High Efficiency High Temperature Modular Power

(HOTHARVEST)

Michael Ohadi
Program Director

Go Process Intensification

November 7, 2017

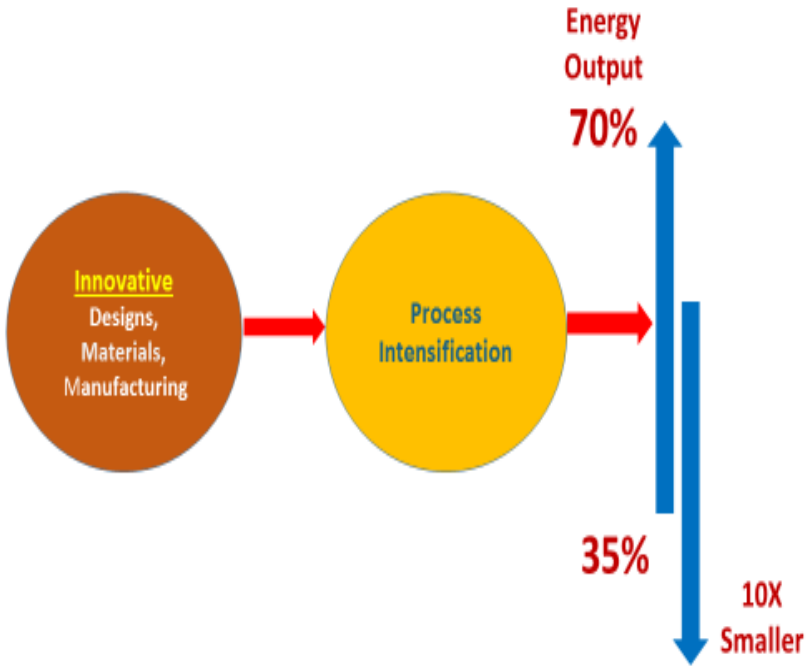
OUTLINE

- Vision
- Technical Introduction
- Program Goals
- Workshop Goals
- Summary

VISION

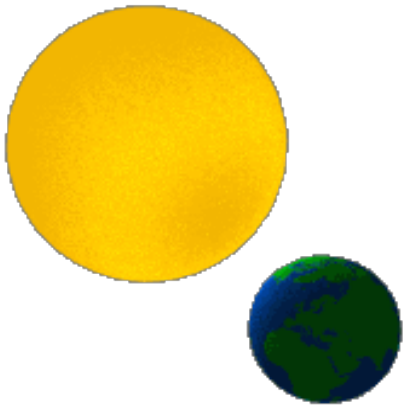
- Component and system development for High Temperature High Efficiency Modular Power (≤1MWe) Utilizing Innovative Designs, Materials, and Manufacturing techniques.

$$\eta_{Carnot} = 1 - \frac{\bar{T}_L}{\bar{T}_H}$$



At 2000 C and 80% of Carnot efficiency = 70%
At 1000 C and 80% Carnot = 61% efficiency

