Supercritical $CO_2$
Power Cycles
Symposium

# $sCO_2$ Waste Heat Recovery System for Turbofan Engine – System Optimization and Component Design

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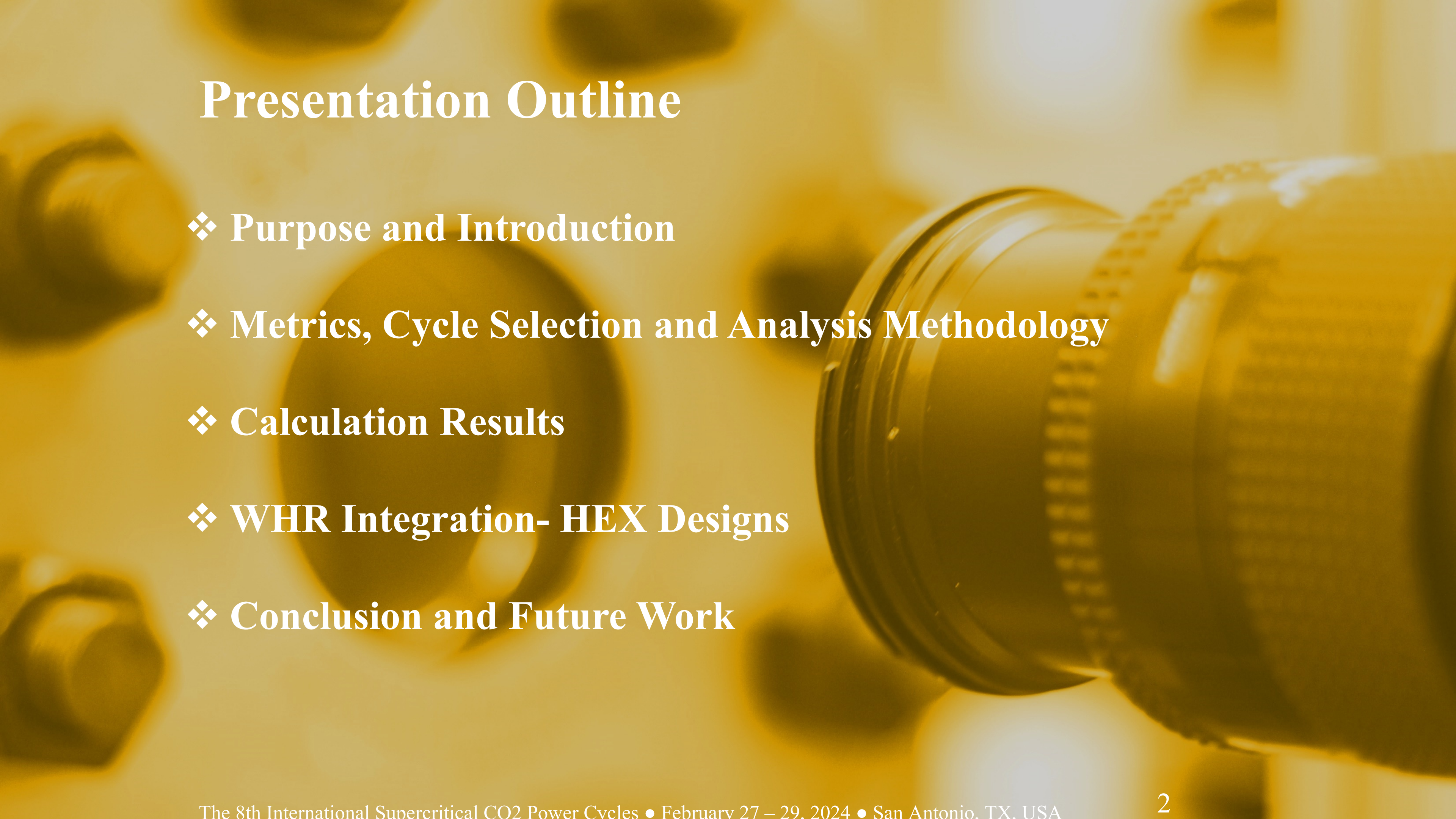
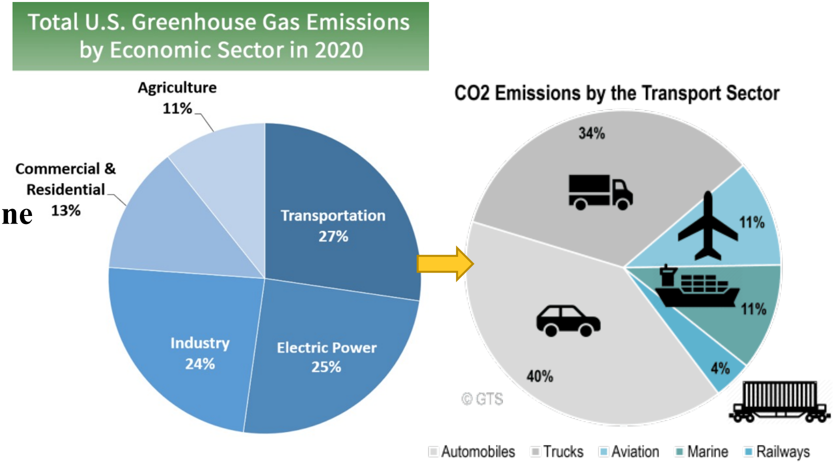


# Presentation Outline

- Purpose and Introduction
- Metrics, Cycle Selection and Analysis Methodology
- Calculation Results
- WHR Integration- HEX Designs
- Conclusion and Future Work

# Purpose

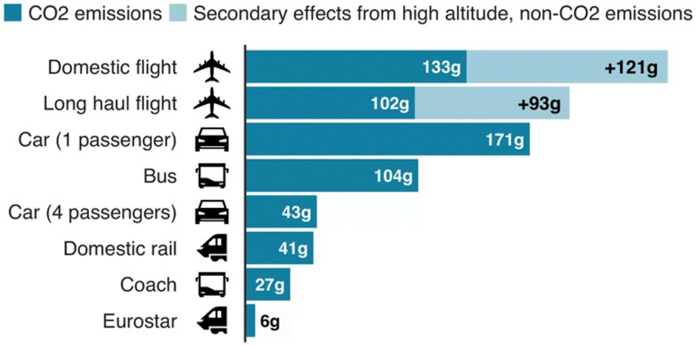
- From most recent publicly shared data, the transportation sector is one of the largest producers of CO2 emissions
- Transportation accounts for ~1/3rd of global CO2 emissions
    - Aviation is ~3% of the total CO2 emissions
- Government driven programs and other supported efforts aimed at reducing aviation emissions have given rise to many approaches
    - An indirect approach of using the waste heat from exhaust streams via a waste heat recovery (WHR) system


