity while the average flow rate is nearly half of what was modeled for this design. For this reason, with further work and analysis of exhaust gas flow, the operational requirements would be much less than what is presented. The maximum flow was modeled to ensure the system could handle material across the range of flow rates experienced during testing. An alternative route of capturing the exhaust gas and then processing it as a batch under controlled flow was considered; however, containing the amount of gas expelled during a test poses safety and operational risks greater than immediate gas processing.

Table 1. Exhaust Gas Components

Component	% Weight
O_2	22.9%
N_2	76.6%
H_2O	0.15%
CO_2	0.36%
NO_x	0.0029%
SO_x	0.00008%

Table 2. Hourly Feed/Production Rates

Stream	Max. Flow (kg/h)	Avg Flow (kg/h)
Feed		
AC Feeder	31,200	15,800
Exhaust Gas	12,320,000	6,220,000
Production		
Flue Gas	12,276,000	6,206,000
CO_2 Product	44,000	14,000

Table 3. Alternative Technology Matrix

Commercially available carbon capture technologies were evaluated on the below categories to determine an appropriate method applicable to the volume of this process.

	Feasibility	Main Unit Operator	Estimated Price	Safety	% CO_2 Removal	Sorbent (Price/ Availability/ Quantity)	Operational Burden	Total
Absorption with Amine Solvent	3	4	1	3	5	2	3	21
Absorption with Tertiary Blend Solvent	3	4	1	2	4	2	3	19
Adsorption with MOF	1	3	2	3	3	2	2	16
Adsorption with AC	**5**	**3**	**4**	**3**	**3**	**4**	**4**	**26**
Calcium Looping	2	3	5	2	4	4	3	23

Weight: 1 – Insufficient, 3 – Sufficient, 5 - Excellent

Table 4. Material and Energy Balance

Type	Stream / Unit Op	Flow In (lb/h)	Energy In (MMBtu/h)	Flow out (lb/hr)	Energy Out (MMBtu/h)
Feed Stream	Exhaust Gas	27165822	-609.1		
	A-100	68918			
Product Stream	Flue Gas			27068456	-234.8
	CO2 product			97366	-375.3
V-140 Desorption	Heating		1.8		
	Cooling				1.8
Chilled Water Cooling	E-150	4301	4.9	4301	
	E-160	2353	2.7	2353	
	E-170	2074	2.4	2074	
	E-180	2099	2.4	2099	
	E-190	1946	2.2	1946	
Compressor	C-145				2.8
	C-155				2.1
	C-165				1.8
	C-175				1.6
	C-185				1.3
Total		**27,250,000**	**-600**	**27,250,000**	**-600**

Abstract

To assist General Electric Aerospace in their 2030 goals of carbon neutrality, this project aimed to design a carbon capture system to work in conjunction with their existing jet engine testing facility. After exploring several carbon capture methods, the team continued with an activated carbon (AC) adsorption system. This carbon capture system contains six multi-stage fluidized bed reactors with a gas distribution manifold. These reactors contain 23 fluidization sections with a pressure drop of 0.02 atm across each. Desorption occurs in an electrically heated/cooled vessel that is vacuum-rated to withstand the maximum pressure exerted by the compression train. The gaseous CO_2 product is liquefied through a series of compressors and heat exchangers until it becomes a supercritical fluid. The maximum CO_2 output of this process is 97,000 lb/hr at 1112.5 operating hours per year; however, the acceptance testing does not run at the maximum engine throttle throughout the course of testing, so this is not representative of the true output of CO_2 by the test cells.

The objective of this project is to assist GE Aerospace in carbon neutrality goals without the need to purchase carbon credits to offset emissions. In 2030, the expected cost of carbon credits based on annual CO_2 emissions would be $8,000,000 yearly. To have an economically attractive process, the capital investment and annual operating cost must be less than the accumulation of the carbon credit payments over a period of years. Liquefied CO_2 can be sold for use in other industries, potentially offsetting the cost of the capture facility further. The current Total Capital Investment was calculated at $528 million, and the estimated annual operational costs were found to be $97.7 million.

