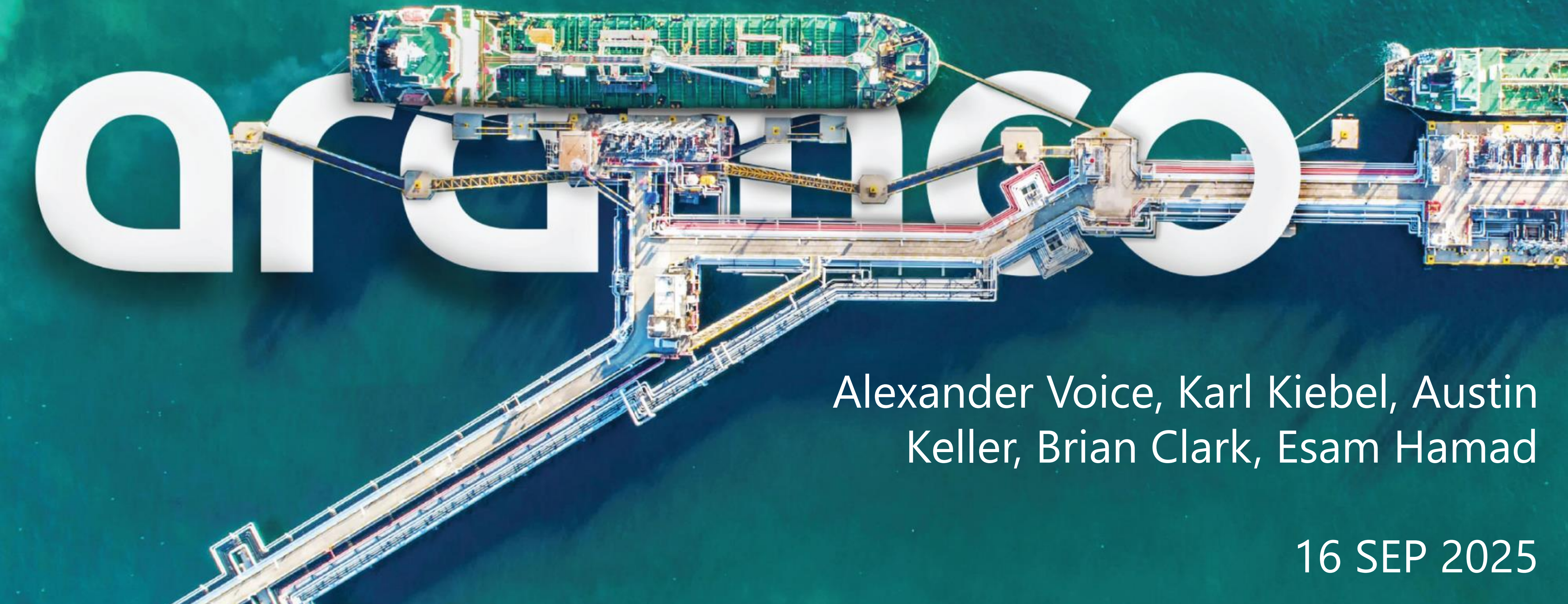
# Development of Cross-Flow Absorber (XFA) for Modular, Engine-Based Carbon Capture



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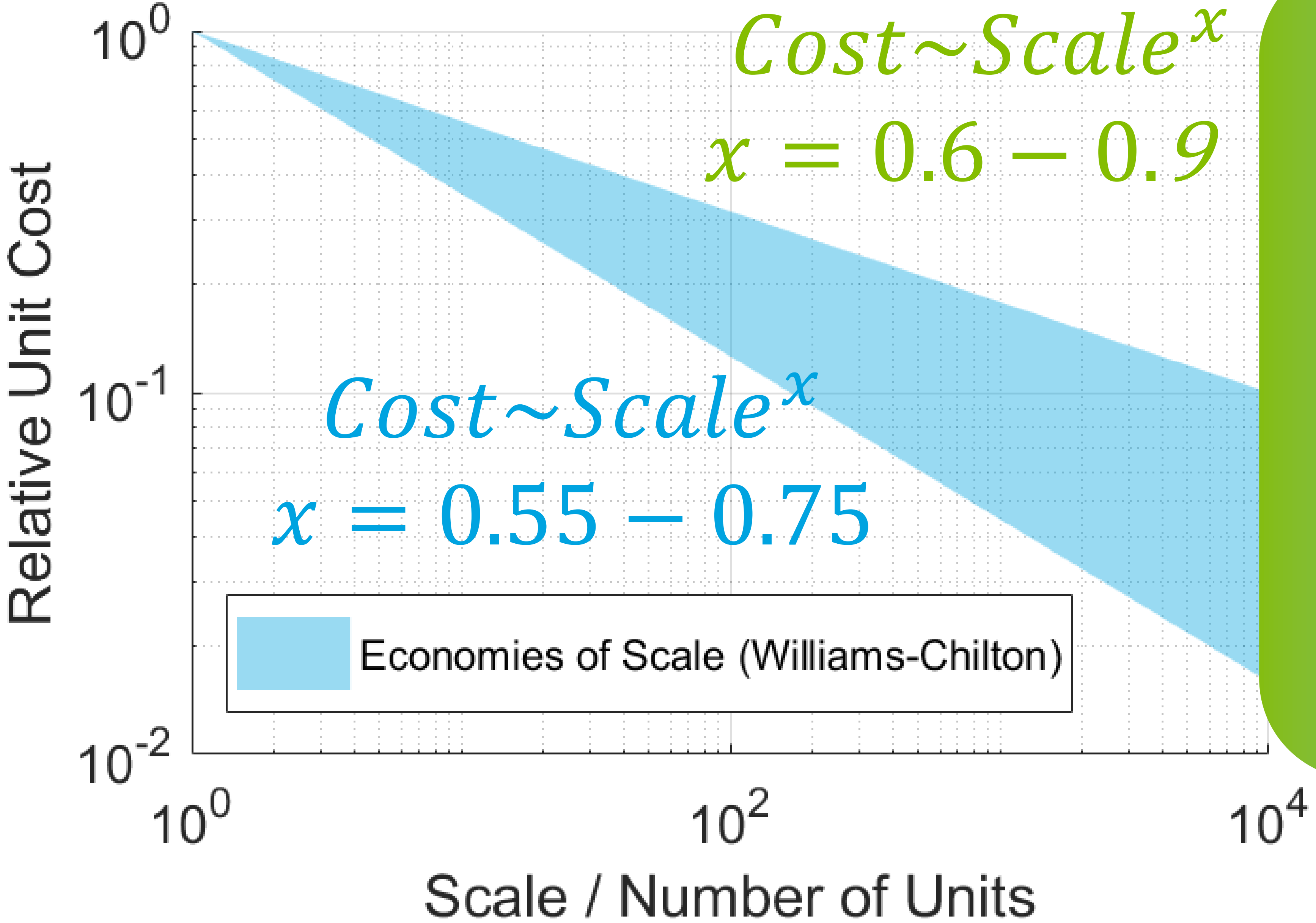
16 SEP 2025


mobile

# The magic of mass production




Scaling the number of units can be just as cost effective as scaling up the size of the plant


12x TEU, 6 TPD
*Onshore CCA and RPB*


*Offshore CCA*
*10 TPD*


2x TEU, 0.1 TPD
*Marine pilot CCA*


2x TEU, 1 TPD
*Marine RPB*

*Marine CCA*

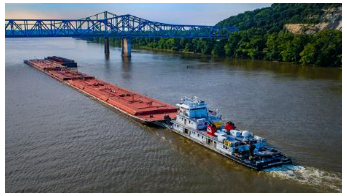
# Research objectives and philosophy in engine-based carbon capture

- ✓Reduce system size
- ✓Reduce cost
- ✓Improve performance

- Build on existing **commercial** technologies and processes
- Leverage **fundamental** understanding to drive incremental improvement
- Holistic mindset and fully **integrated** system design
- Adopt **automotive** practices for lower cost mass production

***MCC Program Scope***


*On-road*

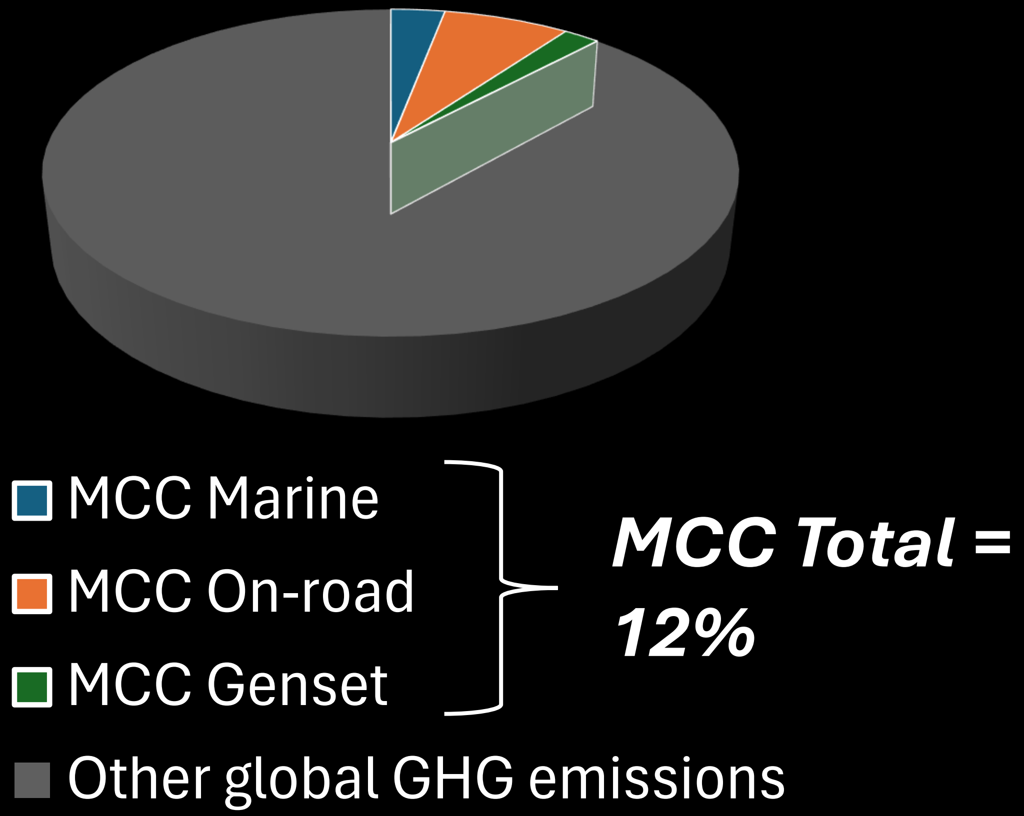

*Marine*


*Genset*

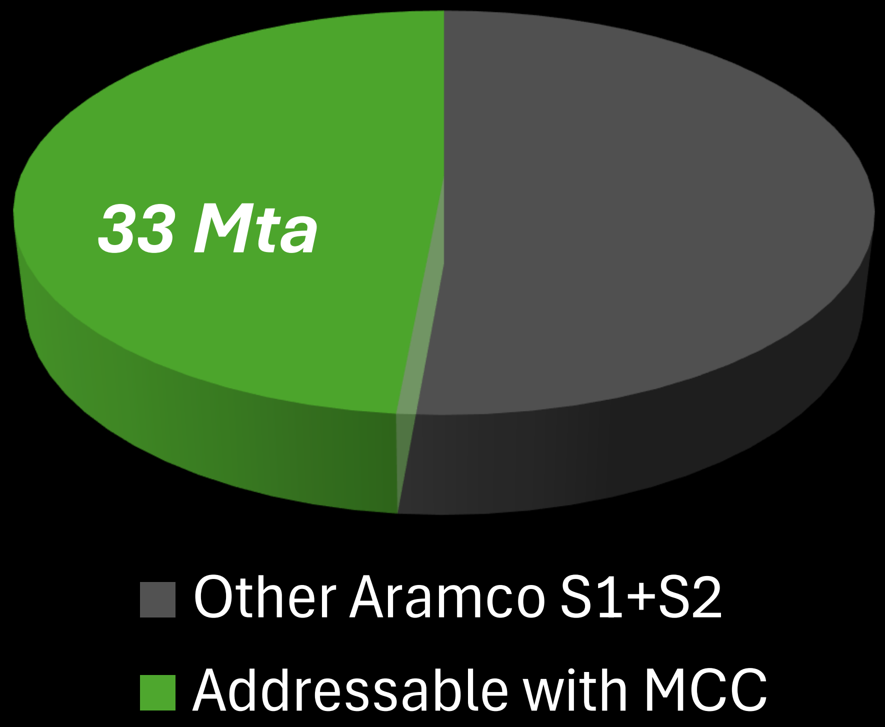

*Locomotive*

# MCC emissions Impact

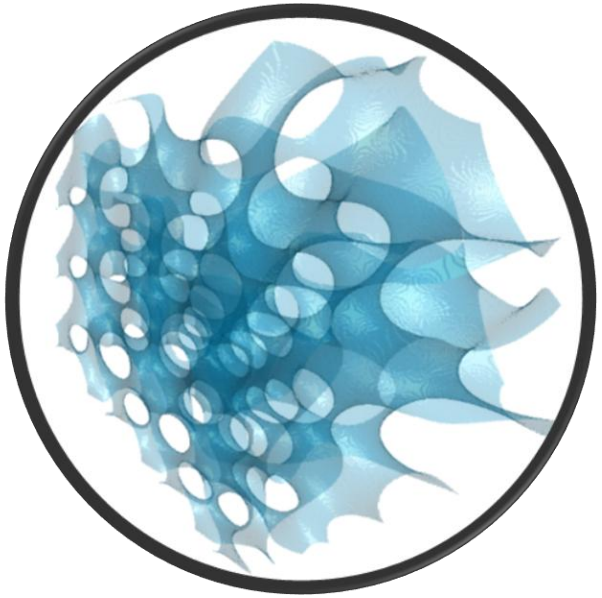
**Global Emissions Impact**




**Saudi Aramco S1 + S2 Emissions**

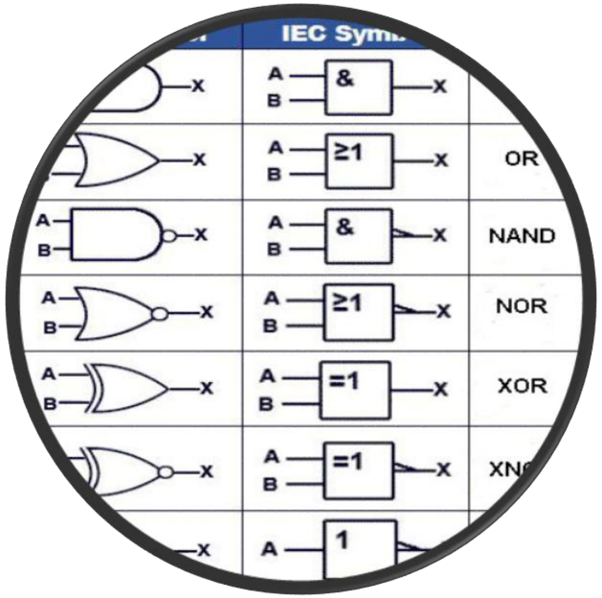


# DRC Process Technology Research Areas & Capabilities



*Materials & Modelling*

*Solvents & additives*




*Controls & Instrumentation*

*Equipment & System Design*

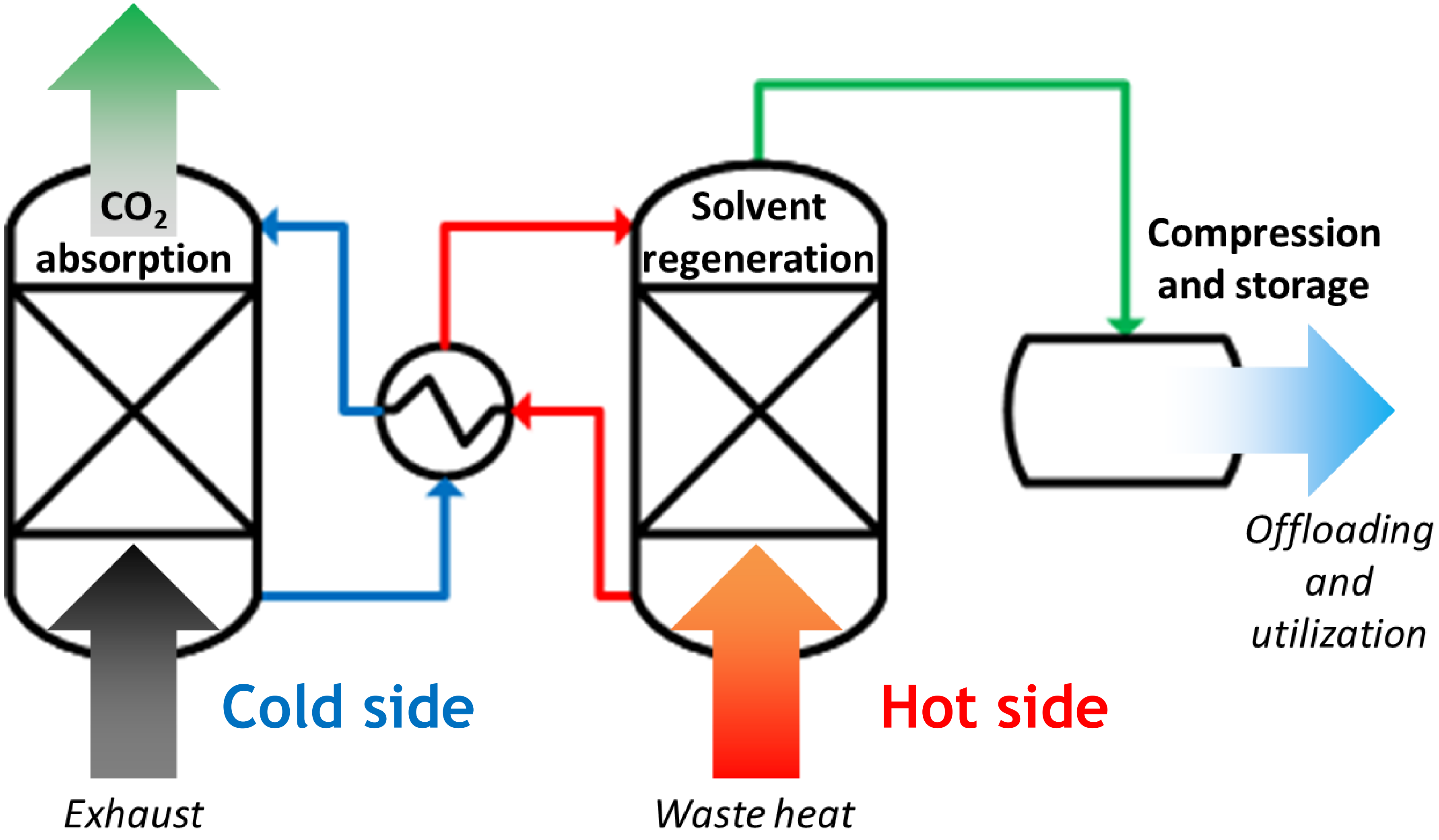
# Thermal Swing Absorption with Aqueous Amines: the state of the art in post combustion carbon capture