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

CO2 Emissions by the Transport Sector

## Emissions from different modes of transport

Emissions per passenger per km travelled



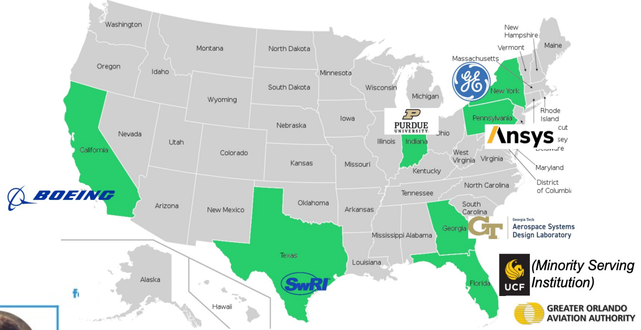
Note: Car refers to average diesel car

Source: BEIS/Defra Greenhouse Gas Conversion Factors 2019

[1] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
[2] https://transportgeography.org/contents/chapter4/transportation-and-environment/greenhouse-gas-emissions-transportation/
[3] https://www.bbc.com/news/science-environment-49349566

# NASA ULI- ALFA

**To explore using liquid ammonia – a non-traditional source – as fuel for a jet engine and generating electricity from the engine's exhaust heat, reducing emissions, and saving on fuel.**



*(Minority Serving Institution)*

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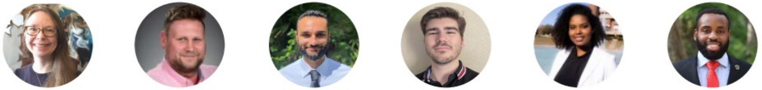

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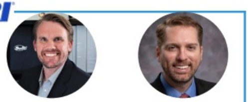

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*Student list on this slide is incomplete*

# NASA ULI- ALFA

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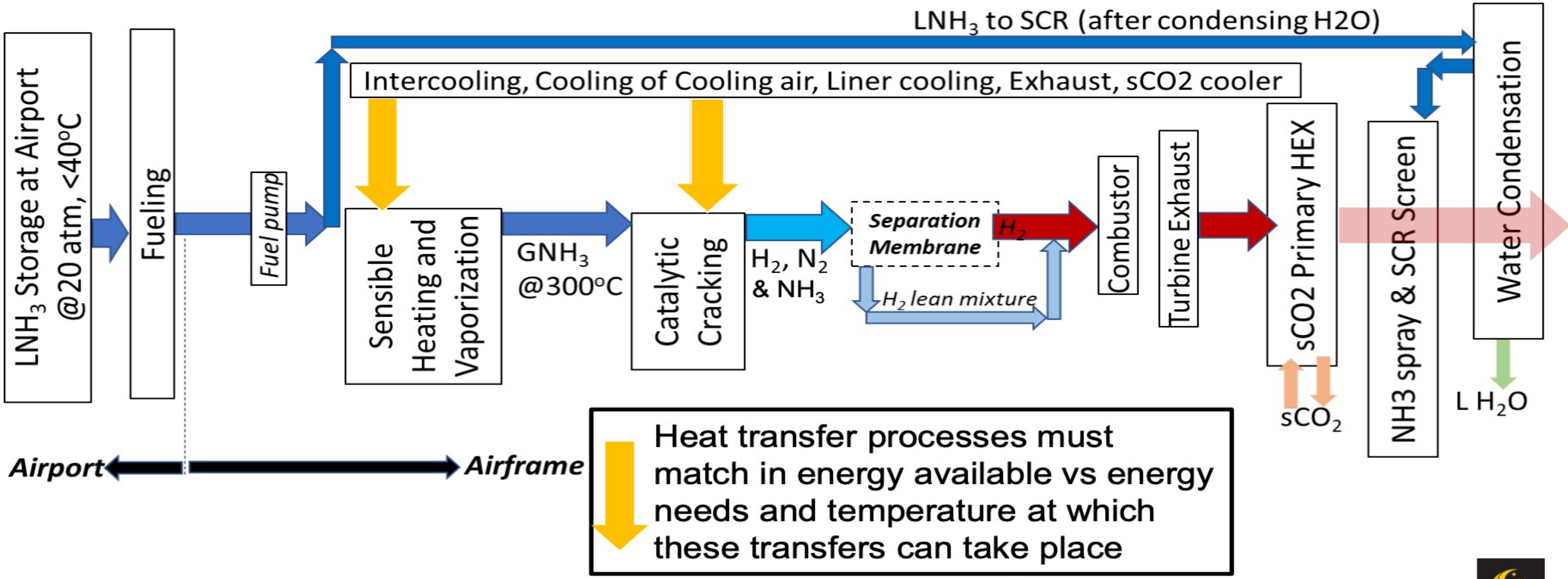

$LNH_3$ to SCR (after condensing H2O)

Intercooling, Cooling of Cooling air, Liner cooling, Exhaust, sCO2 cooler

$LNH_3$ Storage at Airport @20 atm, <40°C

Fueling

*Fuel pump*

Sensible Heating and Vaporization

$GNH_3$ @300°C

Catalytic Cracking

$H_2$, $N_2$ & $NH_3$

***Separation Membrane***

*$H_2$*

*$H_2$ lean mixture*

Combustor

Turbine Exhaust

sCO2 Primary HEX

$sCO_2$

NH3 spray & SCR Screen

Water Condensation

L $H_2O$

***Airport*** ***Airframe***

Heat transfer processes must match in energy available vs energy needs and temperature at which these transfers can take place

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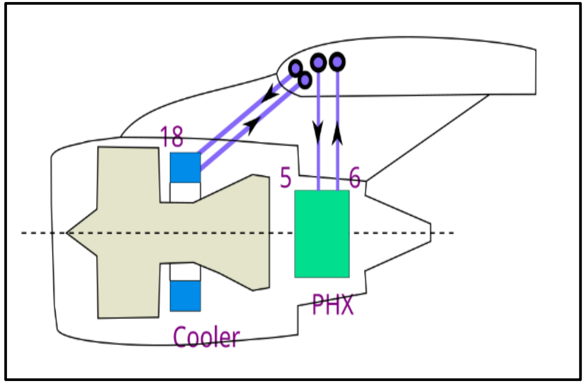
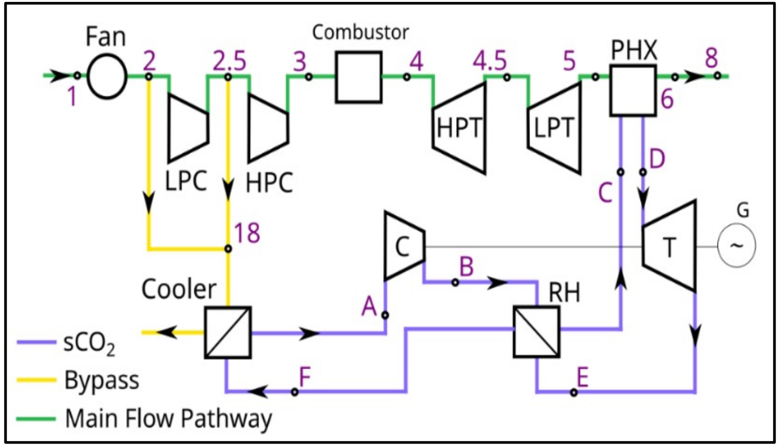
# Introduction