Recommended Process

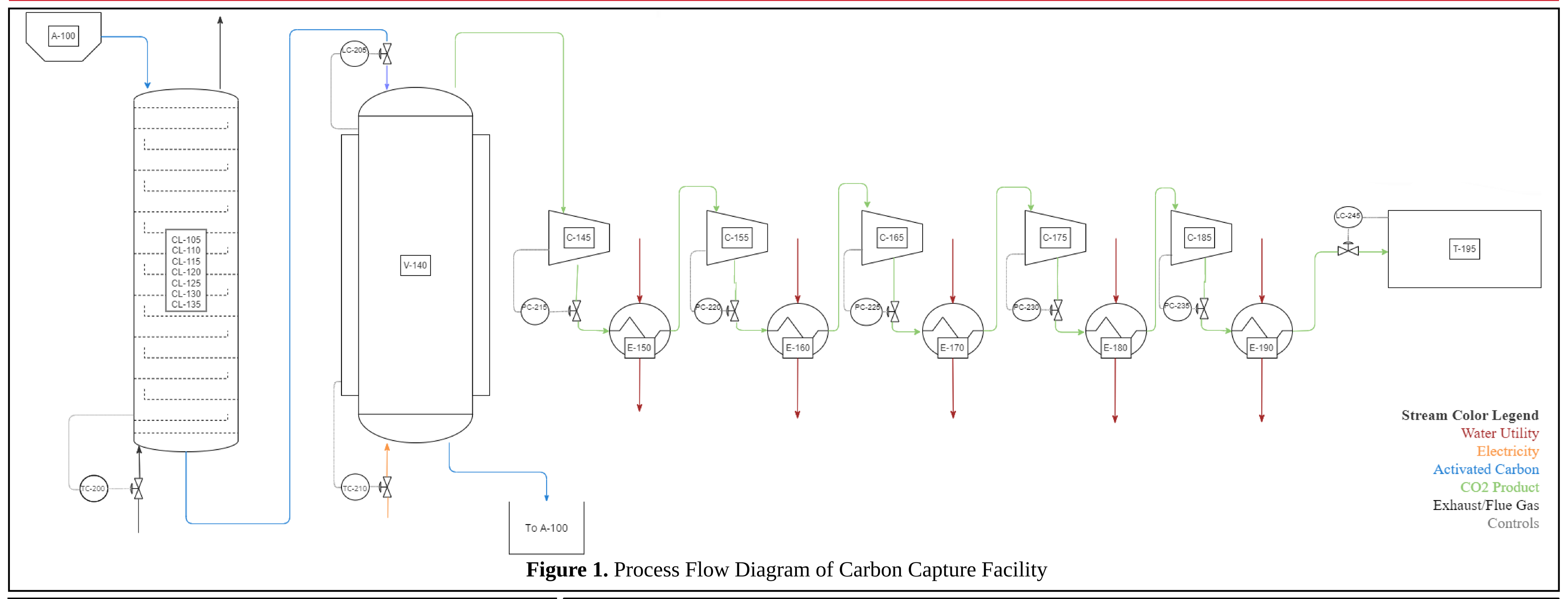

Figure 1. Process Flow Diagram of Carbon Capture Facility

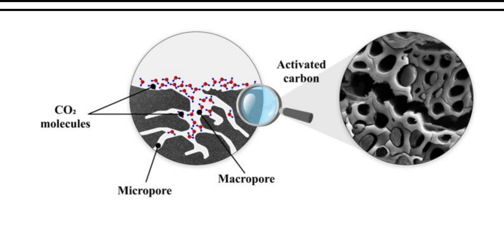

Figure 2. Surface Adsorption of CO2 on Activated Carbons (Serafin and Dziejarski, 2023)