<u>Main stages</u>:

- ➢ $CO_2$ absorption
- ➢ Solvent regeneration
- ➢ Compression and storage

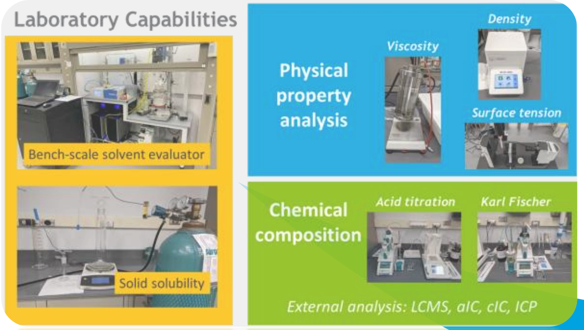
<u>Advantages</u>:

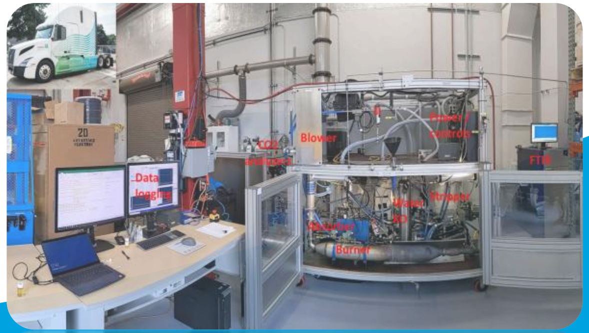
- ✓ Fast reaction rate
- ✓ Thermally driven
- ✓ Very high selectivity and $CO_2$ purity
- ✓ No solids handling



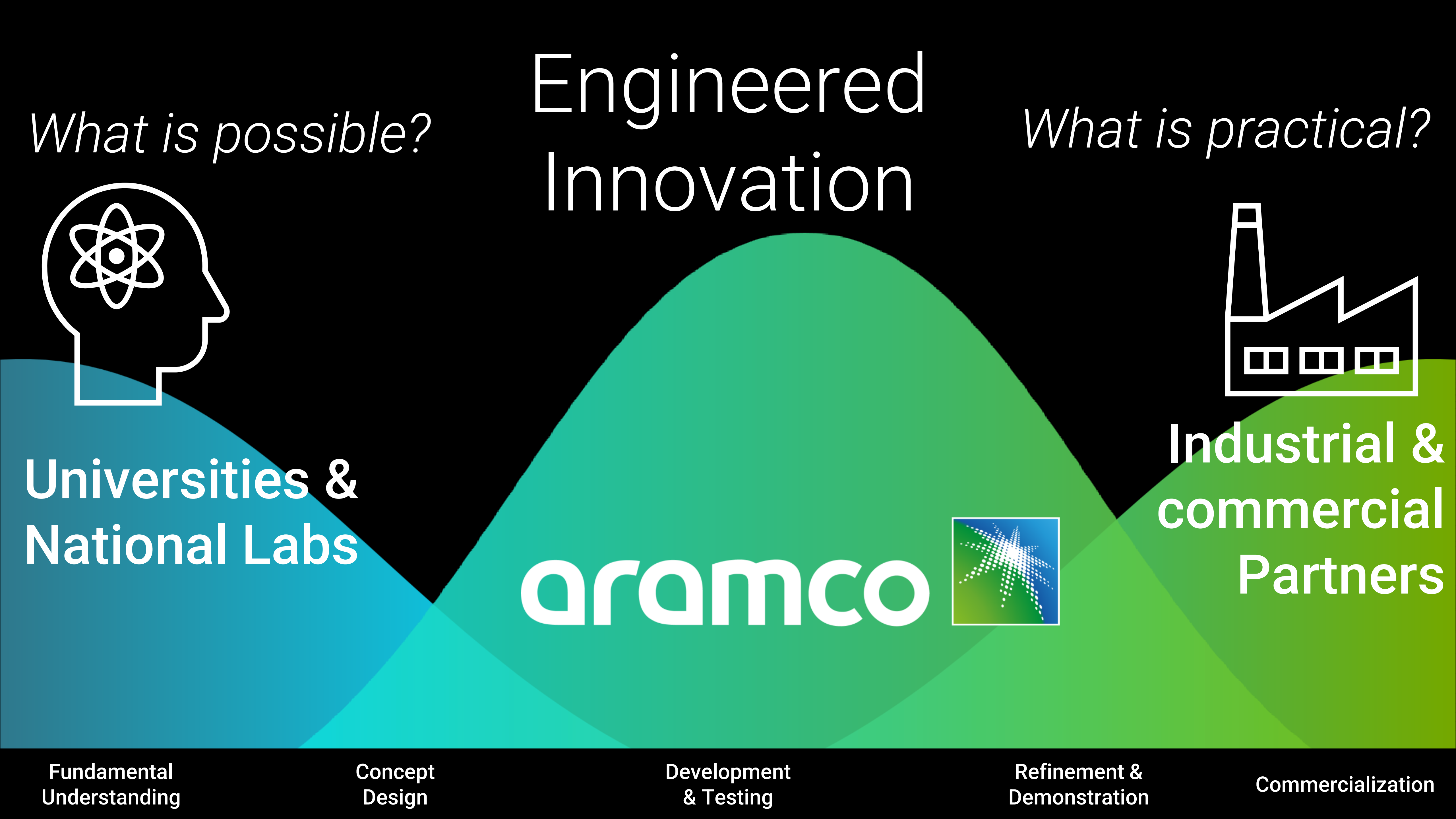
# Pilot & Demo Systems

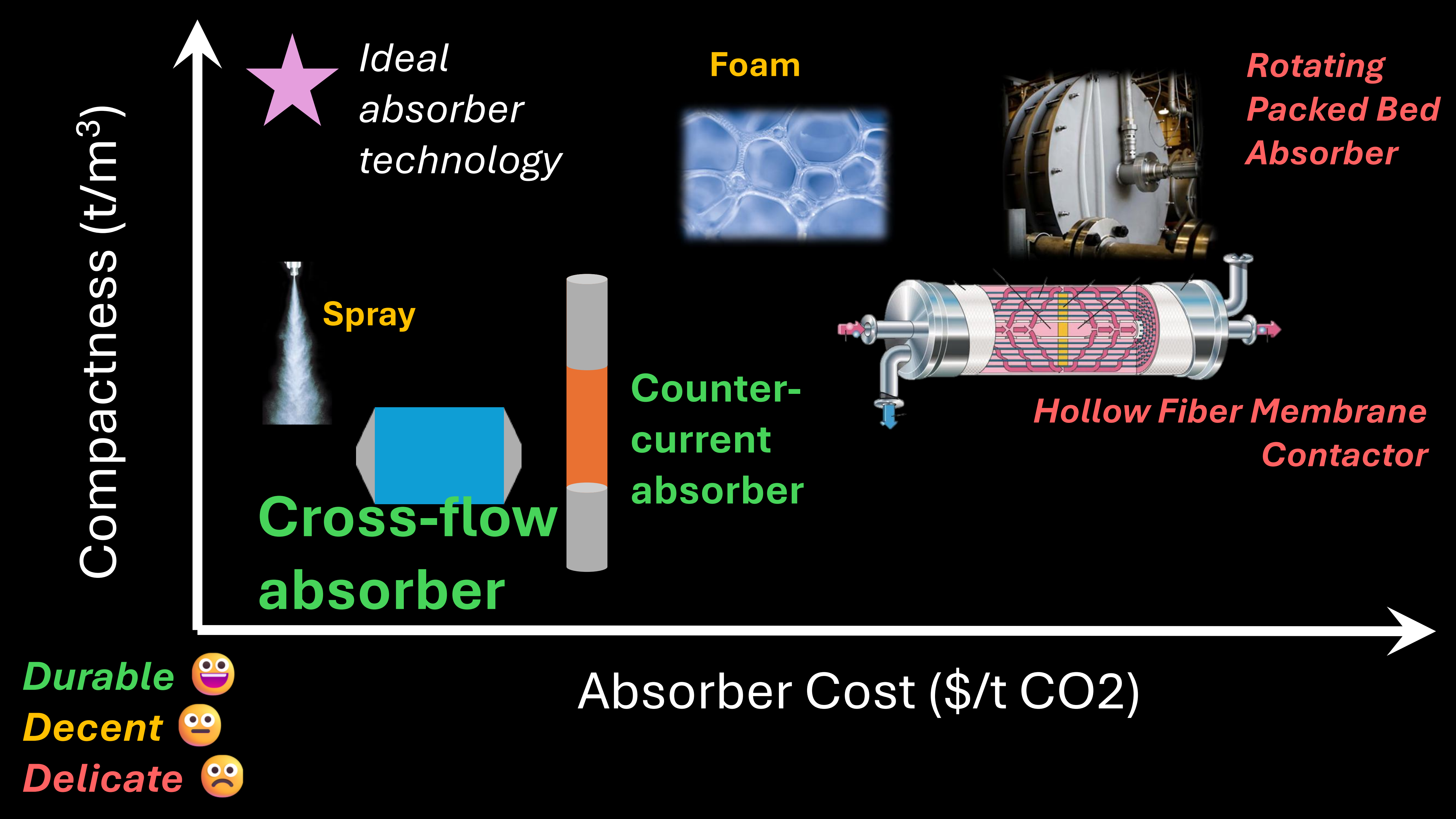
| | Gas Rate | Power Eq. | $CO_2$ Rate |
|---|---|---|---|
| | *kg/h* | *kW* | *TPD* |
| **MINIPLANT (Tech Dev)** | 52.9 | 10.3 | **0.07** |
| **MCC Demo (Onroad Tech)** | 560 | 165 | **0.5** |
| ***Bahri (Ship-based)*** | *7614* | *1485* | ***10*** |
| ***Precombustion (H2)*** | *5127* | *298* | ***7*** |
| ***FLUXBOX (Genset)*** | *5172* | *972* | ***5*** |



*Pilot, demo and lab facilities for modular carbon capture*

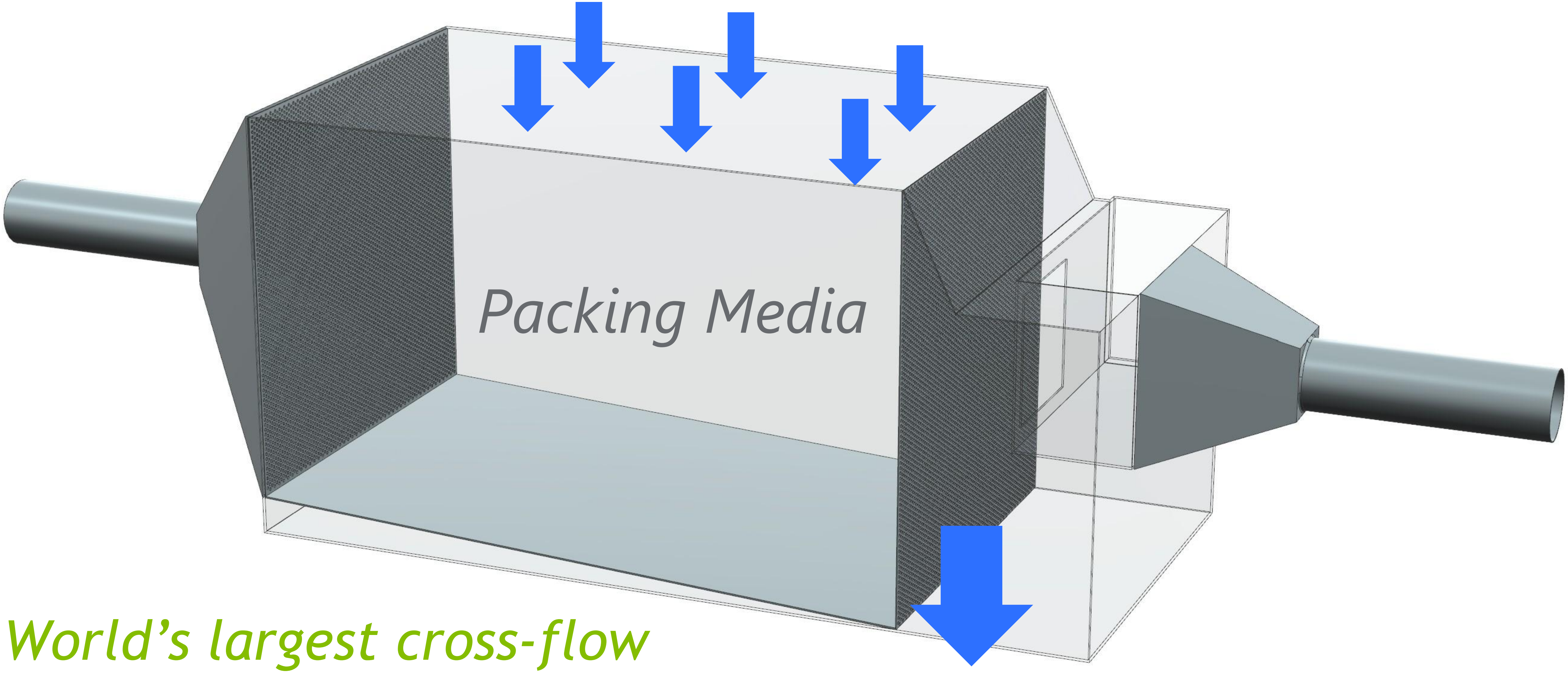

Engineered
Innovation
What is possible?
What is practical?
Universities &
National Labs
aramco
Industrial &
commercial
Partners
Fundamental
Understanding
Concept
Design
Development
& Testing
Refinement &
Demonstration
Commercialization



Ideal absorber technology
Foam
Rotating Packed Bed Absorber
Compactness (t/m$^3$)
Spray
Counter-current absorber
Hollow Fiber Membrane Contactor
Cross-flow absorber
Absorber Cost ($/t CO2)
Durable
Decent
Delicate

# Cross-flow Absorber (XFA) Development Project

# XFA Demo Unit




*World's largest cross-flow absorber for $CO_2$ capture*

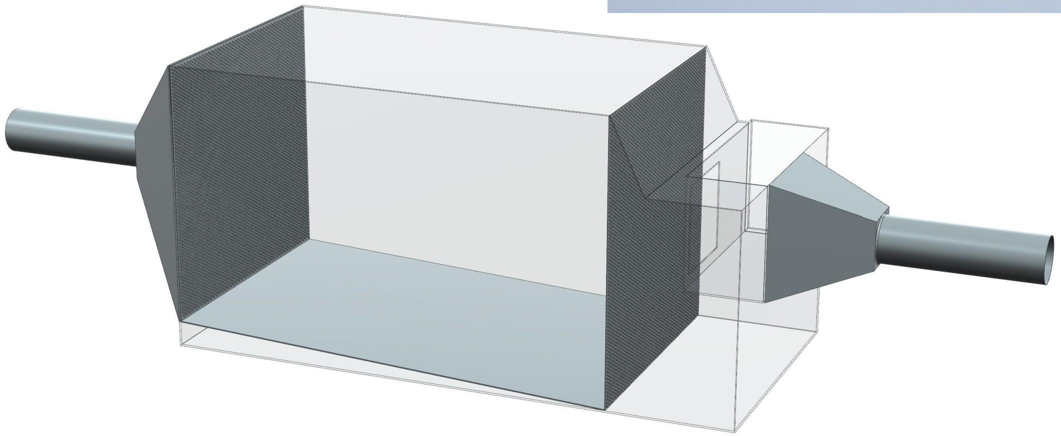
# Key Differentiators of XFA

✓Reduced manifolding – higher packing volume to total volume ratio

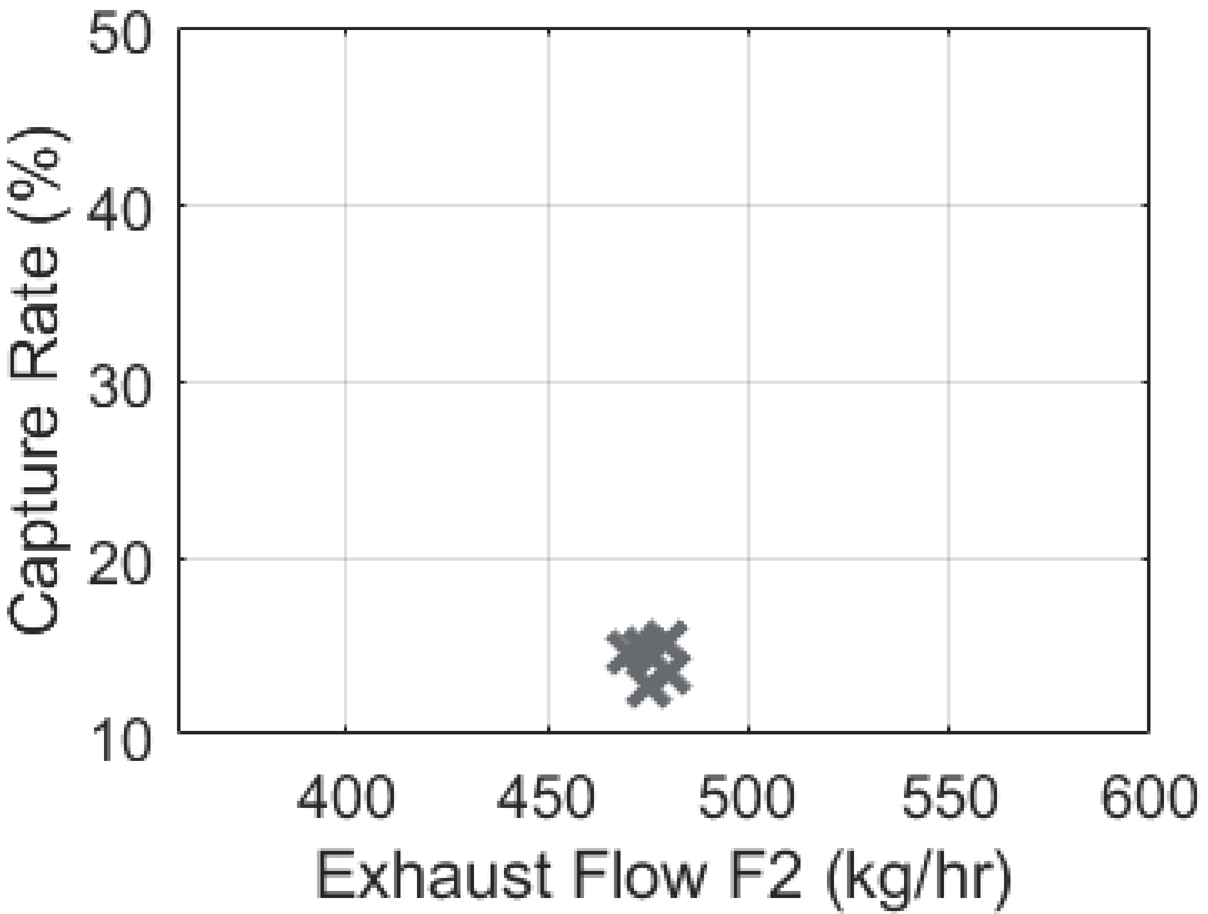
✓Separate gas and liquid flux – high liquid flux at low gas velocity / dP