- **Aircraft engine waste heat can be converted into electricity for onboard systems via Waste Heat Recover WHR**
  - **Environmental control, hydraulics, pneumatics, and other systems that are typically driven by engine power extraction**
- **WHR systems provide a pathway to improve propulsion performance and emissions in current and future aircraft**
  - **Using sCO2 as the working fluid - heat transfer capabilities, relatively lower viscosity and higher density**
  - **Steam cycles– heavier and more wasteful**
- **Challenges- Integrating WHRS with minimal effect to engine performance such as pressure drops and fuel burn**





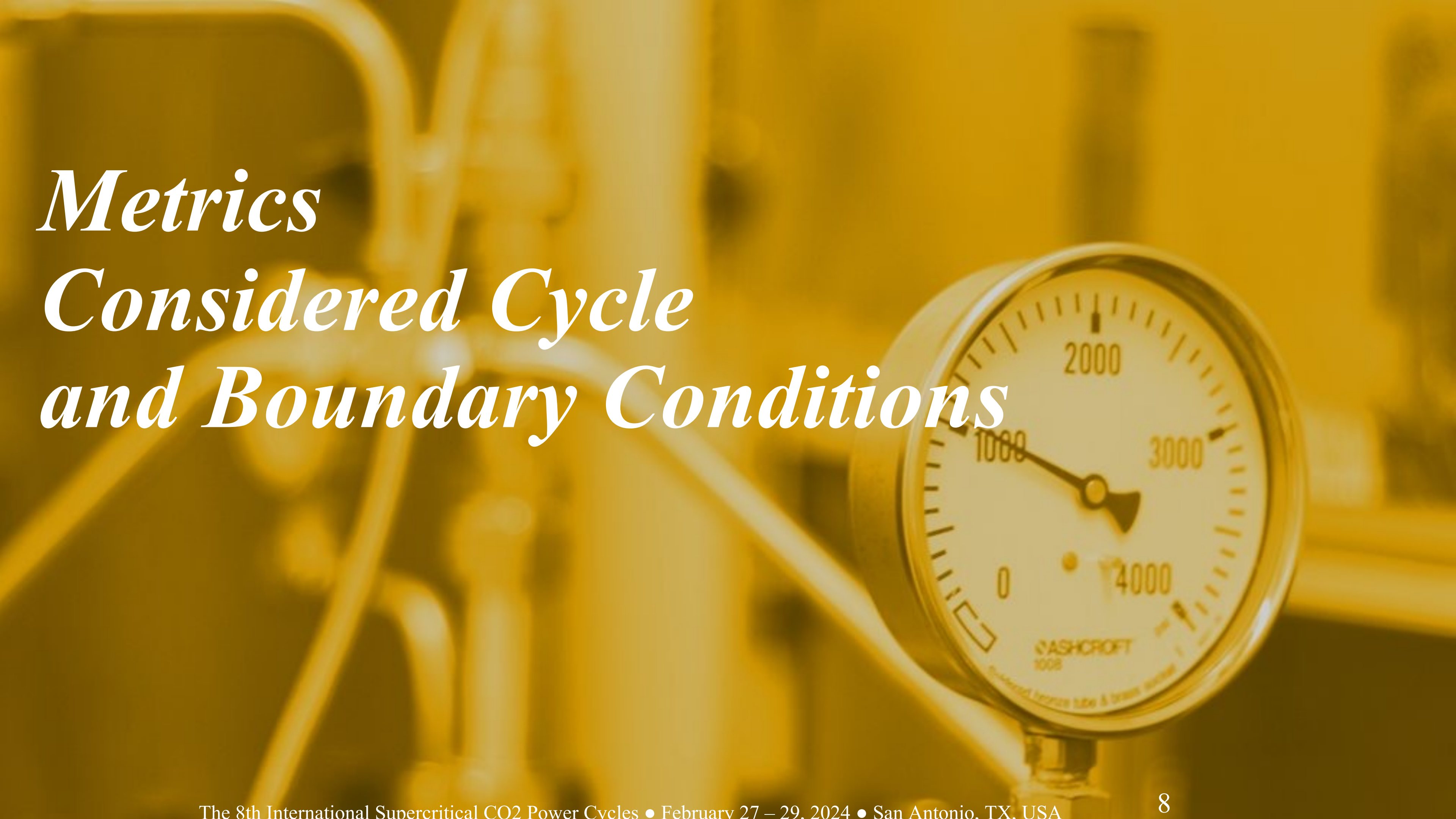
# Introduction (continued)

- What: sCO2 Waste Heat Recovery System optimization

- Why: Starting point for potential configurations of a WHRS in a turbofan engine and to analyze performance

- How:
  1. Conduct sCO2 WHR power system steady-state calculations of various cycles
  2. Design HEXs
  3. Select power cycles for this application
     1. Compare using system-specific metrics

# *Metrics Considered Cycle and Boundary Conditions*



# sCO2 Power Cycle Selection- Metrics

1. **Integration complexity**

2. **Cycle performance- Thermal efficiency**

3. **Overall engine performance - WHRS size**

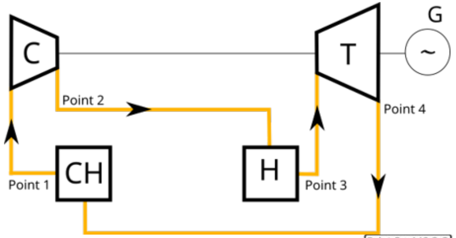
# sCO2 Power Cycle Variations

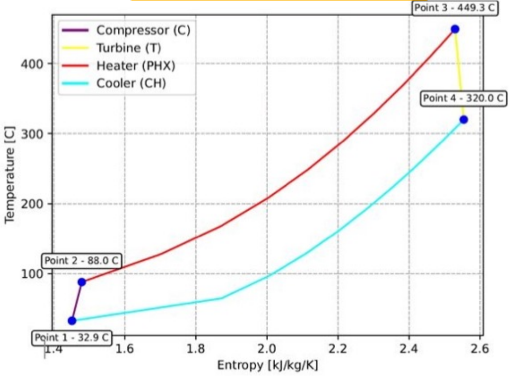
- ❖ Simple Brayton
- ❖ Recuperated
- ❖ Recompression
- ❖ Split expansion
- ❖ Pre-compression
- ❖ Pre-cooling*
- ❖ Cascade*
- ❖ Preheating*