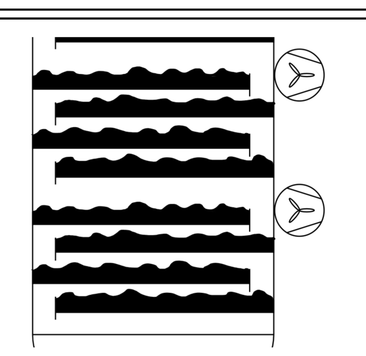

Figure 3. Visualization of Fluidized Bed Adsorption Tower Stages

Sorbent
- Pre-treatment of gas for removal of other pollutants not required
- AC selectivity for CO_2 ensured by pore radius of 8.9 Å

Adsorption of CO_2
- A gas manifold separates and distributes exhaust gas to the six adsorption towers
- Exhaust gas enters the bottom of the tower while a volumetric feeder transfers activated carbon through the top of the tower
- Maintains driving force within the tower by introducing the freshest AC where the lowest CO_2 concentration exists

Desorption of CO_2
- Adsorbate is collected into the desorption vessel throughout the course of a test
- Desorption vessel operates as a batch process
- Temperature is increased to release of CO_2
- Sorbent is regenerated by cooling to ambient and sending back to the feeder. Sorbent can be recycled for 200 cycles (approximately 800 operating hours)

Compression Train
- Purified CO_2 gas is compressed it into a supercritical fluid by a series of compressors and heat exchangers

Process Safety & Environmental Performance

Table 5. Process Chemical Hazards

Compound	Health Hazards	Fire Hazards	Reactivity Hazards
CO_2	Inhalation risk, frostbite risk	N/A	Explosion risk if heated
CO	Inhalation risk	Category 1 flammable gas	Explosion risk if heated
NO_x	Eye damage, burn risk, inhalation risk	Extremely flammable in reducing & combustible materials	Explosion risk if heated
SO_2	Eye damage, inhalation risk	N/A	Product is stable
H_2O	No health hazards	N/A	N/A
AC	No health hazards	N/A	Incompatible with oxidizing agents especially when heated

The process hazard analysis (PHA) utilized the What-If methodology to guide the design of safeguards and controls for this process.

PHA Recommendations

1. Consider adding pressure sensors to alert high-pressure in the compressor trains.
2. Consider adding gas sensors and alarms to alert for leaks in the system.
3. Consider adding insulation to piping in the compressor train.
4. Consider installing temperature sensors to prevent out of scope temperature values in the fluidized bed adsorber.
5. Consider installing flowmeters to monitor flow rate and set safe parameters in the fluidized bed adsorber.
6. Consider adding a weight sensor to ensure the correct amount of activated carbon is added prior to the reaction in the fluidized bed adsorber.
7. Consider installing a flow sensor to alert for high flow rates in the gas manifold.
8. Consider adding insulation in the piping of the gas manifold.

Environmental Performance
- Waste is limited to off-gas from reactors and spent activated carbon.
- Off-gas from adsorption will be vented out of the facility.
- Cooling water and steam could be recycled with future work.
- High-pressure and temperature gases pose the most risk.
- 80% of the CO_2 emissions are expected to be captured.

Open Issues
- Ensuring the desorption vessel is rated at a pressure greater than the maximum pressure of the compression train to prevent a failure scenario
- Operator training to ensure safe and proper plant operation
- How to perform a sorbent change after 800 operating hours

Economic Analysis

GE Aerospace aims to achieve carbon neutrality by 2030 through carbon capture at the emission source or purchase of carbon credits; therefore, this process is considered desirable if the capital and production costs with sale of liquefied CO_2 offsets the cost of purchasing carbon credits over the estimated lifetime of the facility.

Annual Economic Evaluations:
Estimated Carbon Credit Cost: $7.90 million by 2030, $12.9 million by 2050
Potential Sales of CO_2: $31.3 million
Production Costs: $97.7 million

Total Capital Investment: $528 million

The process design and economic evaluation were based on the maximum exhaust gas flow rate. As the engine only reaches this output for a fraction of the acceptance test and subsequent carbon capture, these calculations overestimate the process output and cost of production.