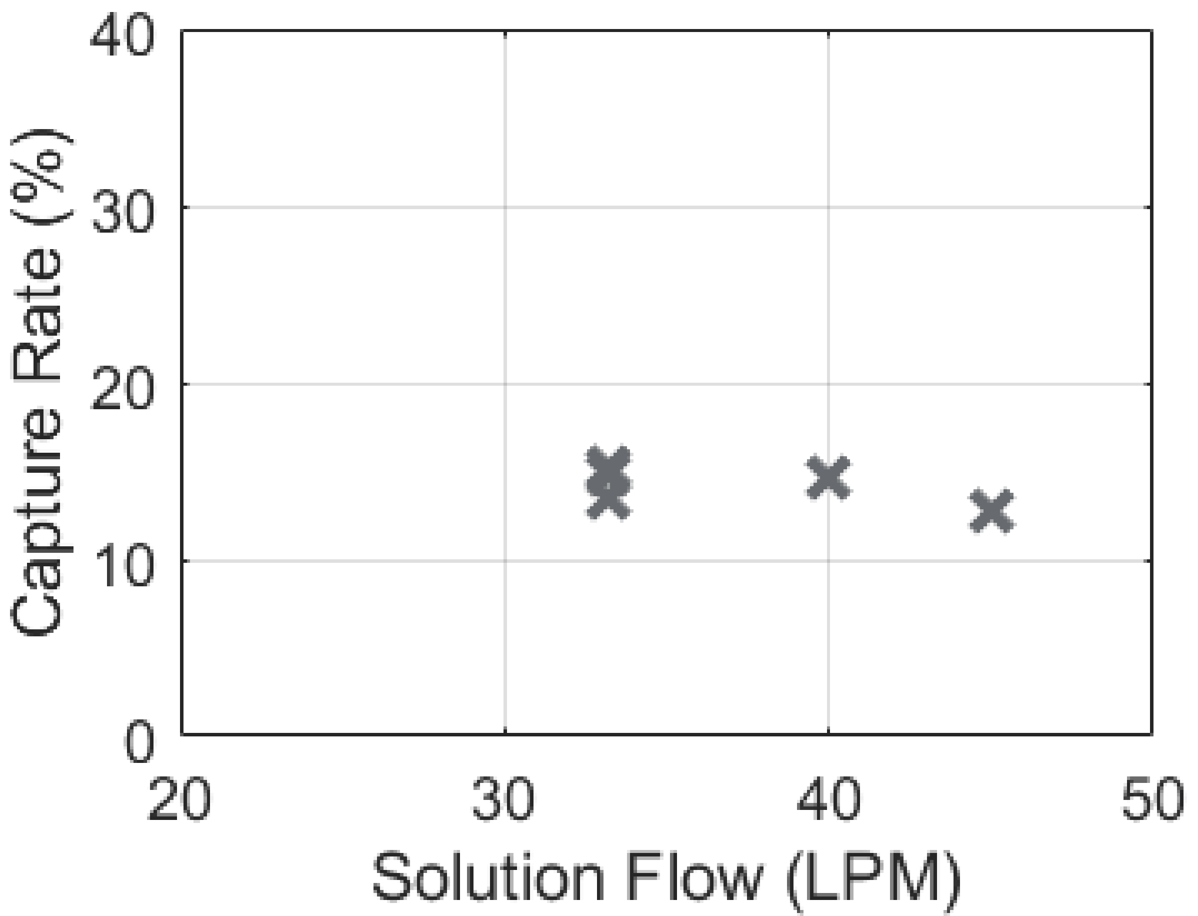
✓More wieldy and constructable. Attractive aspect ratio / form factor for containerization and lower cost


- ❖Unconventional – increased design and modelling cost, performance uncertainty
- ❖Increased packing volume (~10-15%) due to reduced driving force
- ❖Liquid collection & distribution



# Results: Performance of the Gen 1 XFA (off-the-shelf)

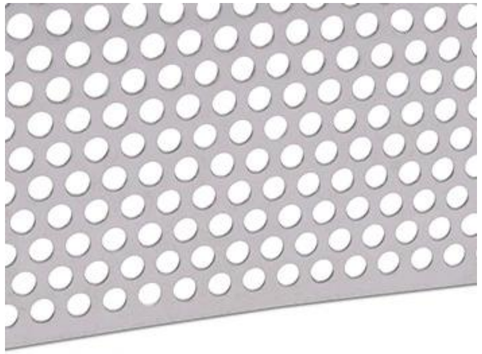


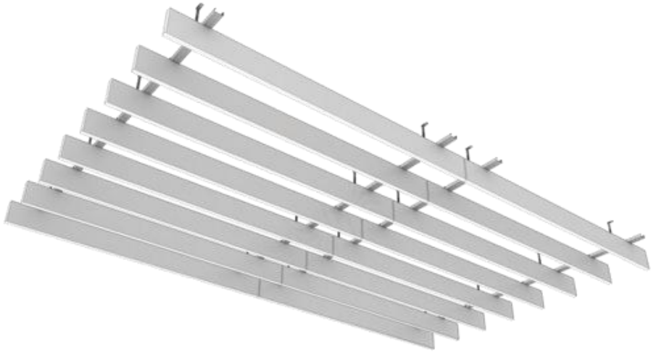



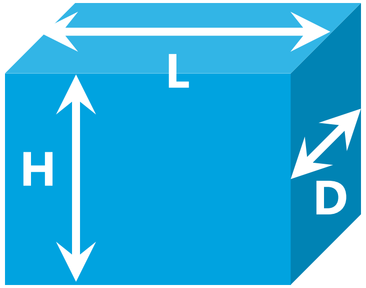

Off-the-shelf XFA designed for building emissions control performed poorly

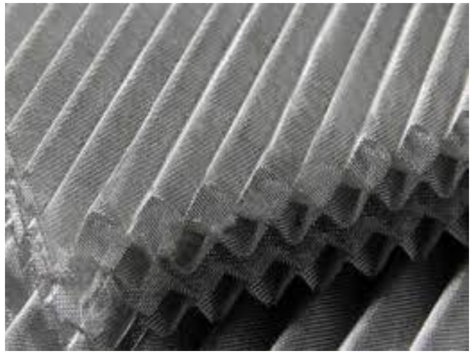
# Remedies

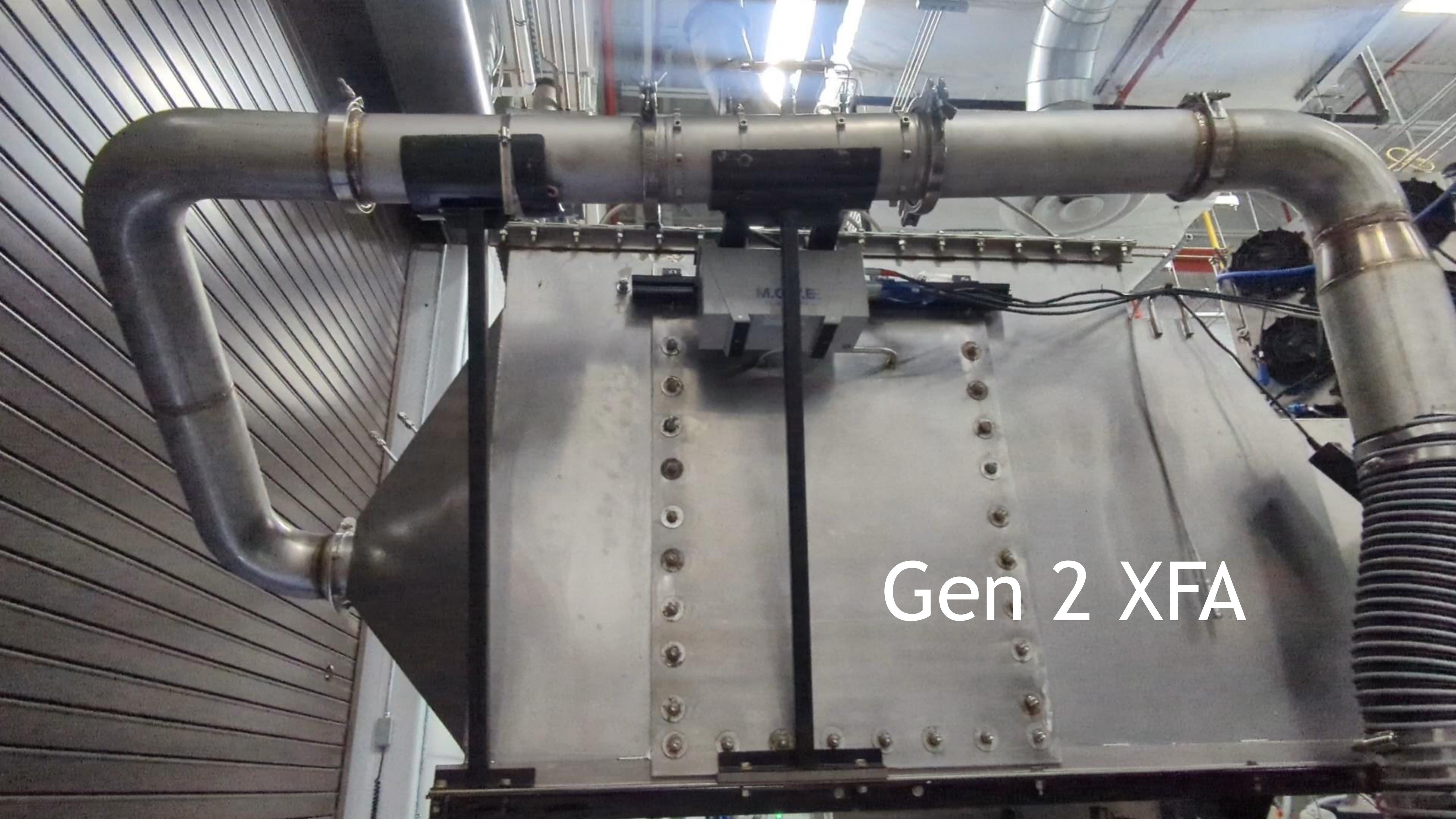
- **Poor gas distribution** → Shrouded gas distribution plate to reduce open area from ~40% to ~3%
- **Poor liquid distribution** → Replaced perforated tube distributors with spray nozzles
- **Significant gas bypass** → Extended baffles to seal against top packing surface; added layer of random packing
- **Poor packing irrigation** / low wetted area → tracked down specialized gauze packing with enhanced performance at low liquid rates
- **Aspect ratio** →increase height and reduce length/depth to increase liquid flux