*Integration complexity; WHRS size

**$sCO_2$ power cycle layouts consist of combinations of compressor (C), turbine (T), Cooler/fan CHX, primary heat exchanger/core (PHX) and recuperative heat exchanger (RHX)**

Simple Brayton
•**Pros**: Simple design; reliable operation
•**Cons**: Lower efficiency; no heat recuperation



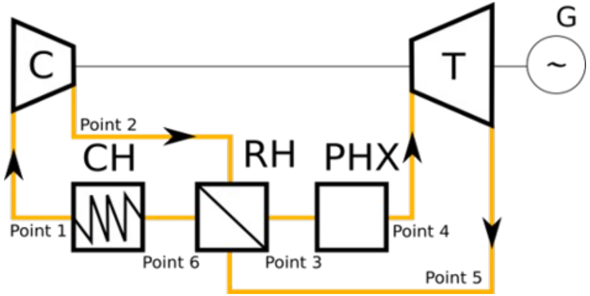


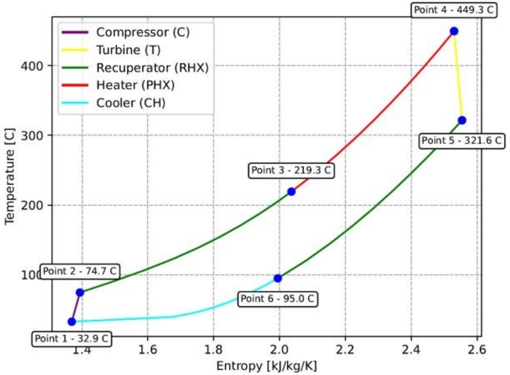
| Components | Simple Brayton | Recuperative | Re-compression | Split expansion | Pre-compression | Pre-cooling | Cascade | Preheating | |
|---|---|---|---|---|---|---|---|---|---|
| **Compressor** | 1 | 1 | 2 | 2 | 2 | 3 | 1 | 1 | - |
| **Turbine** | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | |
| **RHX** | 0 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | |
| **PHX** | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | |
| **CHX** | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | |

# sCO2 Power Cycle Variations

Recuperated

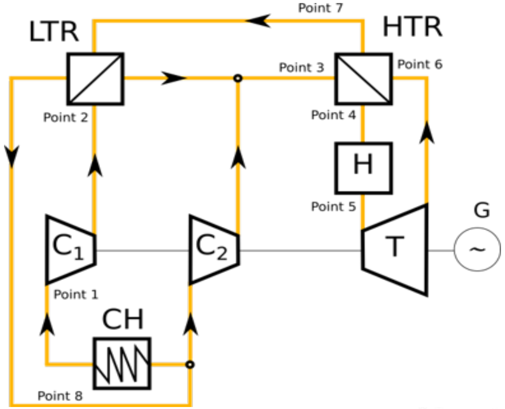
- **Pros**: Higher efficiency - reduced waste heat load.
- **Cons**: Increased complexity, higher costs

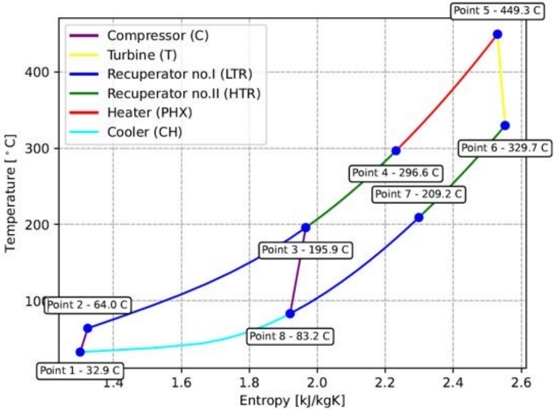




Recompression

- **Pros**: Enhanced efficiency; improved thermal matching.
- **Cons**: Increased complexity, higher costs