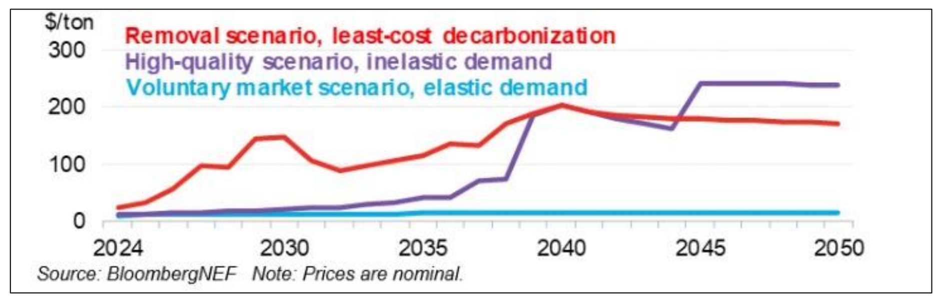

Figure 4. Projected Cost of Carbon Credits by 2050 (BloombergNEF)

Table 6. Operating Costs

Raw Materials	$0.39 MM
Utilities	$46.0 MM
Operations	$0.805 MM
Maintenance	$30.9 MM
Operating Overhead	$18.4 MM
Depreciation	$0.913 MM
Cost of Manufacture	$97.4 MM
Total Production Cost	$97.7 MM

Technology Risk

Activated Carbon Adsorption/Desorption Scale-Up
- Processes have only been proven for capture efficiency in pilot-scale operations
- Underutilized in industrial applications, new issues may arise from new technology

Carbon Dioxide Storage/Transportation
- CO_2 product will be stored in a tank as a supercritical fluid
- Holding tank leakage could lead to indirect CO_2 emissions
- Issues with the holding tank could pose economic impacts for the sale of the product
- Transportation of the liquid CO_2 is technically out of scope, but business issues could arise if there is a problem with transportation and the tank is full

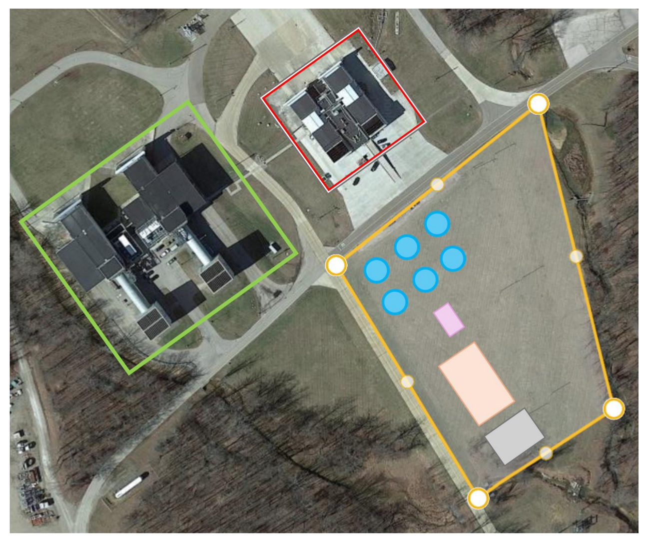

Figure 5. Siting of Test Cells A/B (Red), C/D (Green), Fluidized Bed Reactors (Blue), Desorption Bed (Pink), Compressor Train (Orange), and Storage Tank (Gray) at GE Aerospace Testing Facility (Image Generated by Google Earth)

Siting Consideration

The process boundary for this processing plant will begin at the exhaust sources. The carbon capture plant will sit on an open field that is approximately 21,000 m^2.

Recommendations

It is the recommendation of Team 5046-2403 to continue refining design elements, optimizing the process, and implementing testing to ensure scalability of the facility. With the implementation of this processing facility, GE Aerospace would reach its sustainability goals without the need to purchase carbon credits and contribute to leading the effort on carbon capture, utilization, and storage.

Future Work:
- Design of gas manifold
- Analysis of exhaust temperature and integration of gas cooling if required prior to adsorption
- Expansion of plant to include operation of smaller test cells shown in the red box of Figure 5
- Pilot plant test of gas manifold distribution efficacy for six reactors
- Activated carbon degradation study
- Analysis of carbon capture efficiency
- Optimization of compressor train
- Determination of CO_2 customer requirements for transportation of product

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