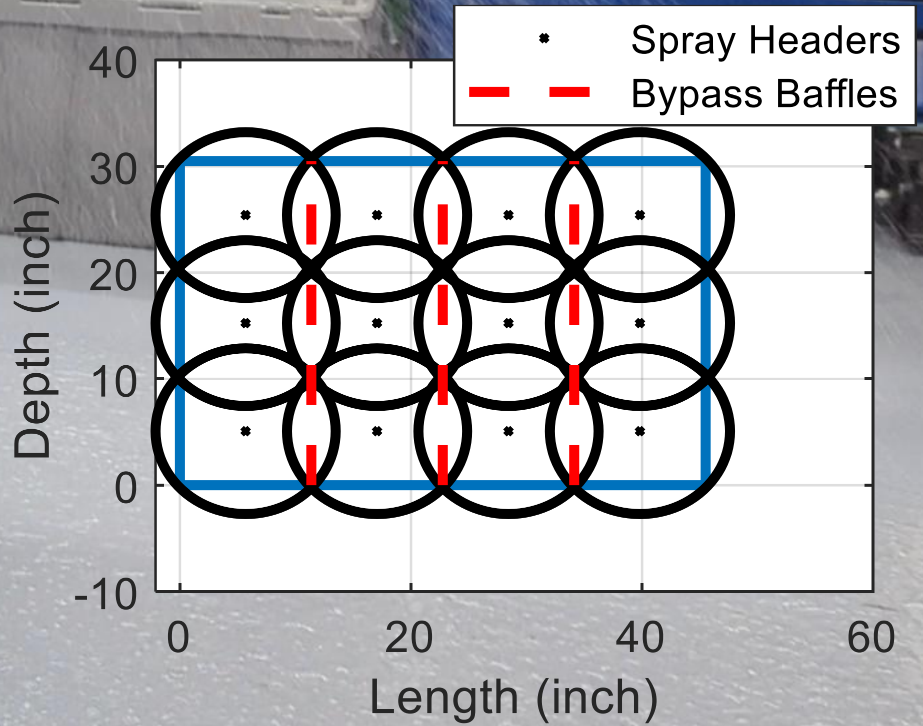




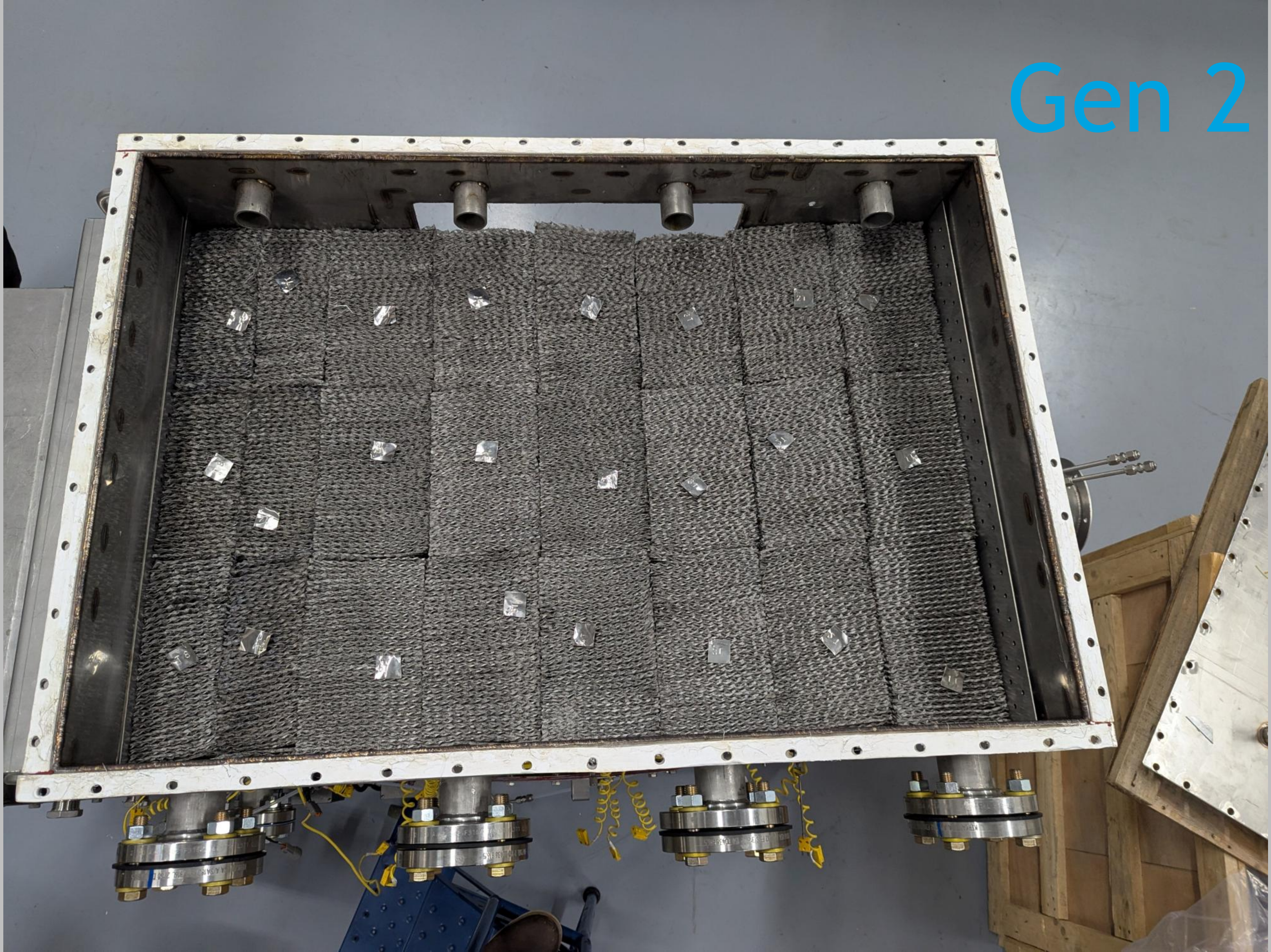




Gen 2 XFA

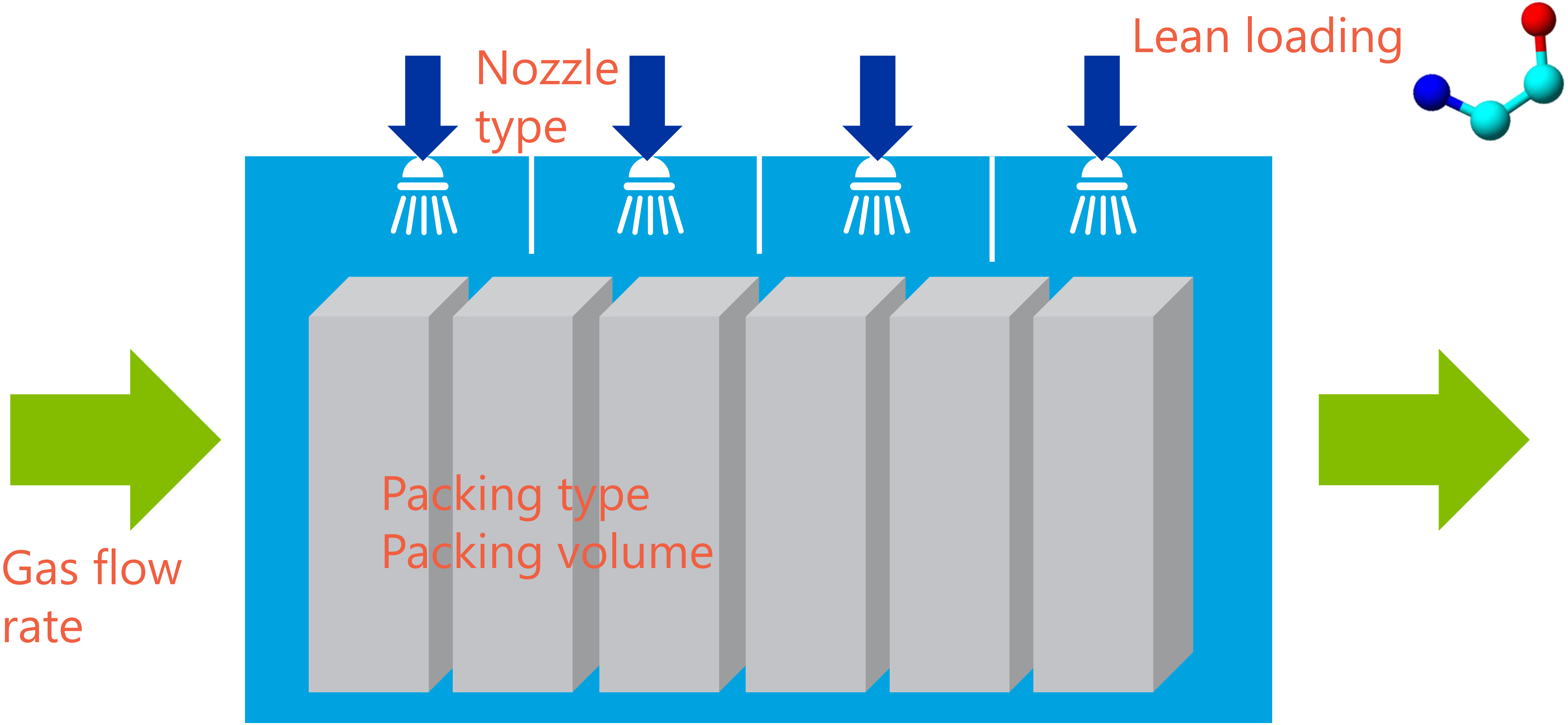
# Gen 2 XFA – Spray headers



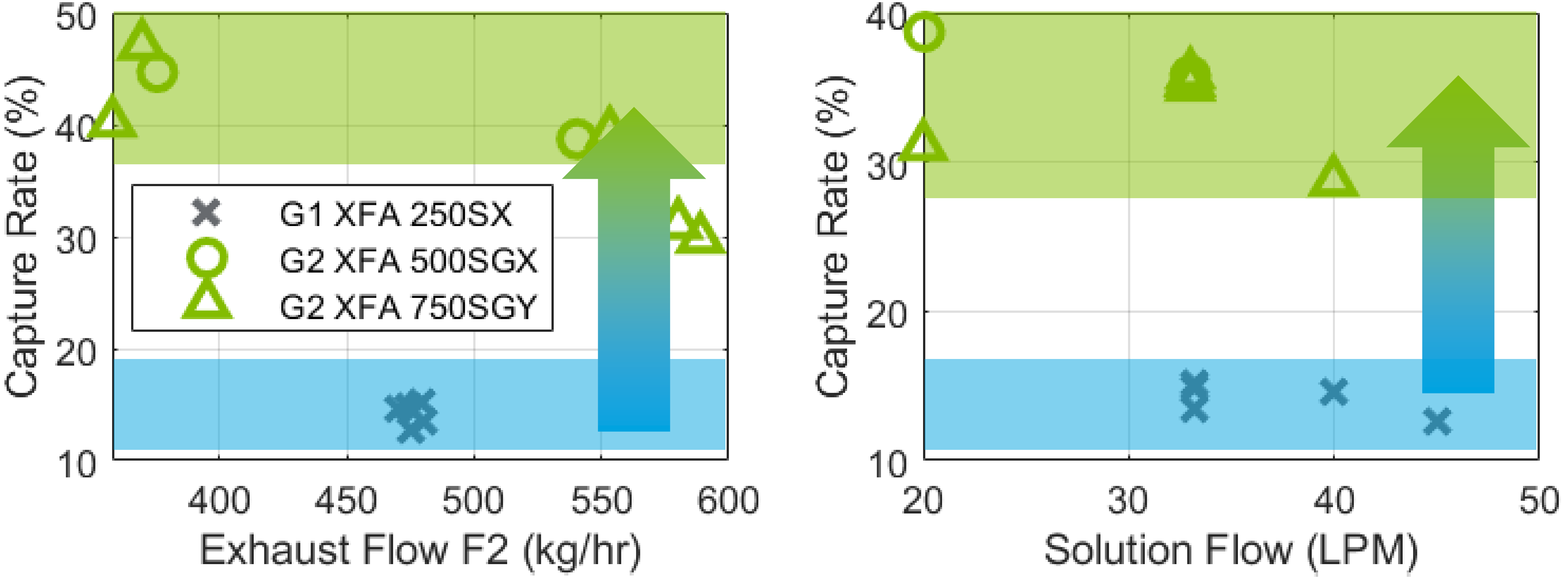
# Gen 2 XFA



# Gen 2 XFA Test Matrix



# Results: Improvement with Gen 2 XFA

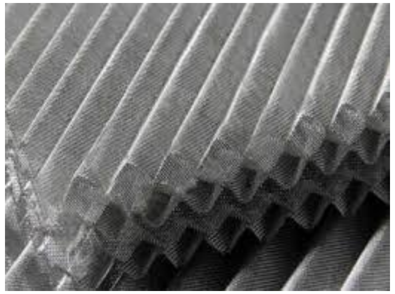



Gen 2 XFA shows ~160% improvement compared with Gen 1

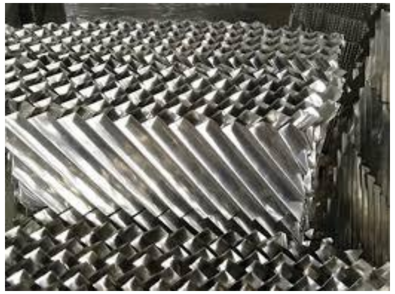
# Results: Effect of packing & process variables

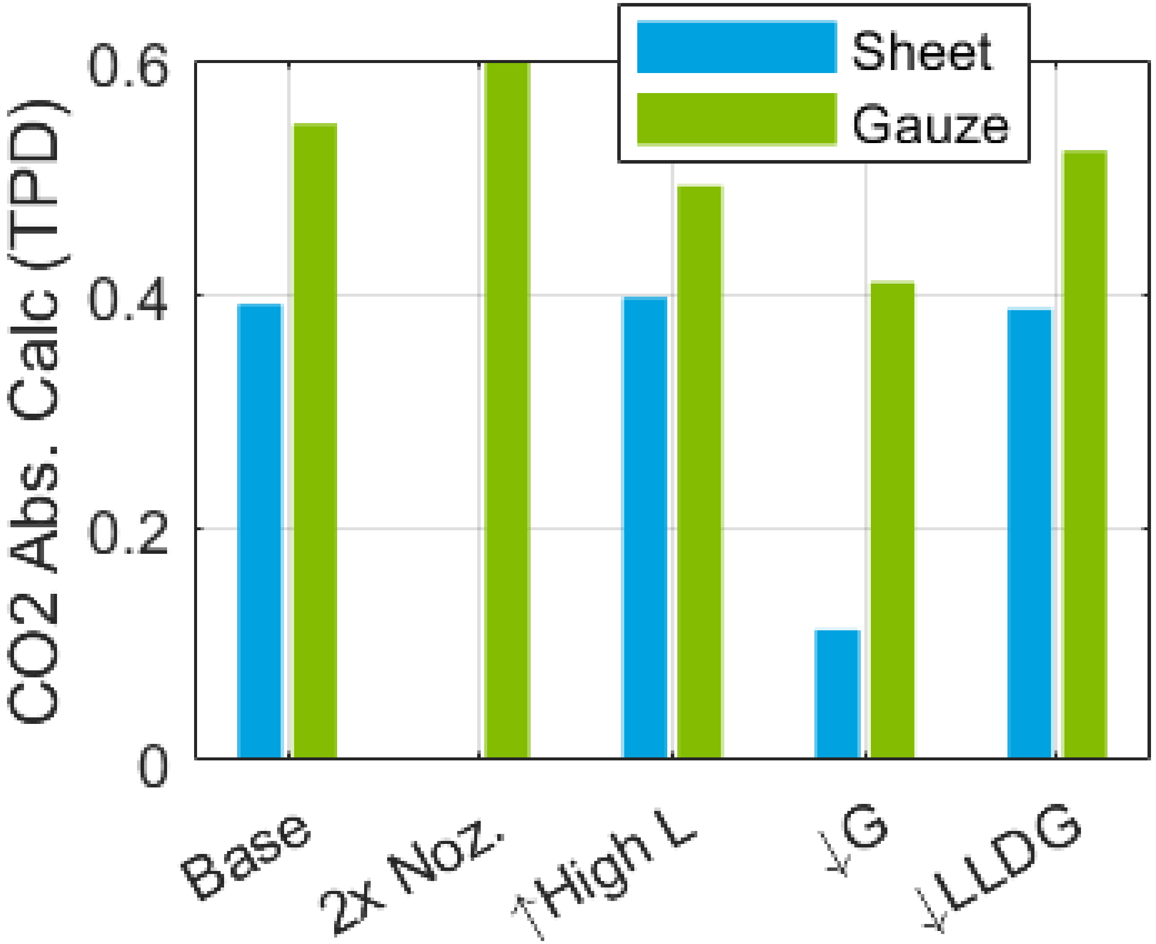
Gauze packing (500 SGX) shows improved performance for many conditions

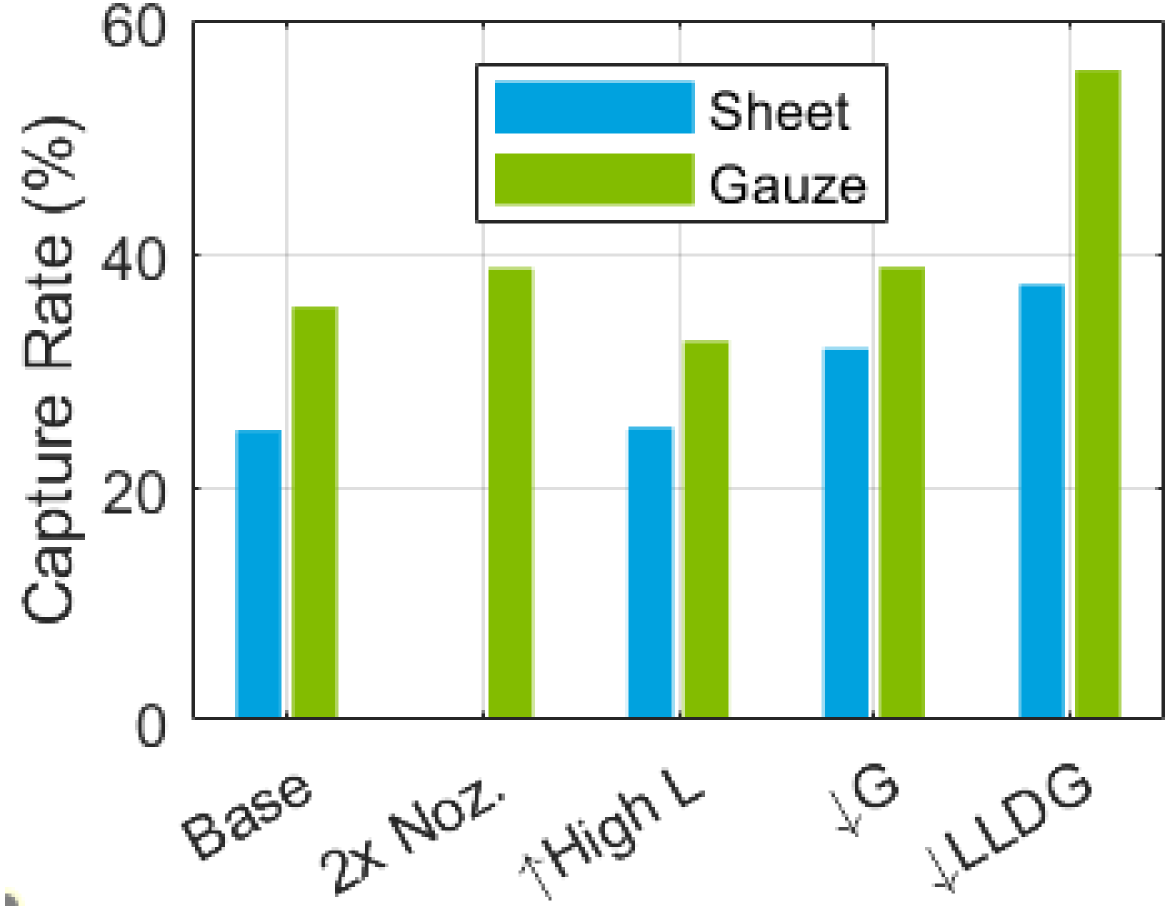
Gauze



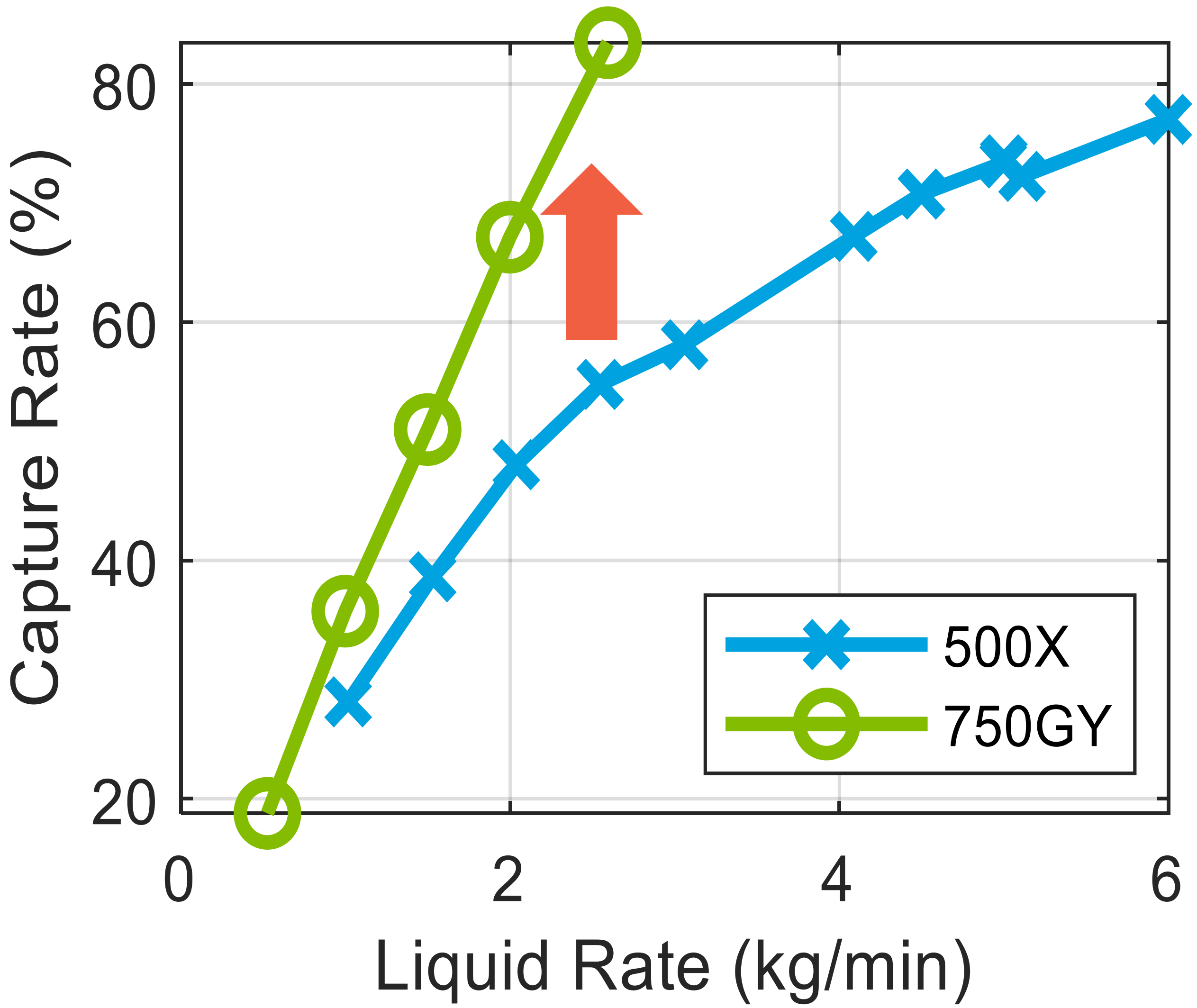
Sheet





# Gauze (750SGY) vs. Sheet (500X) Packing



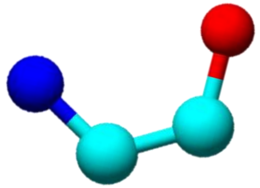

Results of separate testing in 5” column (~150 kg/day)