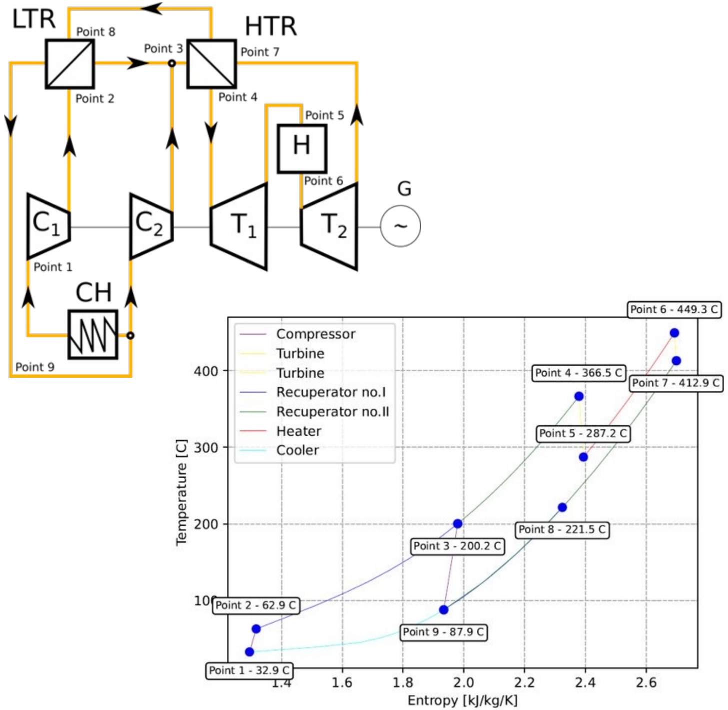




# sCO2 Power Cycle Variations

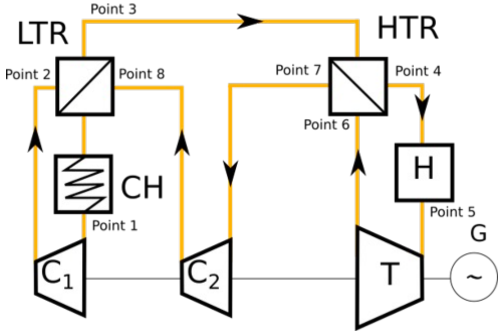
Split Expansion

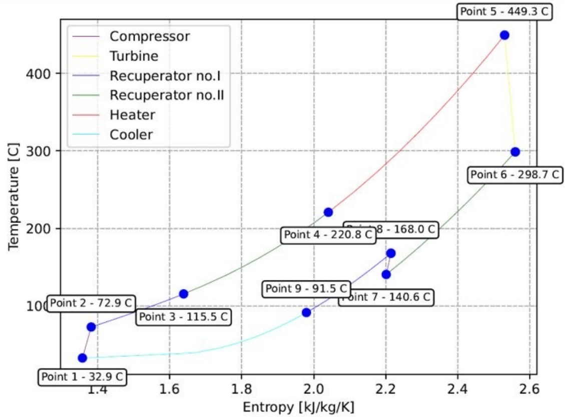
- **Pros**: Tailored expansion stages, improved thermal efficiency
- **Cons**: Increased complexity, higher costs



Precompression

- **Pros**: Heat source matching, staged compression
- **Cons**: Increased complexity, higher costs

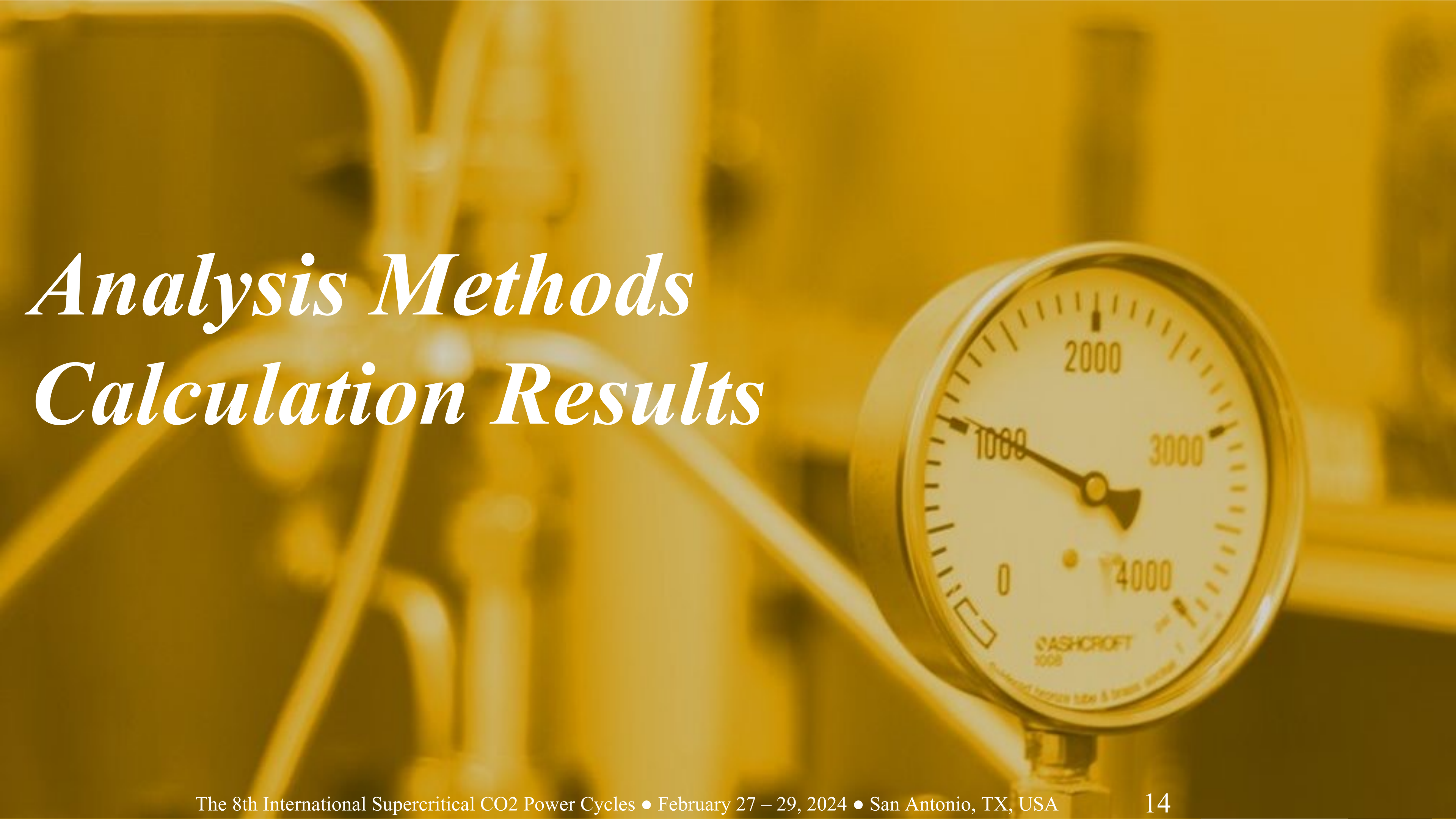




# Boundary Conditions for sCO2 Brayton Cycle-Turbofan engine parameters

| **Case** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **unit** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Altitude** | 0 | 0 | 0 | 0 | 0 | 0 | 1,668 | 9,668 | 10,668 | 10,668 | **m** |
| **Ambient temperature** | 320 | 315 | 310 | 300 | 290 | 288.15 | 277.31 | 225.31 | 218.81 | 218.81 | **K** |
| **Mach Number** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 0.50 | 0.64 | 0.74 | **-** |
| **Inlet parameters for PHX/Core (sCO$_2$ heater)** | | | | | | | | | | | |
| **$T_5$** | 865.3 | 856.7 | 848.0 | 830.9 | 816.2 | 813.5 | 792.4 | 684.3 | 684.1 | 679.8 | **K** |
| **$P_5$** | 124.13 | 125.02 | 125.967 | 128.03 | 130.47 | 130.96 | 111.28 | 47.74 | 45.38 | 47.29 | **kPa** |
| **Mass flow $_5$** | 59.25 | 60.45 | 61.69 | 64.33 | 67.21 | 67.77 | 59.95 | 28.56 | 27.16 | 28.4 | **kg/s** |
| **Inlet parameters for Air cooler/Fan (sCO$_2$ cooler)** | | | | | | | | | | | |
| **$T_{18}$** | 355.91 | 351.01 | 346.11 | 336.29 | 326.73 | 324.95 | 318.46 | 275.71 | 275.85 | 280.58 | **K** |
| **$P_{18}$** | 140.41 | 141.26 | 142.13 | 143.95 | 145.89 | 146.26 | 127.22 | 51.68 | 49.19 | 52.81 | **kPa** |
| **Mass flow rate $_{18}$** | 23.49 | 23.97 | 24.46 | 25.51 | 26.67 | 26.89 | 23.80 | 11.34 | 10.78 | 11.28 | **kg/s** |

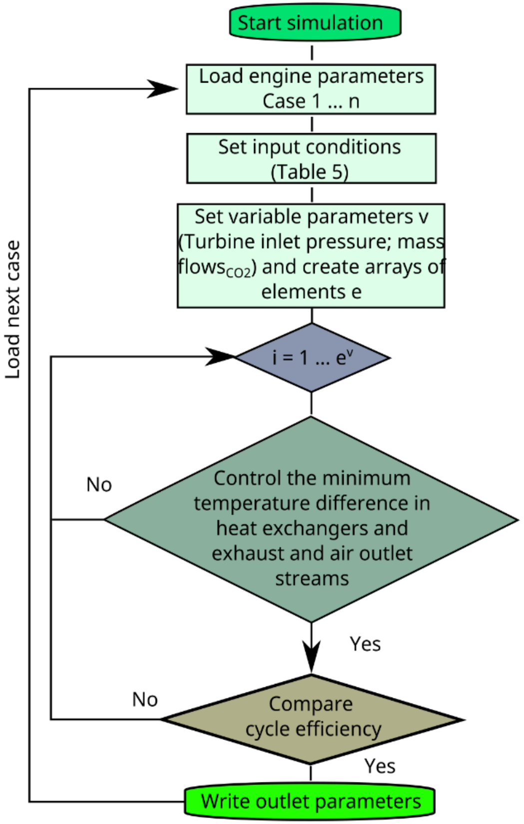
**Engine cycle analysis is performed for cruise operation at case 10 using engine data for a typical 250 passenger aircraft**



# *Analysis Methods*

# *Calculation Results*

# Methodology and Validation


Start simulation

Load engine parameters
Case 1 … n

Set input conditions
(Table 5)

Set variable parameters v
(Turbine inlet pressure; mass flows$_{CO2}$) and create arrays of elements e

i = 1 … e$^v$

Control the minimum temperature difference in heat exchangers and exhaust and air outlet streams

No

Yes

Compare cycle efficiency

No

Yes

Write outlet parameters

Load next case

- **Thermodynamic Equations**
  - **Thermal efficiency, turbine and compressor work, heater and cooler heat added and removed, turbine and compressor isentropic efficiency**

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_t - W_c}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

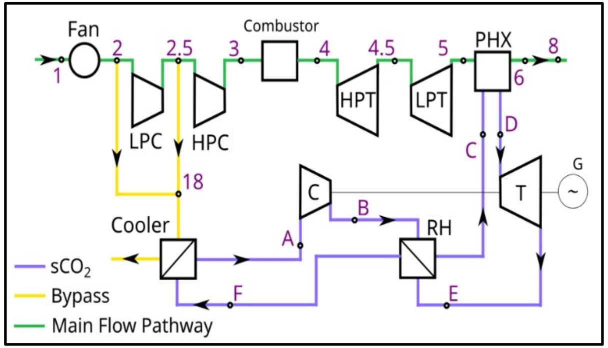
$$W_t = \mathrm{m}_{sCO2}(H_{in} - H_{out})$$

$$W_c = \mathrm{m}_{sCO2}(H_{out} - H_{in})$$

$$Q_{in} = m(H_{out} - H_{in})$$

$$Q_{out} = \mathrm{m}(H_{in} - H_{out})$$

$$\eta_t = \frac{H_{in} - H_{out_{real}}}{H_{in} - H_{out_{id}}}; \ \eta_c = \frac{H_{out_{id}} - H_{in}}{H_{out_{real}} - H_{in}}$$



ASME GT2023-103166
AIAA Scitech AIAA 2023-0307
Bell, I.H., Wronski, J., Quoilin, S., Lemort, V., "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp", Industrial & Engineering Chemistry Research, Vol. 53, No. 6, 2014, pp. 2498- 2508. https://doi.org/10.1021/ie4033999.

# Cycle Assumptions

- **Net Power is held at 492 kW, estimated from electric power extracted per engine for a single aisle 250 passenger aircraft and power transfer to the accessory gearbox of a CFM Leap1B**

| Parameter | Assumptions | unit |
|---|---|---|
| ***Minimum compressor inlet temperature (CIT)** | Air temperature + 5.0 K | K |
| **$\Delta T_{PHX}$** | 10 | |
| **WHR unit compressor inlet pressure** | 7.4 | MPa |
| **Recuperator (RH) effectiveness** | 90 | % |
| ****Turbine isentropic efficiency** | 90 | |
| ****Compressor isentropic efficiency** | 75 | |
| **Pressure Ratio** | 3.25 | - |
| **$sCO_2$ mass flow rate** | Variable | kg/s |
| **Net power** | 492 | kW |