Gauze packing – 25-50% greater CO2 absorption rate at same L/G

# Gen 2 XFA Results: Effect on $CO_2$ absorption rate

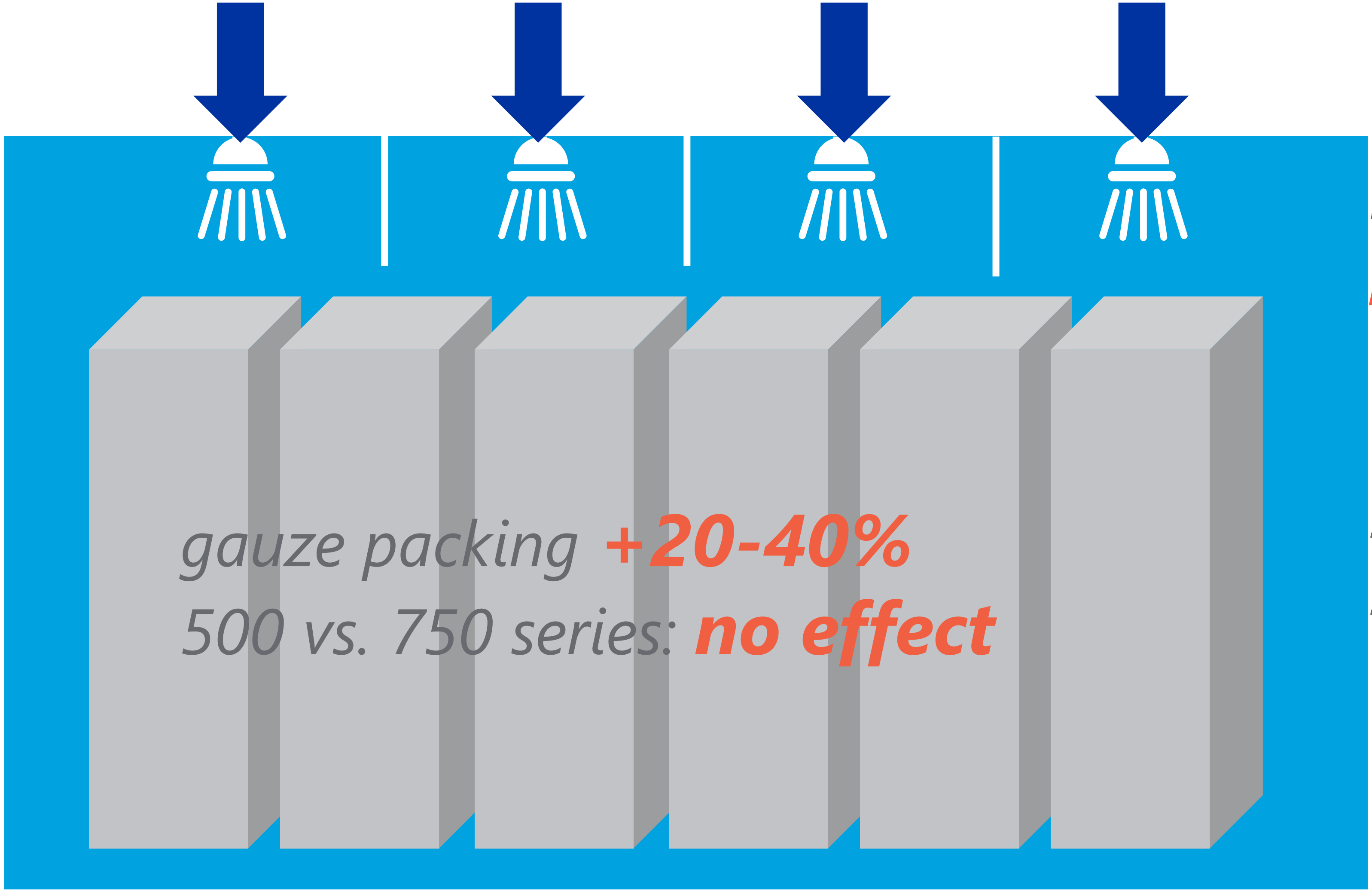
*Optimal L/G* **~2-2.5**

*Lean loading:* **+25-30%**



$$\frac{1}{K} = \frac{1}{\boldsymbol{k_g}} + \frac{1}{k_l}$$

$$n_{CO2} \sim \boldsymbol{P_{CO2}} - P^*_{CO2}$$



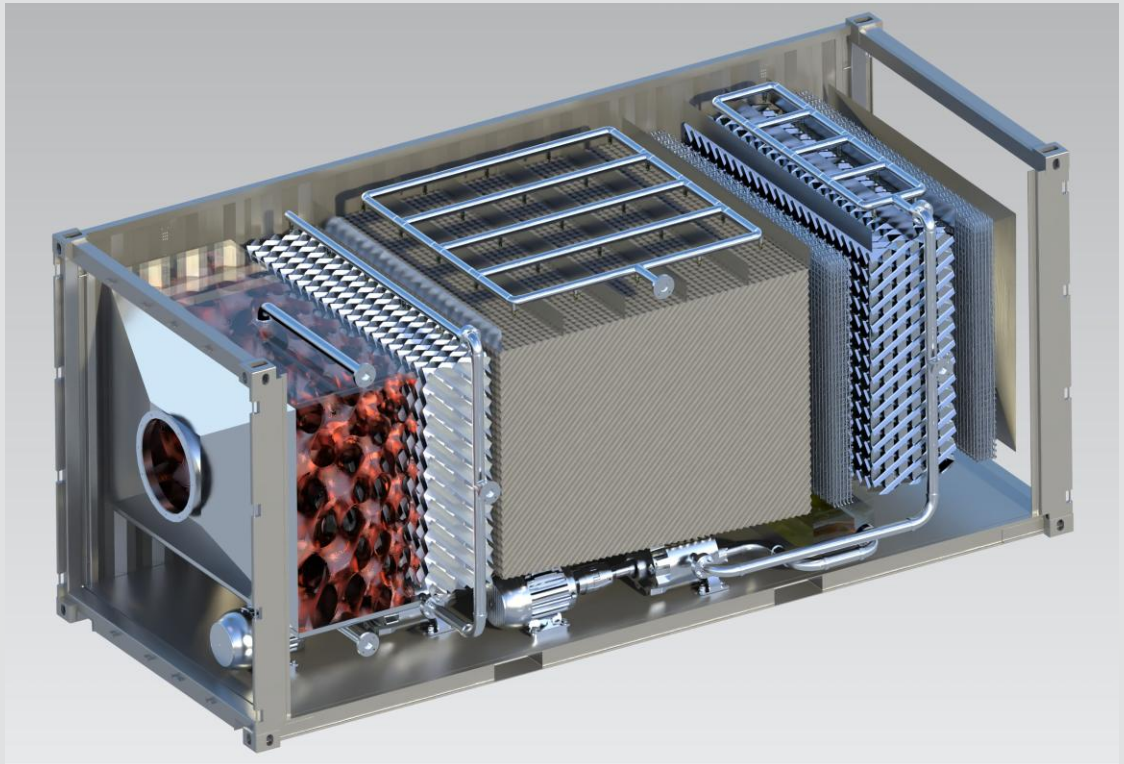

*-50% gas flow rate*
**-25%**

*Nozzle type:*
**no effect**

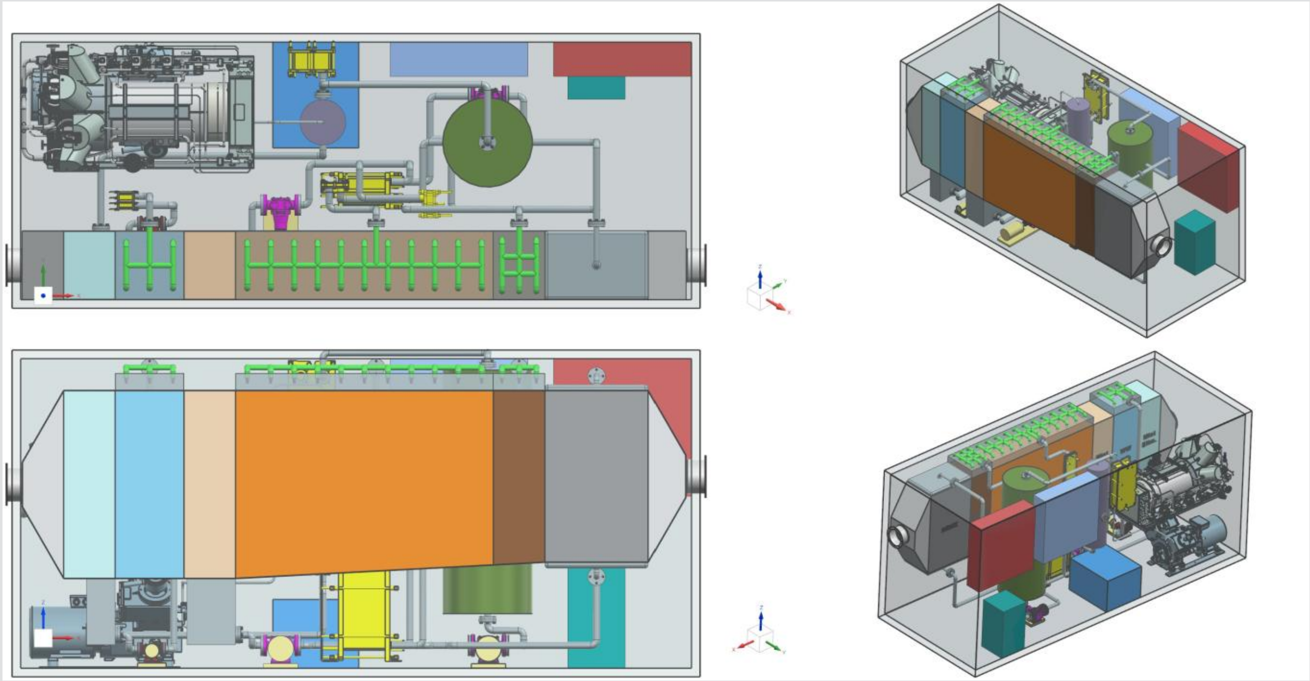
*50% packing vs. 50% nozzles:*
**-3 to -5%**

# System Design & Integration

# Introducing the FluxBox



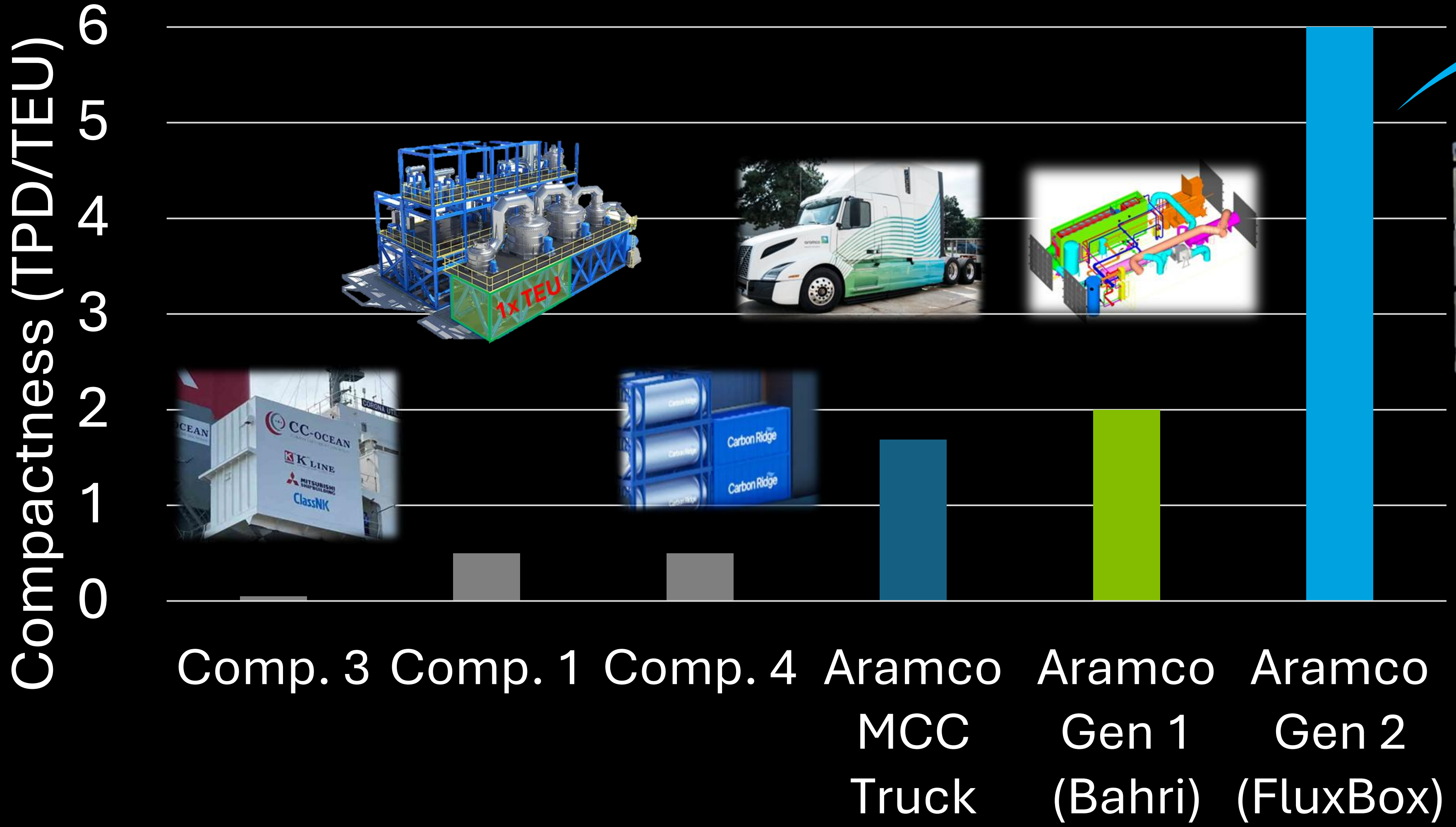
*QCXF-84 Concept: 3MW gas handling only*
*1x TEU package*

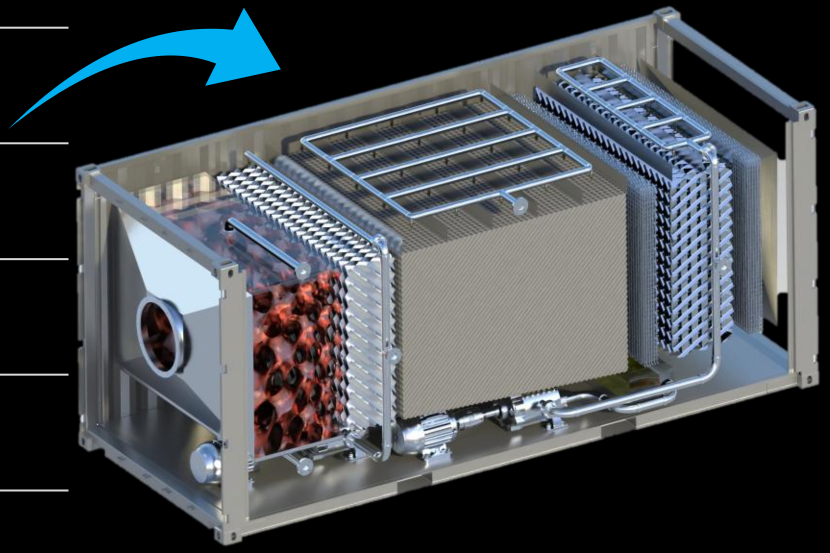


*QCXF-24 Concept: 1MW fully integrated system*
*1x TEU package*

The world's most compact post-combustion carbon capture system

# Introducing the FluxBox – the world's most compact post-combustion carbon capture system



**the FluxBox**

# XFA Project Accomplishments

**Size**

- ✓**10x more compact** modular capture system
- ✓**est. 20% smaller absorber** vs. vertical column

**Cost**

- ✓**50% cost reduction** vs. previous HFMC absorber
- ✓**>95% reduction in dP** vs. HFMC (↓OPEX)

**Perf.**

- ✓**160% improvement** vs. Gen 1 XFA due to packing selection, liquid & gas distribution
- ✓Aspect ratio tradeoffs for larger systems

# Acknowledgements


MCC Team

- Esam Hamad (Project Lead)
- Austin Keller (Research Scientist)
- Karl Kiebel (Research Engineer)
- Brian Clark (Technician)