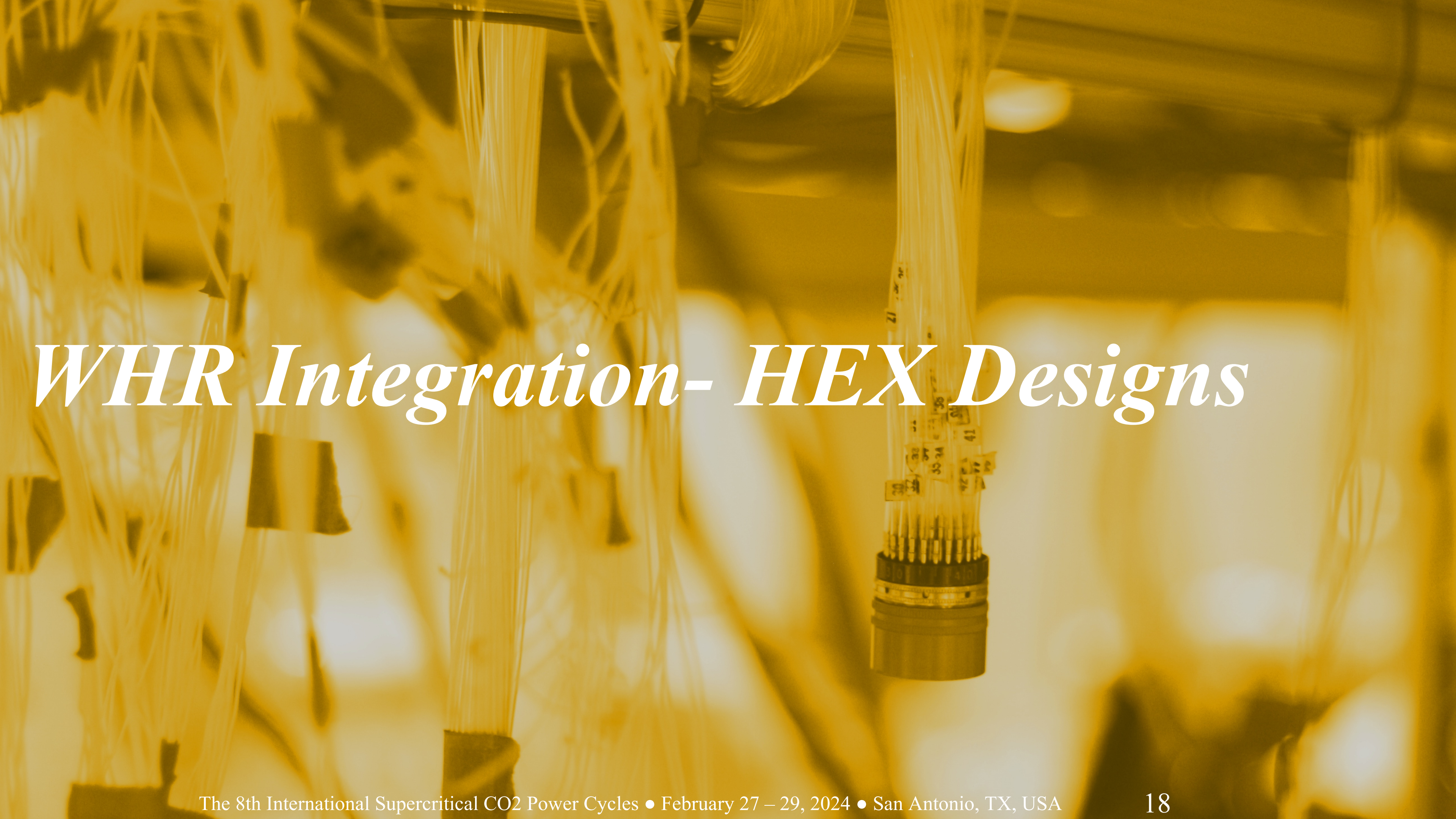
CIT- 306 K

* *Sourced from literature. More applicable magnitudes are used now from detail design of components

# Calculation Results

- Net Power is held at 492 kW
- Efficiency falls between 17-37%
- $m_{sCO2}$ ranges from 5-8 kg/s

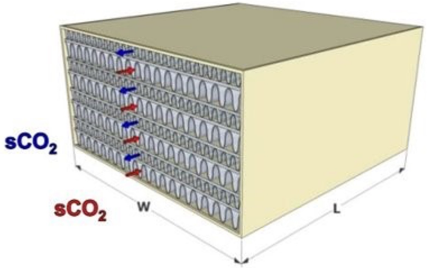
| | Simple Brayton | Recuperative | Re-compression | Split expansion | Pre-compression | |
|---|---|---|---|---|---|---|
| **Cycle efficiency** | **17.11** | **31.84** | **36.18** | **32.36** | **31.96** | % |
| **Turbine power output** | 0.71 | 0.67 | 0.85 | 0.89 | 0.79 | MW |
| **Compressor input power** | 0.21 | 0.18 | 0.36 | 0.40 | 0.30 | |
| **Added heat** | 2.88 | 1.55 | 1.36 | 1.52 | 1.54 | |
| **Removed heat** | 2.38 | 1.05 | 0.87 | 1.03 | 1.05 | |
| **Regenerative heat** | 0.00 | 1.38 | 2.08 | 3.06 | 1.41 | |
| **Net power** | 0.492 | | | | | |
| **mass flow - max** | 5.44 | 5.23 | 7.08 | 7.97 | 5.25 | kg/s |
| **Cooler/fan** | | | | | | |
| **$sCO_2$ flow – cooler** | 5.44 | 5.23 | 4.38 | 5.00 | 5.25 | kg/s |
| **$sCO_2$ pressure** | 7.69 | 7.81 | 8.47 | 8.63 | 7.86 | MPa |
| **$sCO_2$ inlet temperature** | 320 | 95 | 83.2 | 87.9 | 91.5 | C |
| **$sCO_2$ outlet temperature** | 32.85 | | | | | C |
| **Heater/Core** | | | | | | |
| **$sCO_2$ flow – heater** | 5.44 | 5.23 | 6.45 | 7.19 | 5.25 | kg/s |
| **$sCO_2$ pressure** | 25 | 25 | 25 | 25 | 25 | MPa |
| **$sCO_2$ inlet temperature** | 88 | 219.3 | 296.6 | 287.2 | 220.8 | C |
| **$sCO_2$ outlet temperature** | 449.27 | | | | | C |



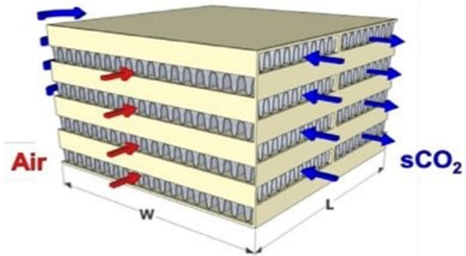
# *WHR Integration- HEX Designs*

# Design Assumptions

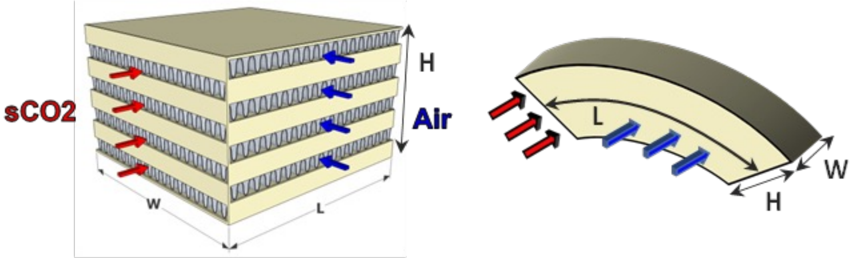
- Design point - cruise operation
- Titanium - the cycle would continuously operate at or above 306 K, which precludes the use of most aluminum alloys.
- Key design parameters- inlet temperature, pressure, and flow rate for the hot (sCO2) and cold (air) working fluids,
- Relevant performance targets include maximum allowable pressure drops for each HEXs
- Plate/Fin design configurations
- Plain fins considered for airside and Offset fins sCO2 side
- TTC INSTED Technology



RECUPERATOR DIAGRAM



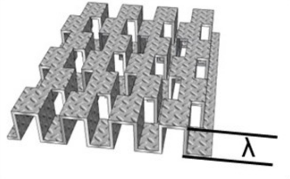
PRIMARY HEATER DIAGRAM



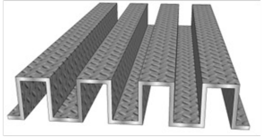
Analytical Representation

Physical Configuration

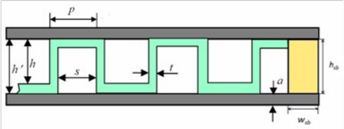
COOLER DIAGRAM



Offset-strip Fin



Plain Fin



Fin Cross-Section

# HEX Performance, WHR Size and Cycle Selection

| HEX | Fluid | Type | Material | Energy Density | e | DP/ P_hot | DP/ P_cold |
|---|---|---|---|---|---|---|---|
| [-] | [-] | [-] | [-] | [kW/Kg] | [%] | [%] | [%] |
| *Heater | Air/sCO$_2$ | Plate/Fin | Titanium | 12.25 | 95 | 5.85 | 0.1 |
| *Cooler | sCO$_2$/Air | Plate/Fin | Titanium | 17.13 | 95 | 2.5 | 0.94 |
| Recuperator | sCO$_2$/sCO$_2$ | Plate/Fin | Titanium | 21.64 | 80 | 0.07 | 0.005 |

*ASME GT2023-103166
*Scitech AIAA 2023-0307

| | Simple Brayton | Recuperative | Re-Compression | Split expansion | Pre-Compression | |
|---|---|---|---|---|---|---|
| **PHX** | 234.73 | 126.15 | 111.01 | 124.13 | 125.68 | kg |
| **Cooler** | 139.14 | 61.49 | 50.67 | 60.04 | 61.15 | |
| **Recuperator** | - | 63.57 | 96.14 | 141.29 | 65.33 | |
| **WHRS Mass** | 373.87 | 251.20 | **257.82** | 325.46 | 252.16 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Cycle efficiency** | **17.11** | **31.84** | **36.18** | **32.36** | **31.96** | % |

**Metrics**
**Overall engine performance - WHRS size**
**Cycle performance- Thermal efficiency**

- ❖ **Based on WHRS size which affect engine performance and the cycle performance indicating best energy transfer from heat to power, the Recompression, Recuperative and Precompression cycles are selected for further analysis for aviation application**

# *Conclusion and Future Work*

# Conclusion & Future Work

- sCO2 WHR power system is optimized to generate 492kW of power at cycle efficiencies between 17% to 37%
- The Recuperative, Recompression and Precompression cycles stand out due to higher efficiencies and compact sizes, ideal for retrofitting existing engines
- Final selection for integration would consider trade off between efficiency and total size (including turbomachinery, machine packaging and piping weights)

- Future work will focus on improving engine performance while integrating the WHR
    - Cooler heat sink as bypass vs fuel systems

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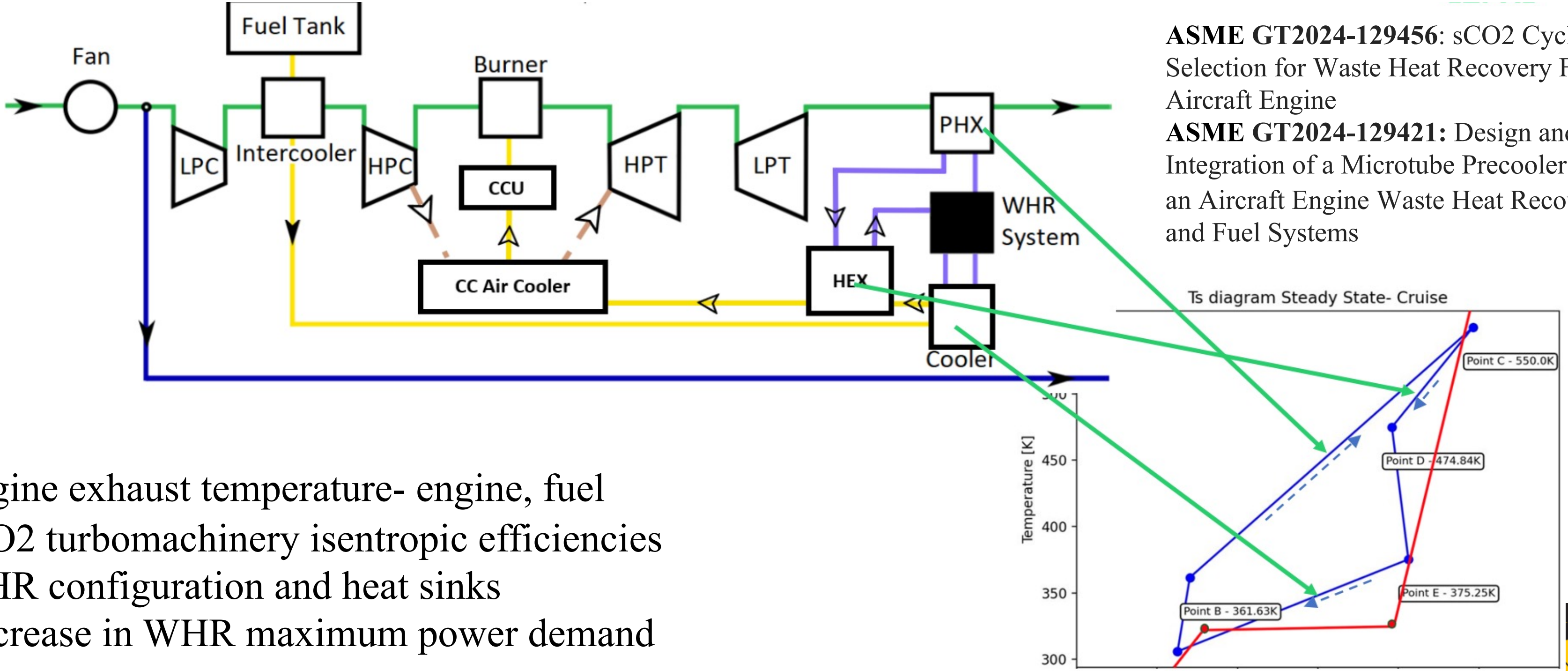

**ASME GT2024-129456**: sCO2 Cycle Selection for Waste Heat Recovery For Aircraft Engine

**ASME GT2024-129421:** Design and Integration of a Microtube Precooler Into an Aircraft Engine Waste Heat Recovery and Fuel Systems

- Engine exhaust temperature- engine, fuel
- sCO2 turbomachinery isentropic efficiencies
- WHR configuration and heat sinks
- Decrease in WHR maximum power demand

# Thank you for your attention!

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