Hardware Support

- Bill Klemm
- Josiah Davis
- Bob Bingham
- Seth Doble



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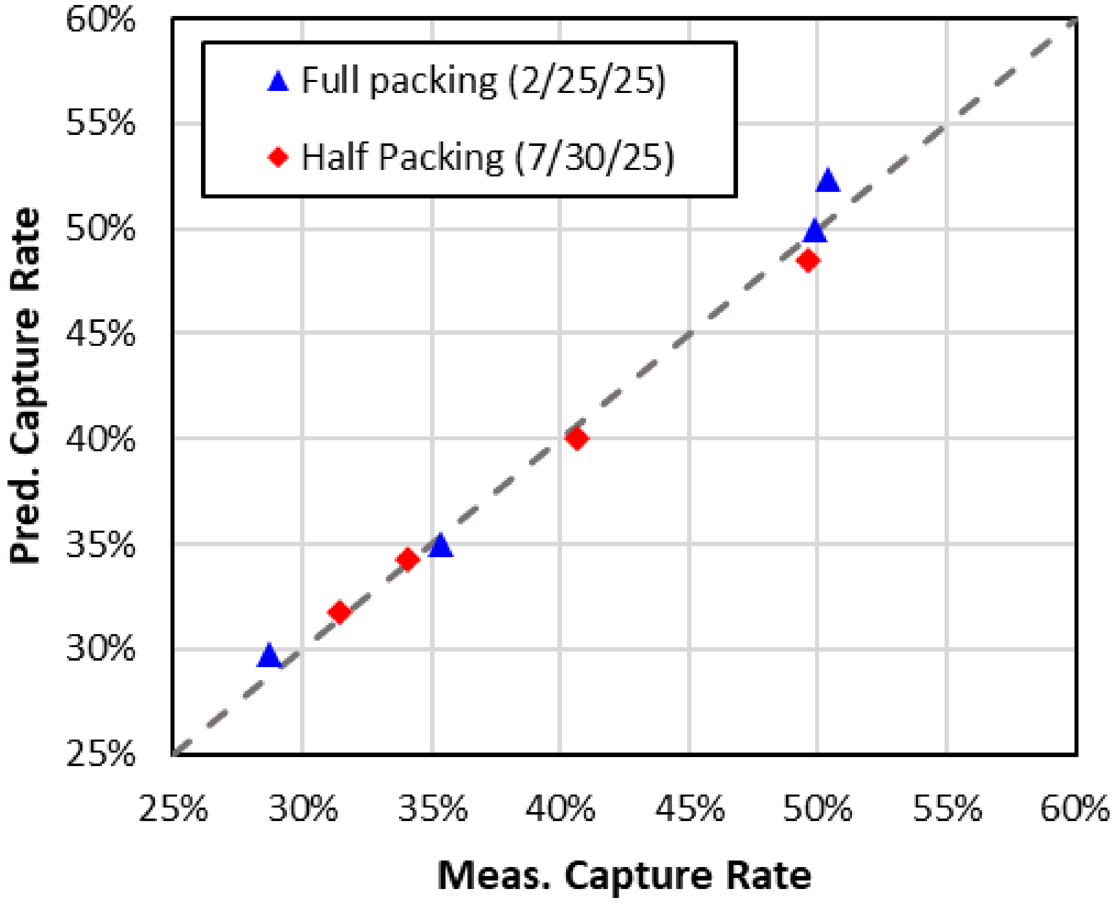
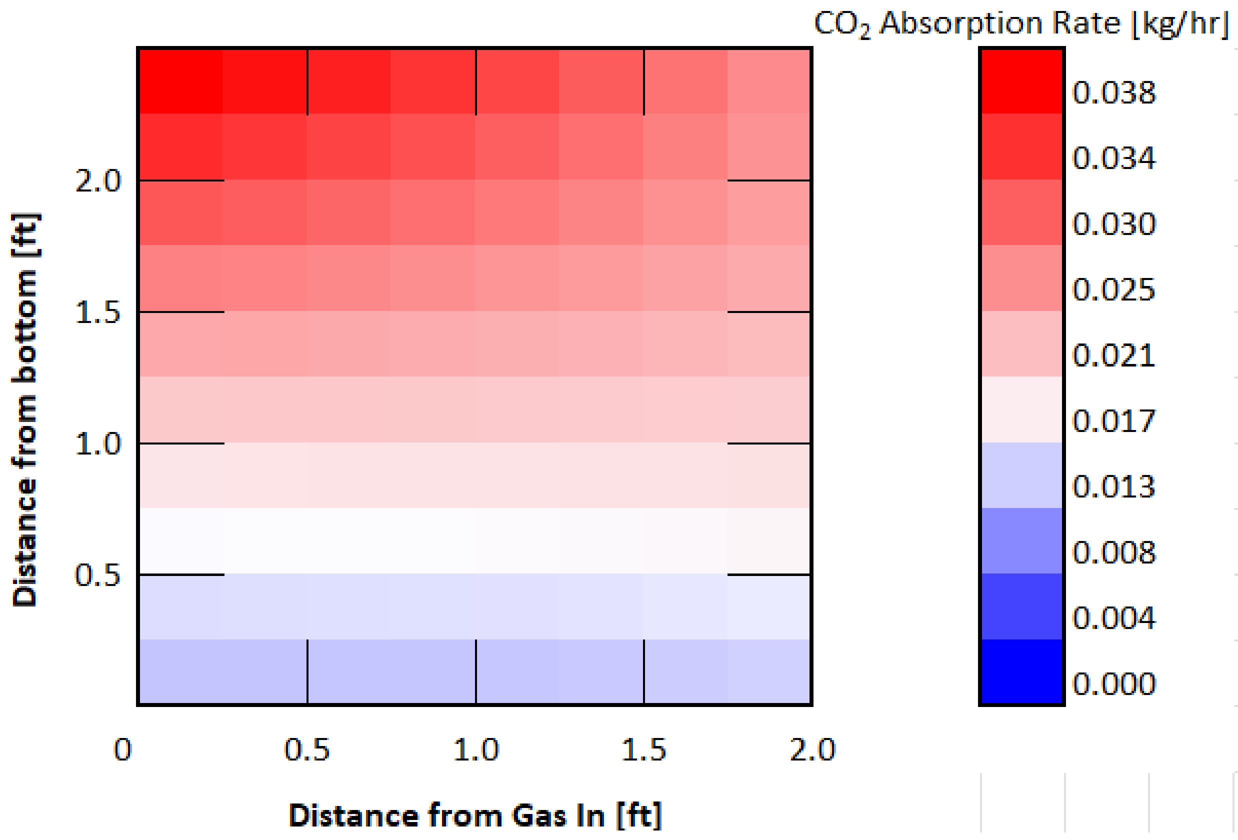
*Ted Parsons (Brentwood Engineering) for providing packing*

# BACKUP

# XFA 2-D Modelling



# Wrap-Up

- ✓Designed, built and tested the **world's largest** cross-flow absorber for CO2 capture meeting project performance targets

- ✓Leveraged cross flow gas handling unit design to produce a concept of the world's **most compact** modular carbon capture system – 10x more compact than any existing systems

- ✓Constructed and validated a new 2-D process modelling tool for **scale-up** and commercial XFA design

# XFA Outcomes and Next Steps

**Accomplishments:**

✓2-D XFA model in ASPEN
✓Gen 1 pilot system fabrication and testing (~2TPD scale) – 2024
✓Gen 2 pilot system design, fab, testing – Q1-Q2 2025
✓Conceptual design of Bahri XFA (8 TPD scale)

**Our Secret Sauce:**

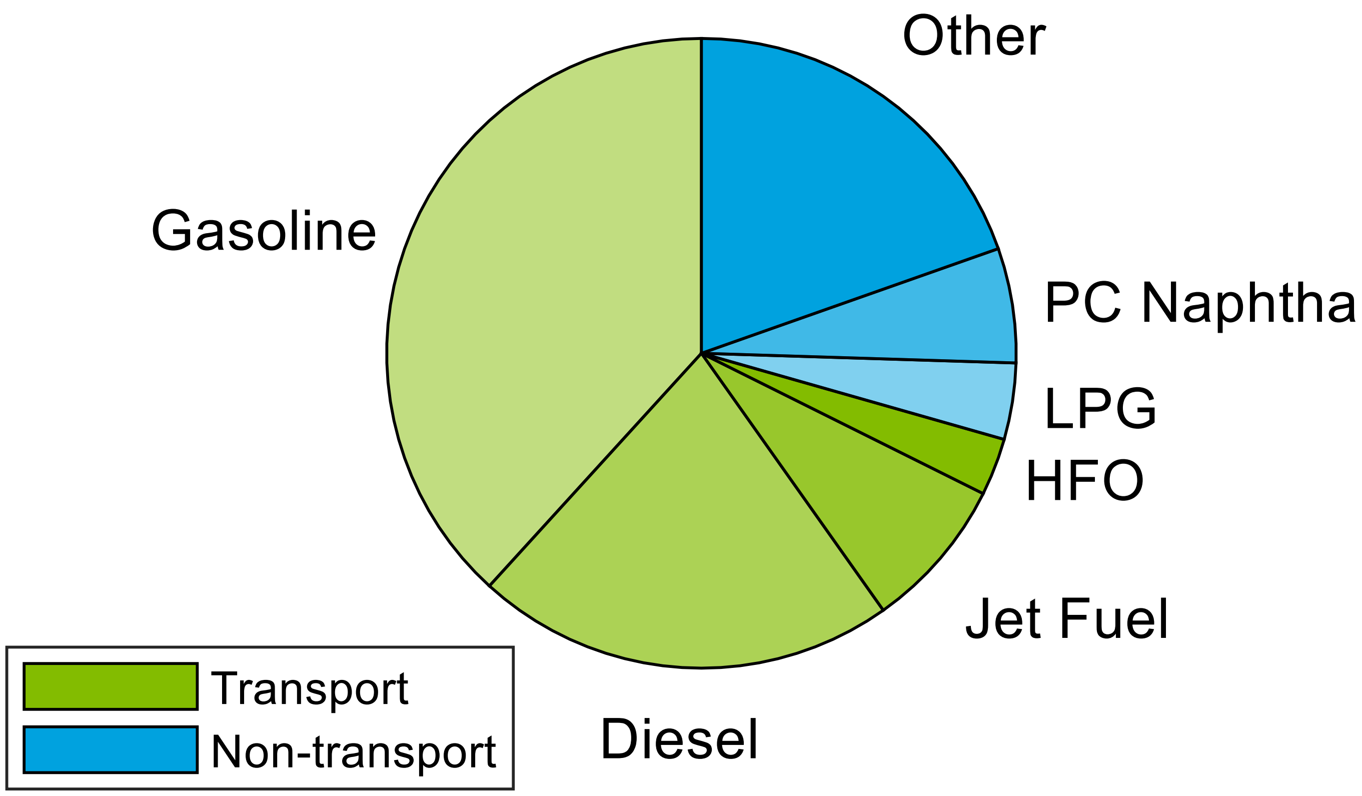
✓Compact design with optimized aspect ratio
✓Gas distribution
✓Packing selection and sizing
✓Liquid distribution and collection
✓Optimal operating conditions

TotalEnergies

University of Sheffield

- *Design of XFA for larger scale*
- *Packing and mass transfer characterization*
- *2-D XFA modelling*

# Why is Aramco working on transport technology?




Around **70% of petroleum** is used in transportation

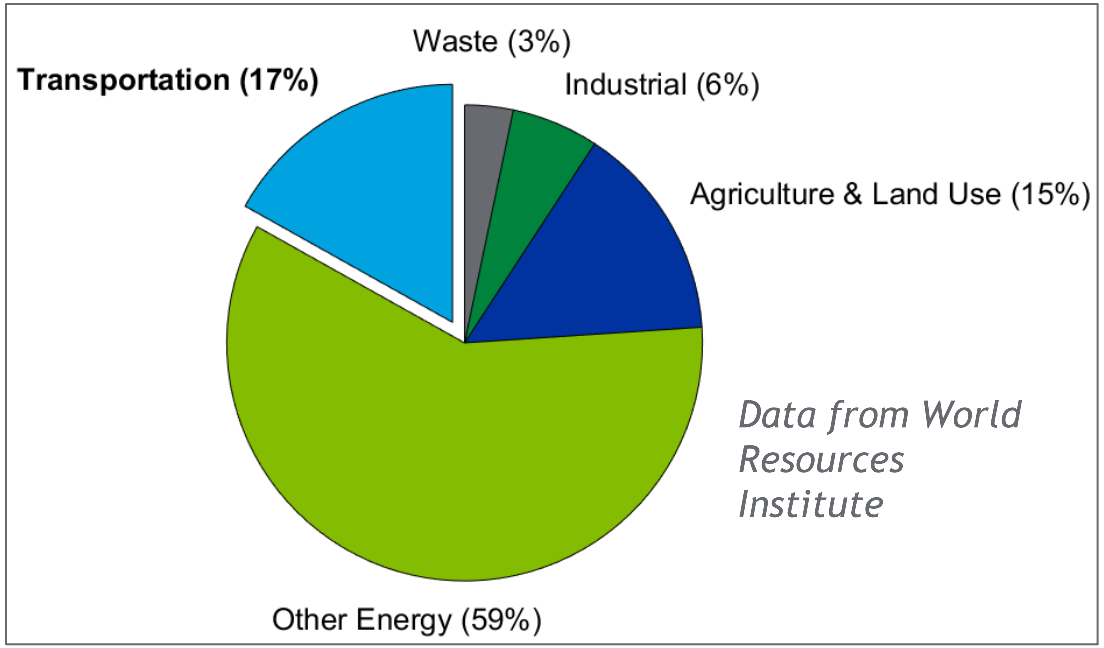
Transport fuels represent an even larger share by value

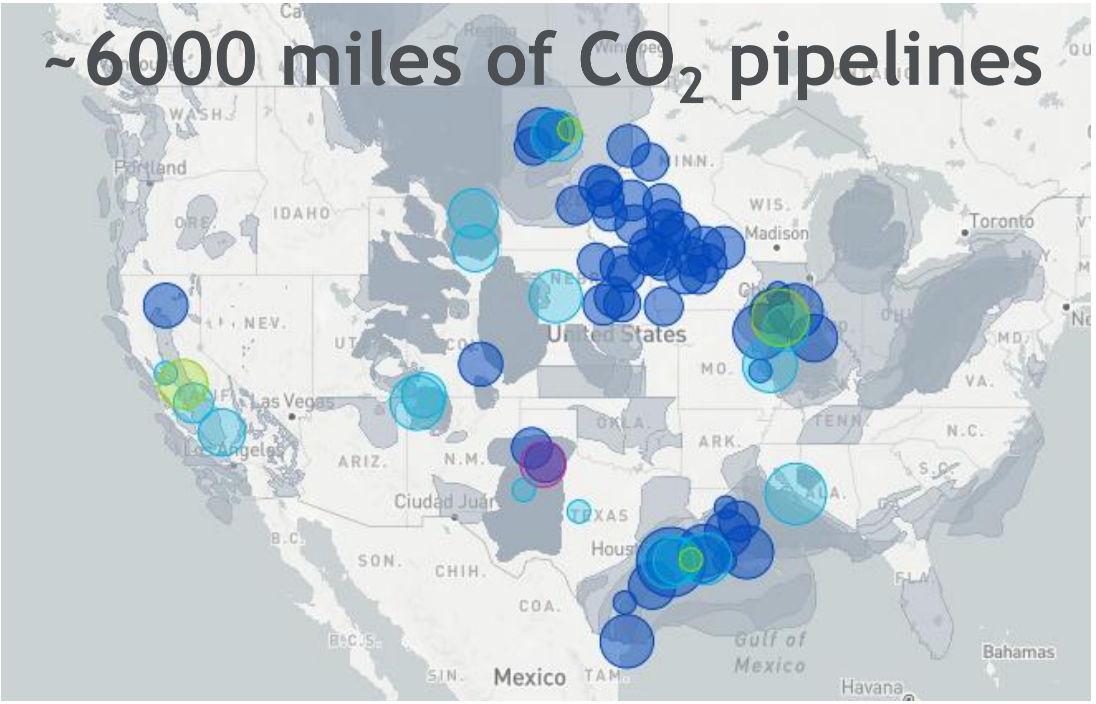
Need for development of sustainable solutions in an emissions constrained future

Deep decarbonization of transport poses technical and economic challenges which require technology development

# Why mobile carbon capture?

- Need for deep decarbonization / existing competitive landscape
- Availability of high-quality waste heat, and other synergies from systems integration
- Cost reduction through mass production
- Very clean exhaust for on-road applications
- Leverage existing $CO_2$ infrastructure and large geological storage capacity
- Deployment as a retrofit to legacy ICE

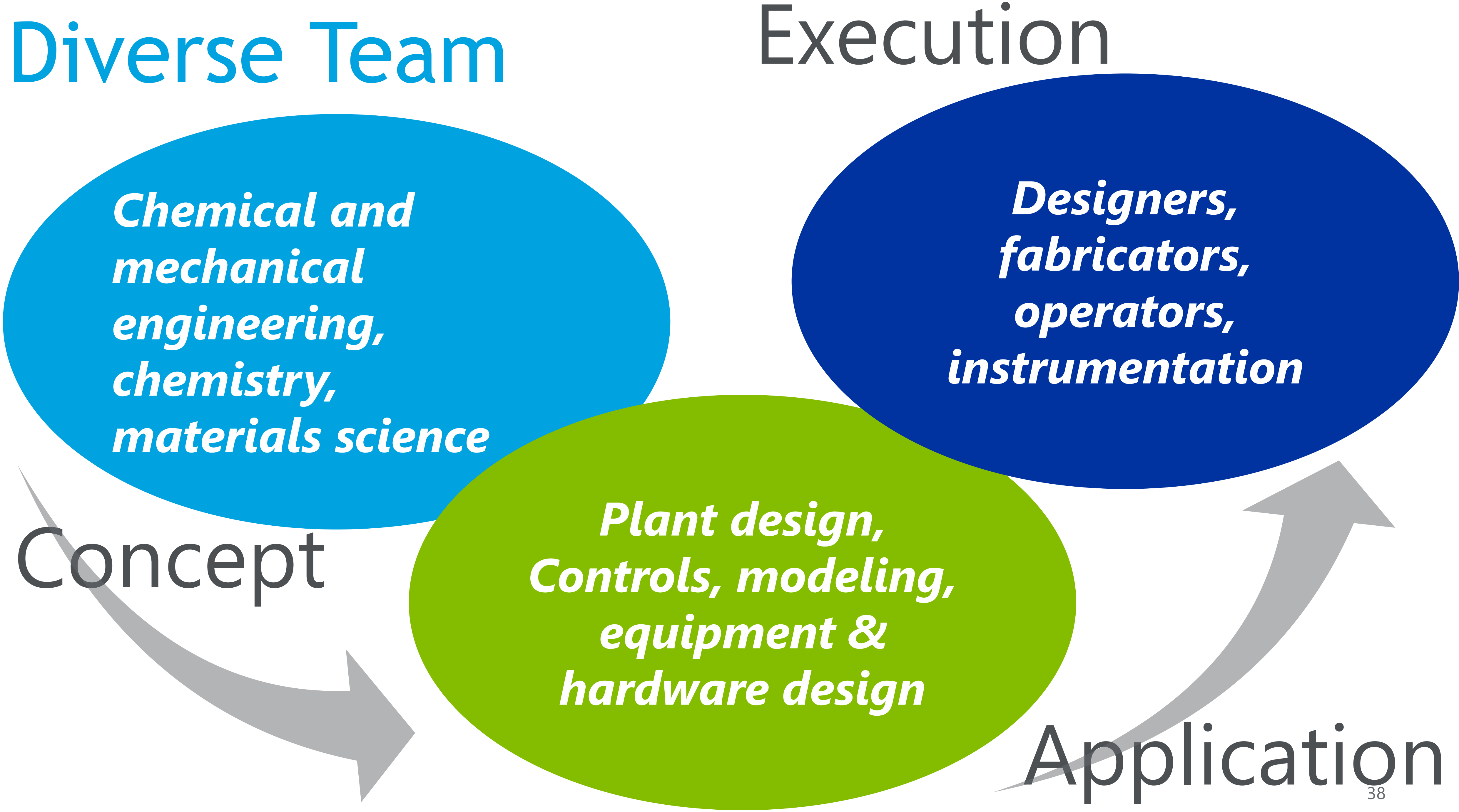


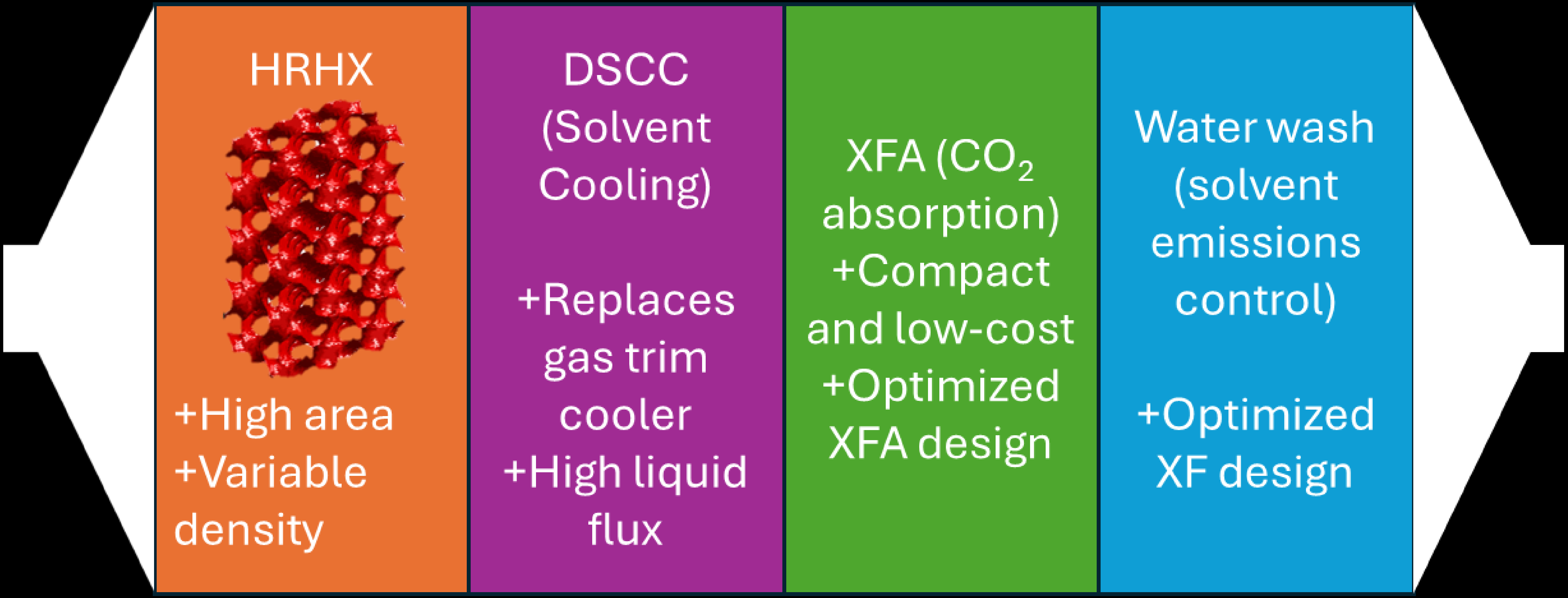



| Parameter | Values | Outcome |
|---|---|---|
| *Solvent* | MEA, AR-1 | **Similar in Gen 1, MEA data used for modelling** |
| *Packing media* | 250X, 500SGX, 750SGY | **750SGY ~ 500SGX > 250SX** |
| *Packing fill* | 50%, 100% | **-3% for 50% nozzle vs. pack** |
| *Nozzle Type* | MPL 1.12 (small), MP 125 (larger) | Not sensitive |
| *Nozzles Active* | 25, 50, 100% | **-9%/-26% for 50%/25% noz.** |
| *Sys. gas rate* | 50%, 0% bypass | **-25% for 50% gas** |
| *Lean loading* | 50%, 0% bypass | **+27% vs. 50% gas** |
| *L/G* | 2.3-4.7 | **Optimal L/G ~2-2.5** |
| *Stripper P* | 1.5-4 bar | Not sensitive |
| *Stripper T* | *100 – 130 C* | *Dependent on P* |

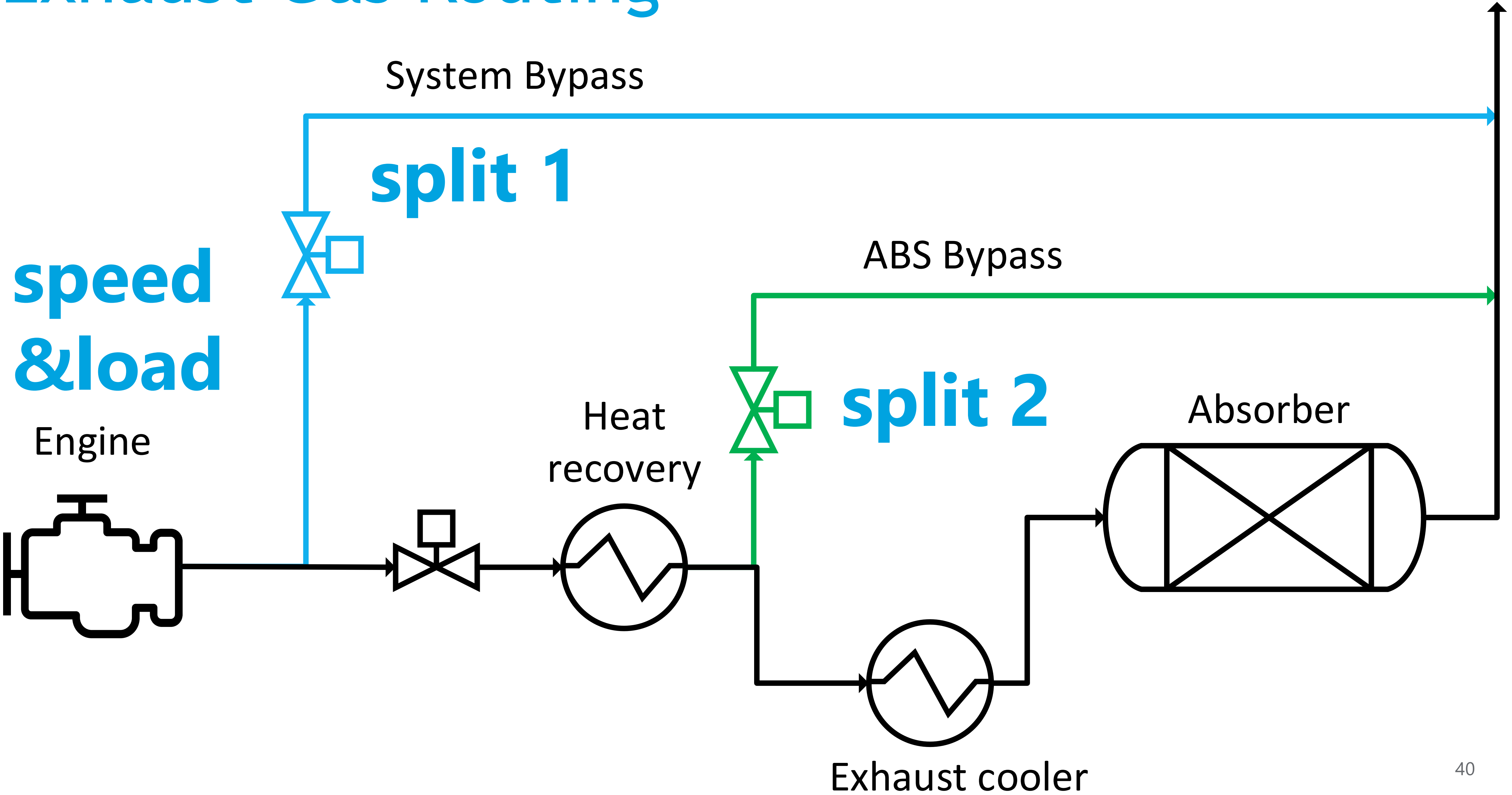
| Parameter | Values | Purpose |
|---|---|---|
| *Solvent* | MEA, AR-1 | MEA for model validation |
| *Packing media* | 250X, 500SGX, 750SGY | Sheet vs. gauze packing |
| *Packing fill* | 50%, 100% | Sizing/scale-up |
| *Nozzle Type* | MPL 1.12 (small), MP 125 (larger) | Minimum dP, turn-up |
| *Nozzles Active* | 3 (25%), 6 (50%), 12 (100%) | Rapid sizing |
| *Sys. gas rate* | 50%, 100% | Gas rate effect |
| *Abs. gas rate* | 50%, 100% | Lean loading + gas rate |
| *L/G* | 2.3-4.7 | Liquid rate effect |
| *Stripper P* | 1.5-4 bar | Lean loading effect |
| *Stripper T* | *100 – 130 C* | *Incidental with pressure* |

# Diverse Team

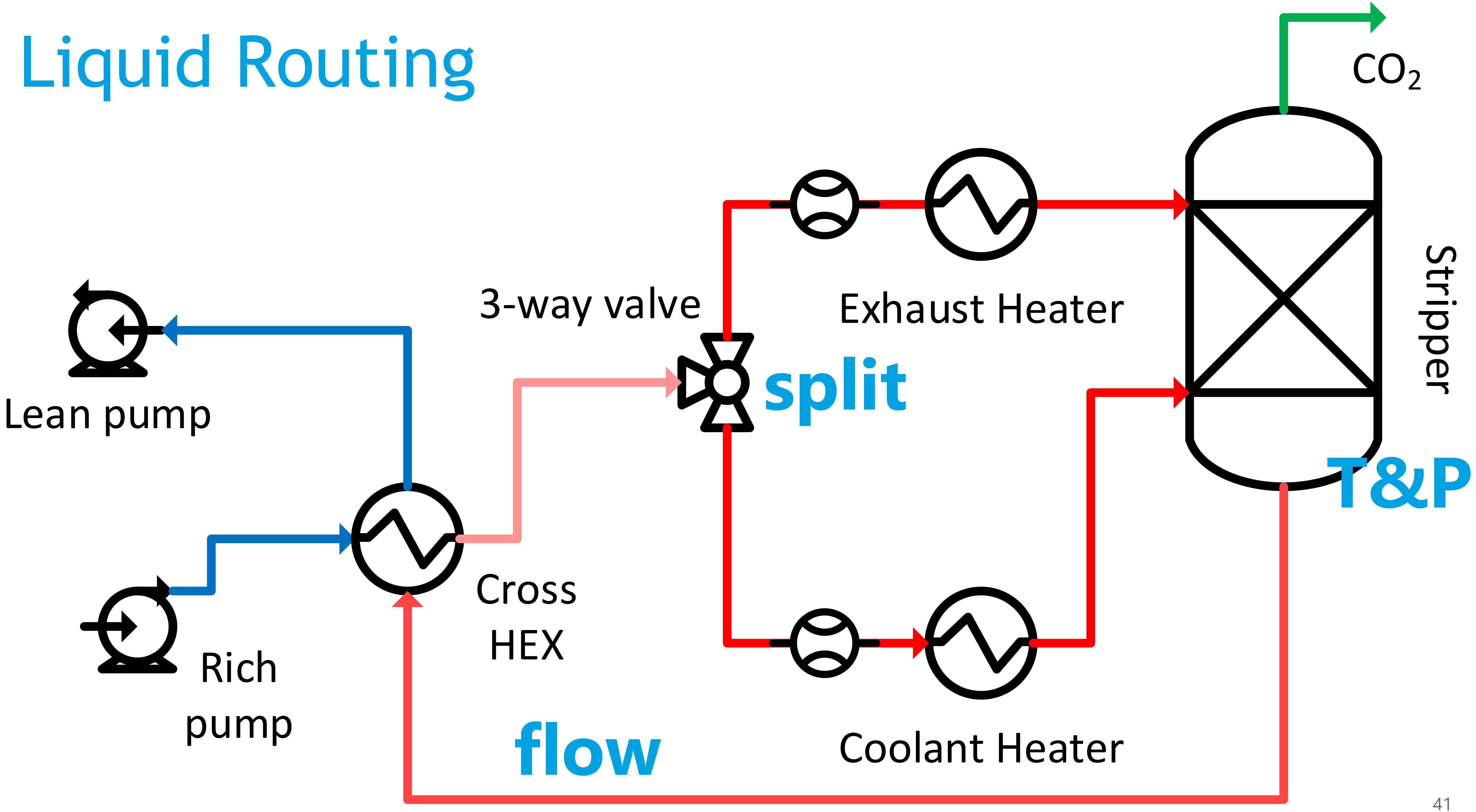



HRHX
+High area
+Variable density
DSCC (Solvent Cooling)
+Replaces gas trim cooler
+High liquid flux
XFA ($CO_2$ absorption)
+Compact and low-cost
+Optimized XFA design
Water wash (solvent emissions control)
+Optimized XF design

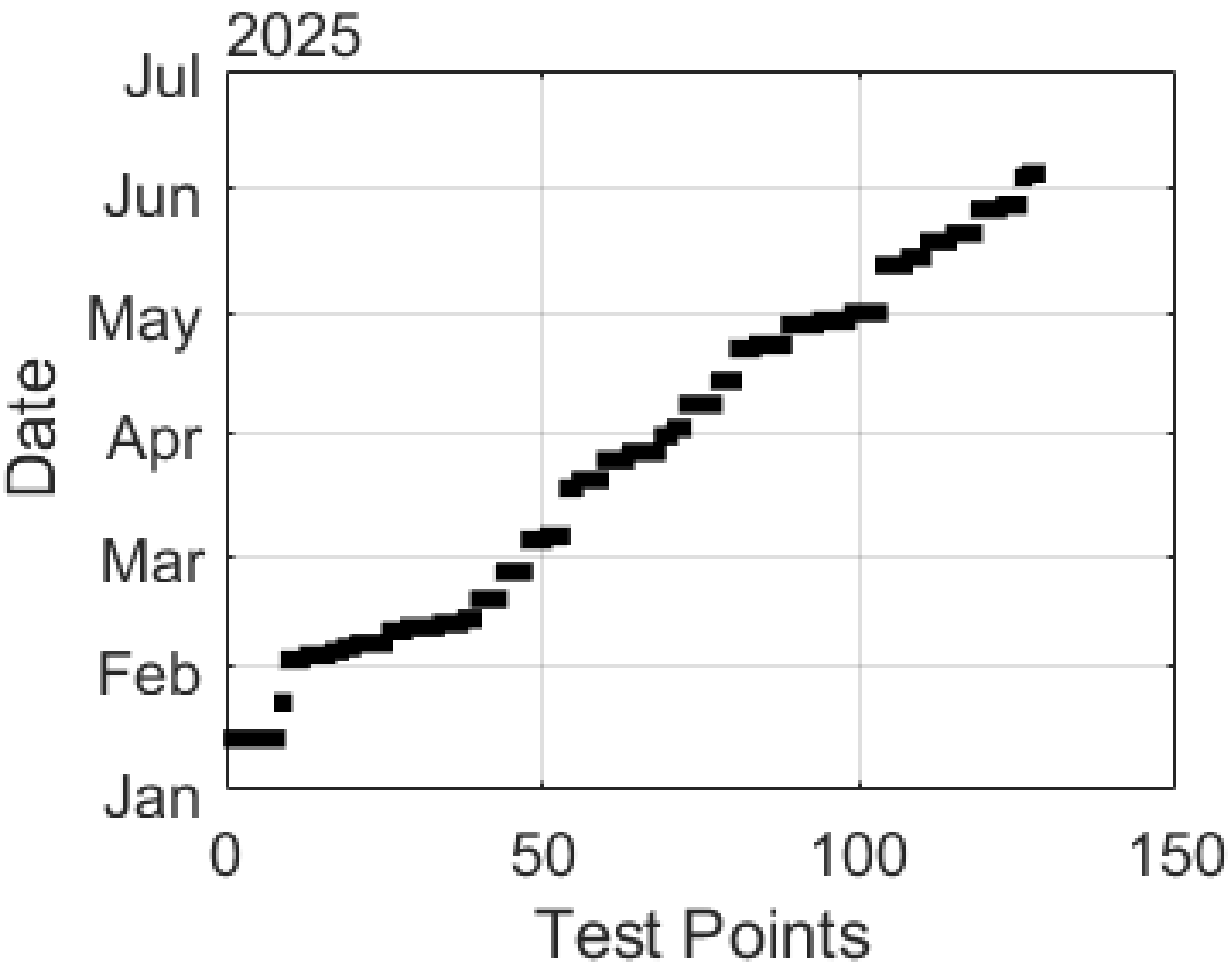
# Exhaust Gas Routing



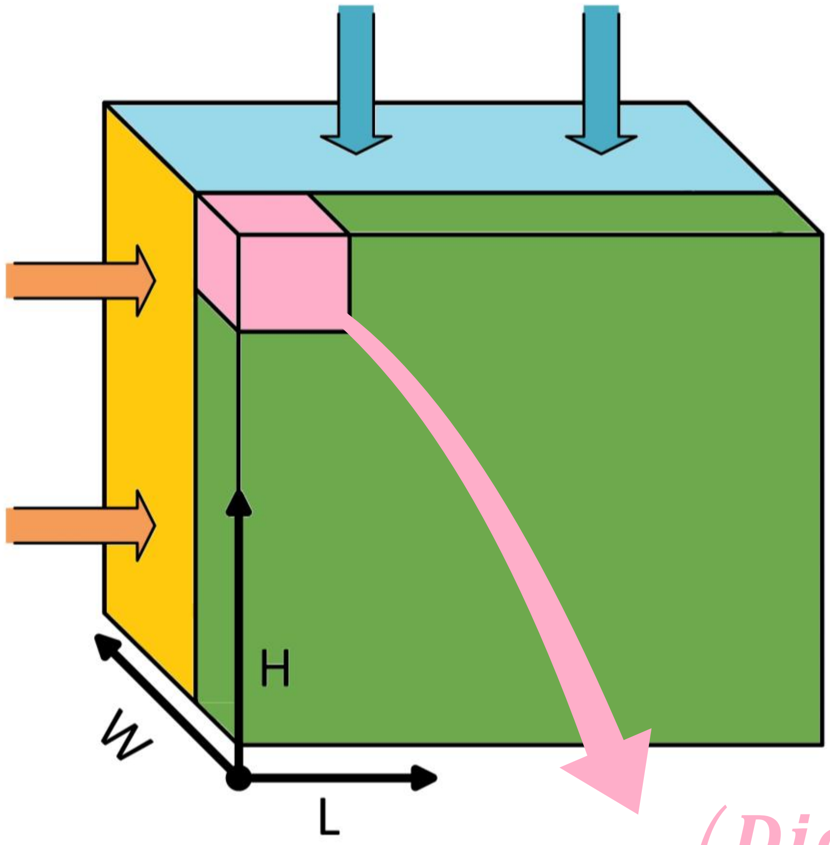
# Liquid Routing

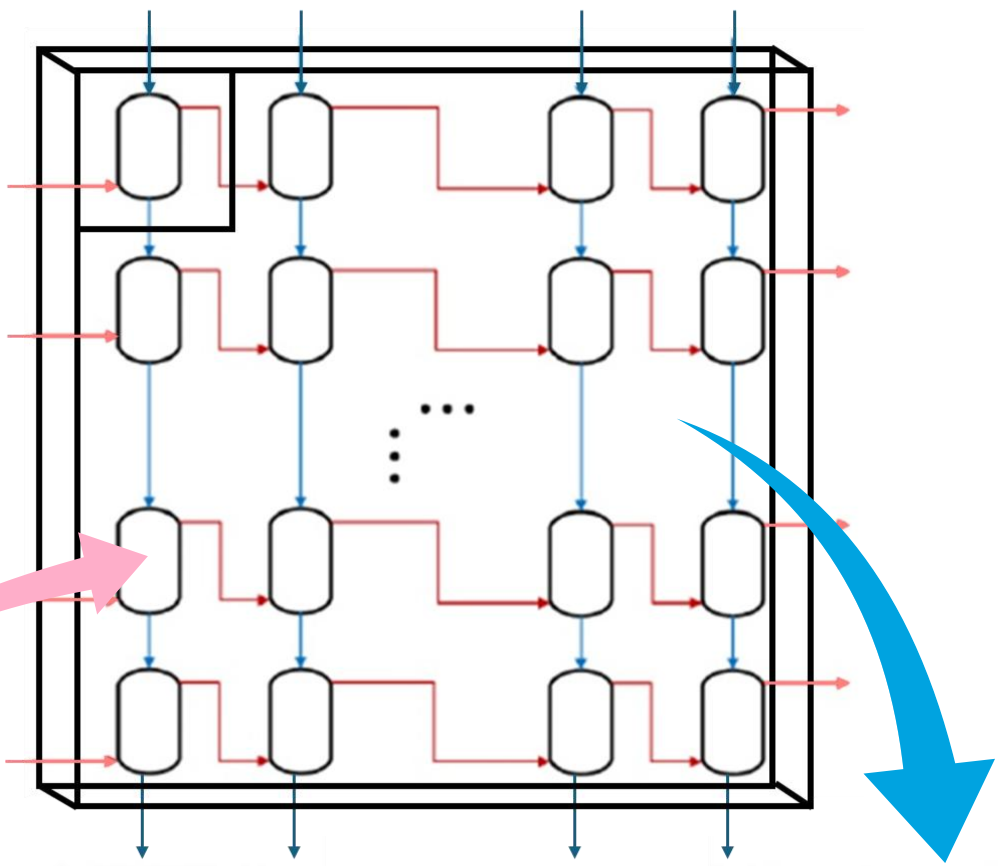


# Testing Productivity

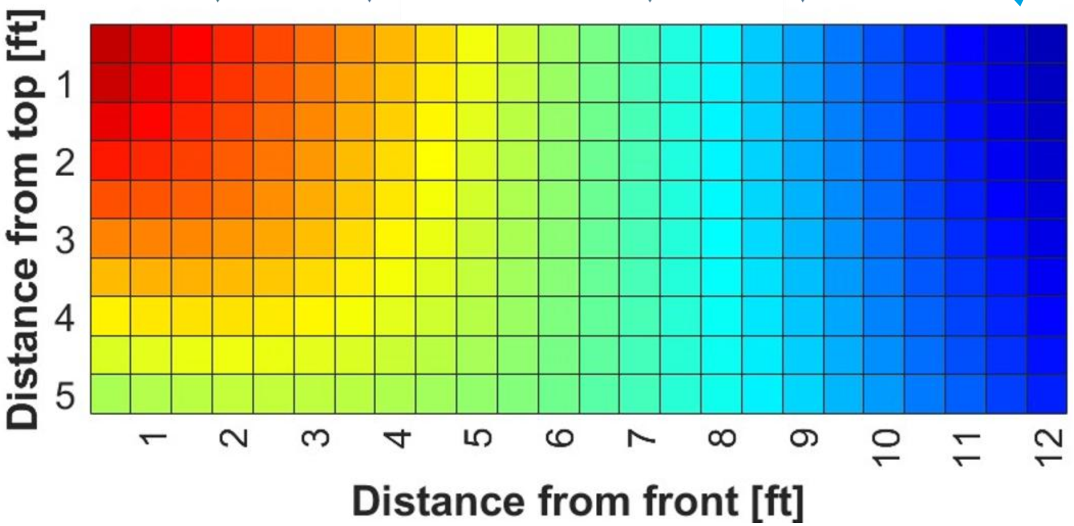



- **Timeframe** Gen 1 testing in Q2 2024; Gen 2 Q1-Q2 2025
- **Achieved** ~40% up-time based on working days incl. training, vacation, visits etc.
- **Best practices** inventory spare parts, equipment and service contracts in place, and rapid trouble-shooting



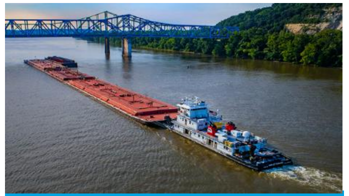
$$Cell\ Height = Depth = \left(\frac{Diam^2 \pi}{4}\right)$$




# Cross-Flow Absorber
# 2-D Modelling

# Carbon Capture from Internal Combustion Engines

## MCC Program



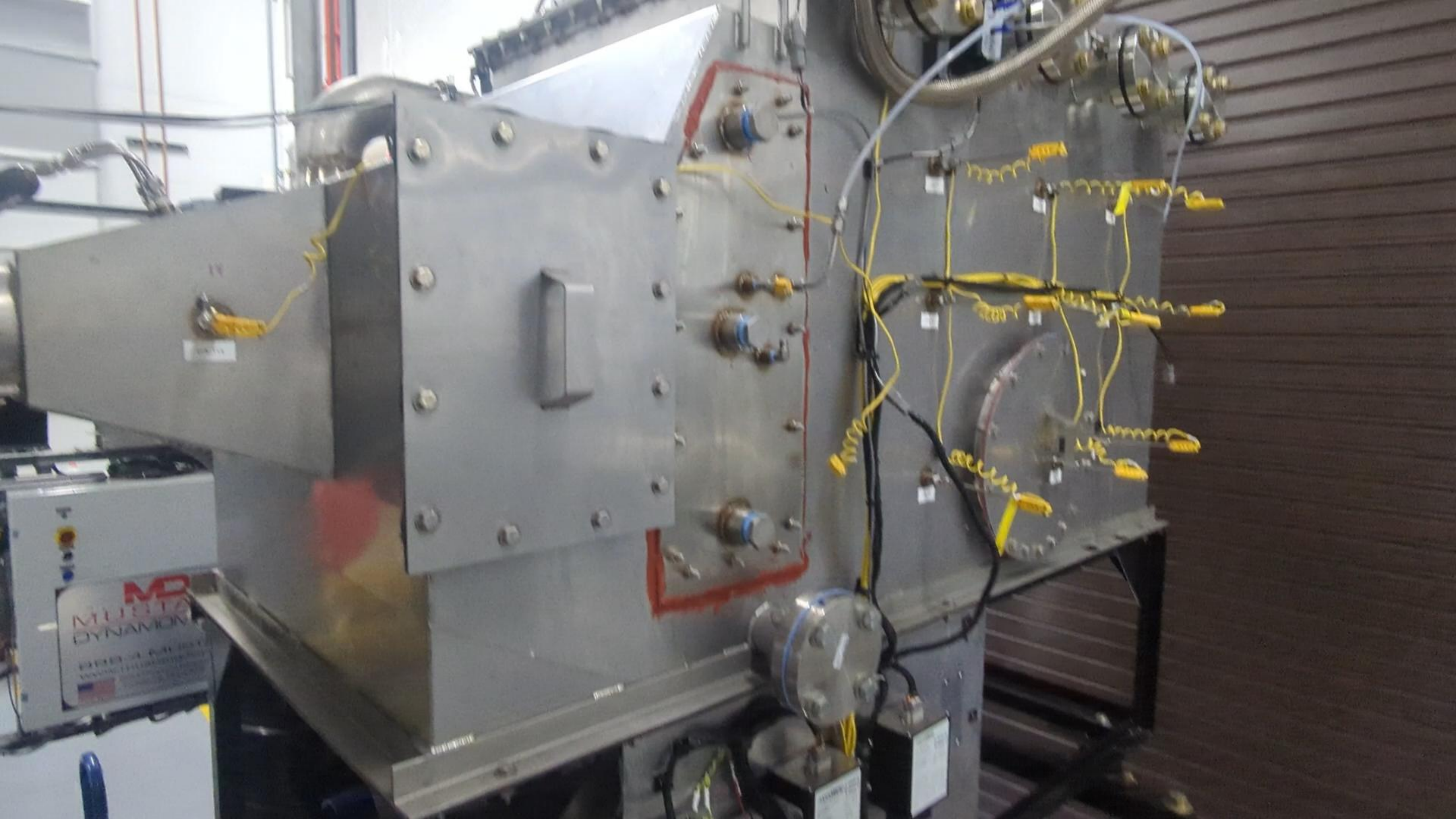

| | Heavy duty & Off-road | Marine Vessels | Mobile Power | Railroad |
|---|---|---|---|---|
| Team role | **design and commercialization** | **R&D and piloting** | **design and commercialization** | **Design and piloting** |
| Partners & interests | Private and Public Entities | Private | Private | Private |
| Target Capture | 60% w/o additional fuel<br>90% with additional fuel | 60% w/o additional fuel (small and medium ships) | 70% w/o additional fuel<br>90% with additional fuel | 60% w/o additional fuel<br>90% with additional fuel |
| Target Cost \$/ton $CO_2$ | **<\$200** | **<\$150** | **<\$150** | **<\$200** |
| Partners & interests | | | | |

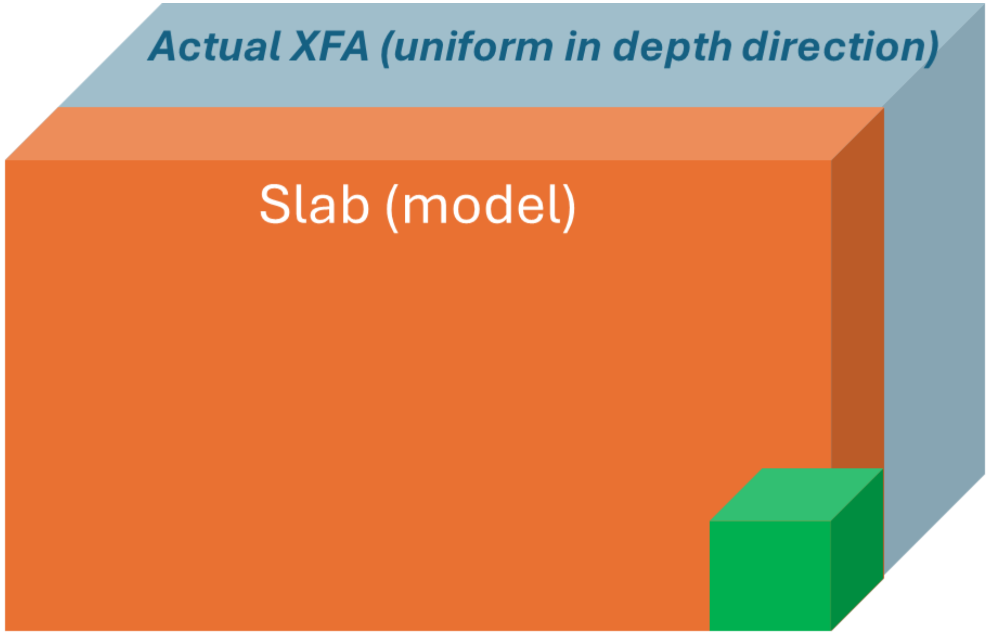
| Characteristic | Benefit |
|---|---|
| Fast reaction rate with $CO_2$ | Absorber size, increase rich loading |
| High heat of absorption | Heat requirements for solvent regeneration |
| High cyclic capacity | Solvent circulation rate |
| Thermally and oxidatively stable | Solvent replacement cost |
| Low viscosity | Pumping work, heat and mass transfer |
| Low volatility | Solvent loss and secondary emissions |
| Low environmental persistence | Ecological impact in case of release |
| Low toxicity | Ecological impact in case of release |
| High solubility | Fully liquid under various of conditions |

# Solvent Development Summary

| Solvent | Purpose | Contactor | Status |
|---|---|---|---|
| Mono ethanolamine (MEA) | Baseline, model validation | XFA, CCA | Tested on MP and MCC Demo with CCA and XFA |
| AR-1 | Optimized for engine-base capture using hollow fiber membrane (HFMC) contactors | HFMC | Tested on MP and MCC Demo with HFMC |
| AR-2 | Optimized for improved performance under cold ambient conditions | HFMC | Tested on MP and MCC Demo |
| AR-3 | Optimized for CCA and XFA | HFMC, XFA, CCA | Preliminary testing and development |
| AR-4 | Significantly improved corrosion and degradation vs. MEA | XFA, CCA | Conceptual, preliminary testing planned Q4 2025 |
| AR-5 | Optimized for engine-based capture in hot, dry climates | XFA, CCA | Conceptual, preliminary testing planned Q4 2025 |

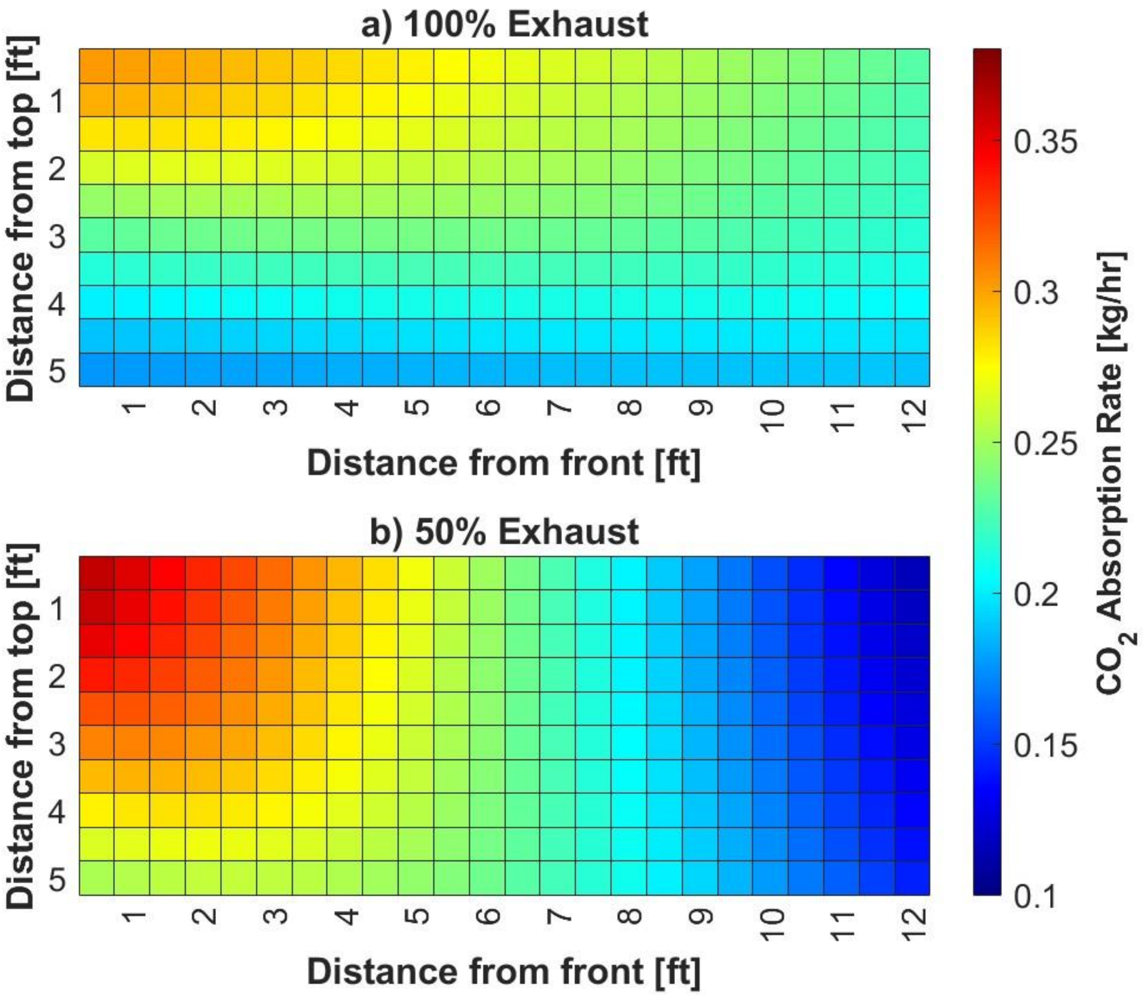
| Technology | Pros | Cons |
| --- | --- | --- |
| **Atomizing spray nozzle** | Very simple, cheap; Very high specific area | High dP required; Unpredictable and prone to clogging / fouling |
| **Counter-current absorber (CCA)** | Very well studied, low cost | Bulky, tall and unwieldy |
| **Cross-flow absorber (XFA)** | Cheaper and more constructable than CCA Reduced gas manifolding; High liquid flux with low gas dP | Lower driving force may require 10-15% more packing; No XFA packing / less well studied |
| **Foam screens** | Very high specific area | Unpredictable and less operable; Less well characterized; Liquid in gas entrainment |
| **RPB** | Highly intensified absorption – increased area and mass transfer | More expensive to build and operate |
| **HFMC** | Very simple and highly compact | Susceptible to oil, soap, particle fouling; Not compatible with traditional amine solvent |






$$Height = Depth = \left(\frac{Diam^2\pi}{4}\right)$$

**Counter-flow absorber "unit cell"**


a) 100% Exhaust
Distance from top [ft]
1
2
3
4
5
Distance from front [ft]
1
2
3
4
5
6
7
8
9
10
11
12
b) 50% Exhaust
Distance from top [ft]
Distance from front [ft]
0.35
0.3
0.25
0.2
0.15
0.1
$CO_2$ Absorption Rate [kg/hr]