Process Intensification

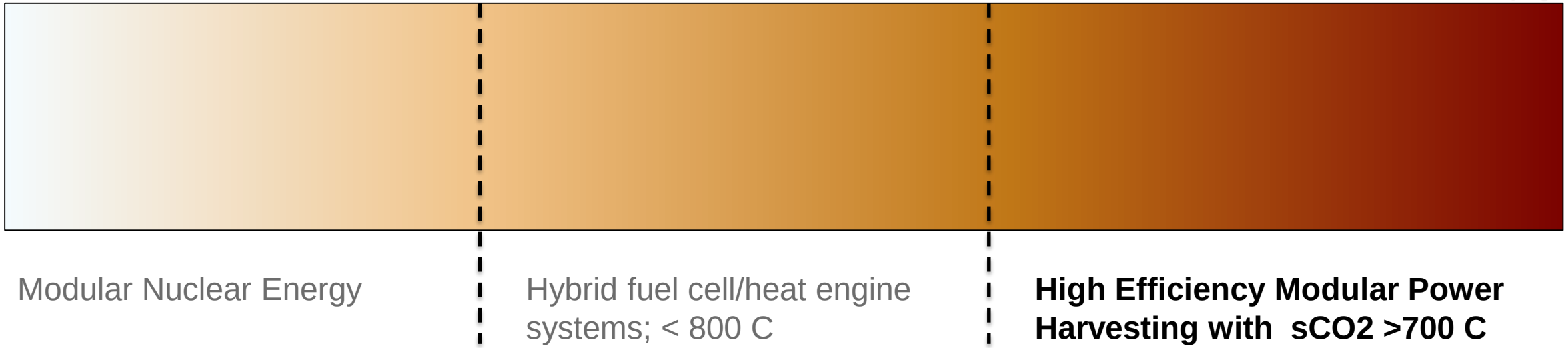


1,037 miles/hr spinning on its axis
66, 600 miles/hr orbiting the sun

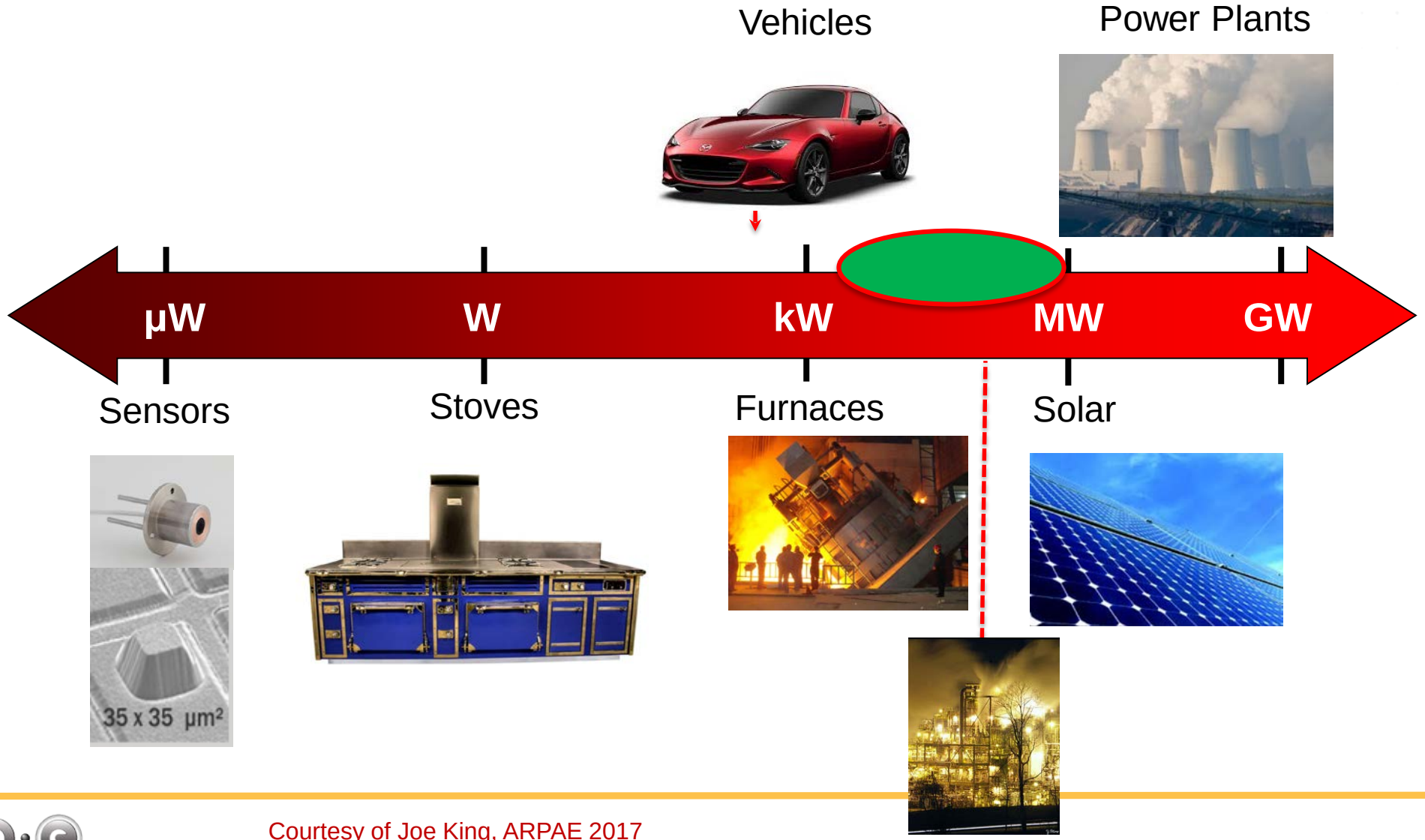
VISION

- ≤1MWe Modular Power
- 60% 1st law thermodynamic cycle efficiency
- Compact (~ 1MWe should fit inside a 40 ft container
- $2000/KWe installed at scale cost
- Choice of working fluid left open
- Cycle design/type open

Envisioned program is complementary with other potential ARPA-E high efficiency modular power programs



From Microwatts to Gigawatts



Courtesy of Joe King, ARPAE 2017

Potential first Users

- Potential heat sources across key Industries:

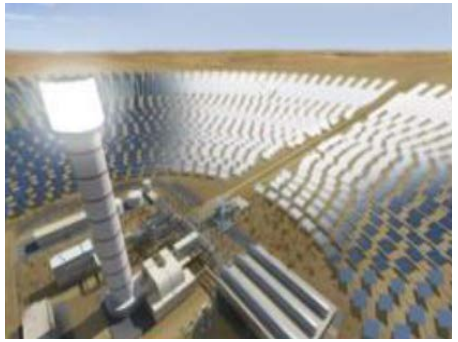
❖ **Biomass-to-electricity**

Oil and Gas

❖ **Marine**: Cruise Ships, LNG, Naval,…

❖ **pharmaceutical/Process**

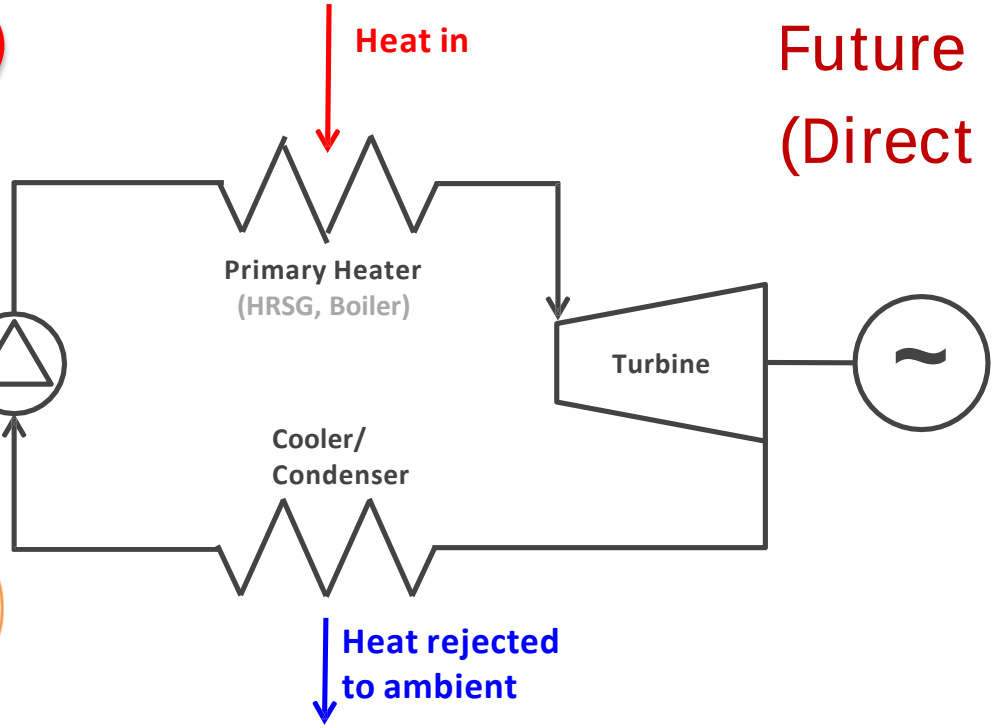
❖ **Power Generation**:

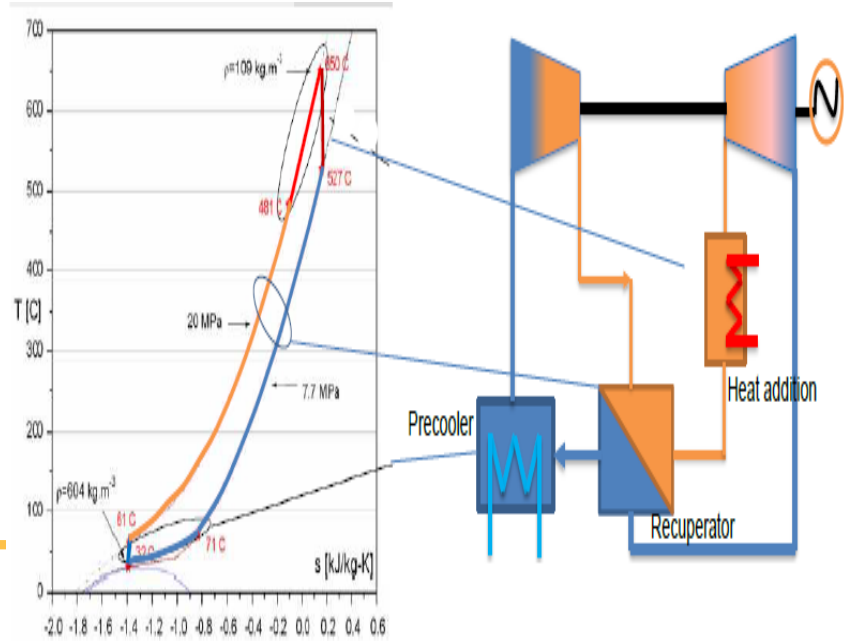


❖ **Industrial**: Transportation, Cement, Air Separation, Process industries

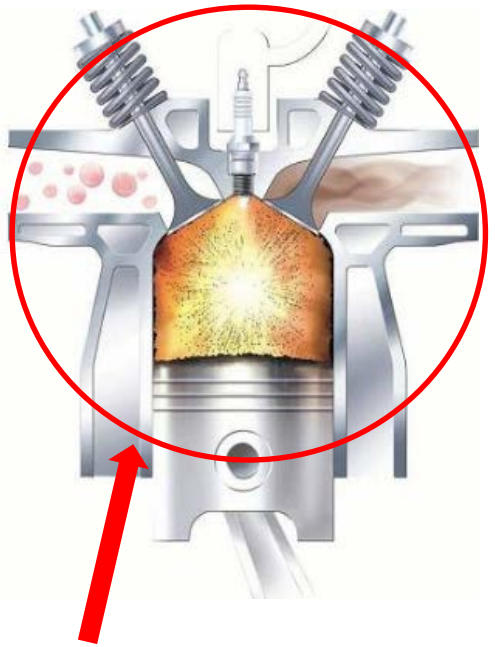
What are we talking about?

Current Approach





Future
(Direct Fire)

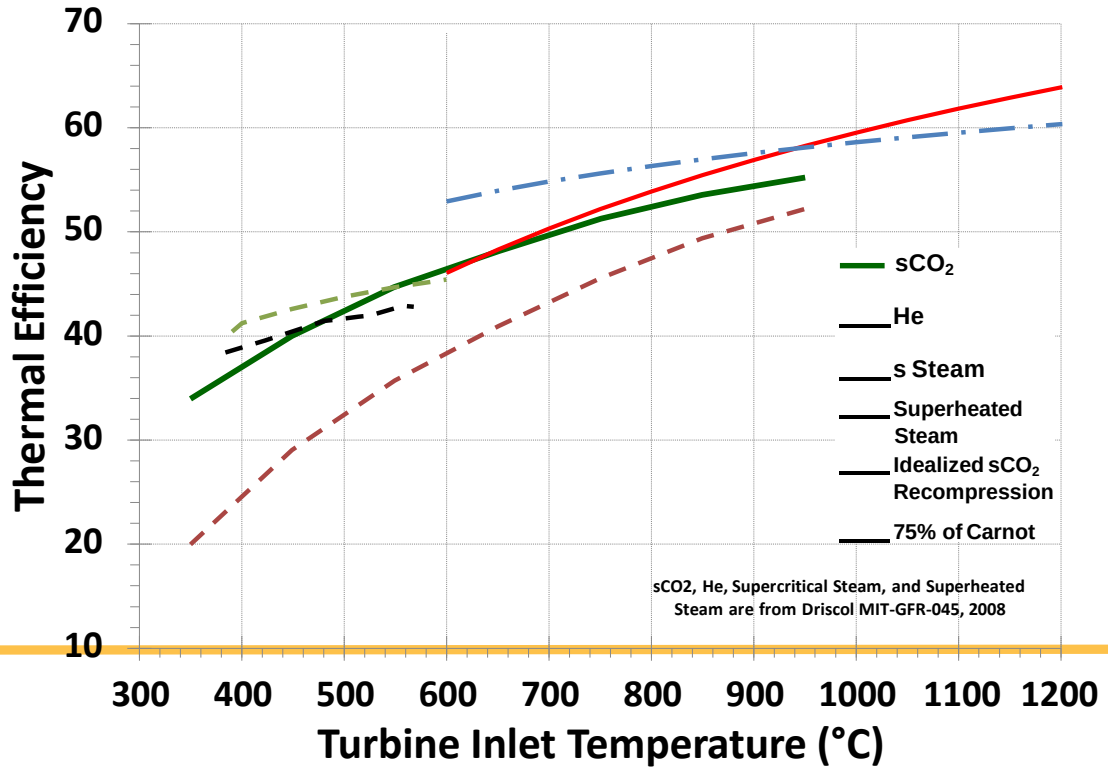


HOT ZONE

Parameters that can affect efficiency

- Choice of working fluid
- Turbine design
- Turbine inlet temperature and pressure
- Recuperator design
- Gas Cooler - air or water cooled

  - Heat/Fuel source
  - Indirect cycle:
    - Oxygen enriched air
  - Cycles designed to reduce compression work



Courtesy of Thar Energy

arpa·e
CHANGING WHAT'S POSSIBLE
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Increased Temperature

- Increased temperature at the turbine inlet = increased cycle efficiency

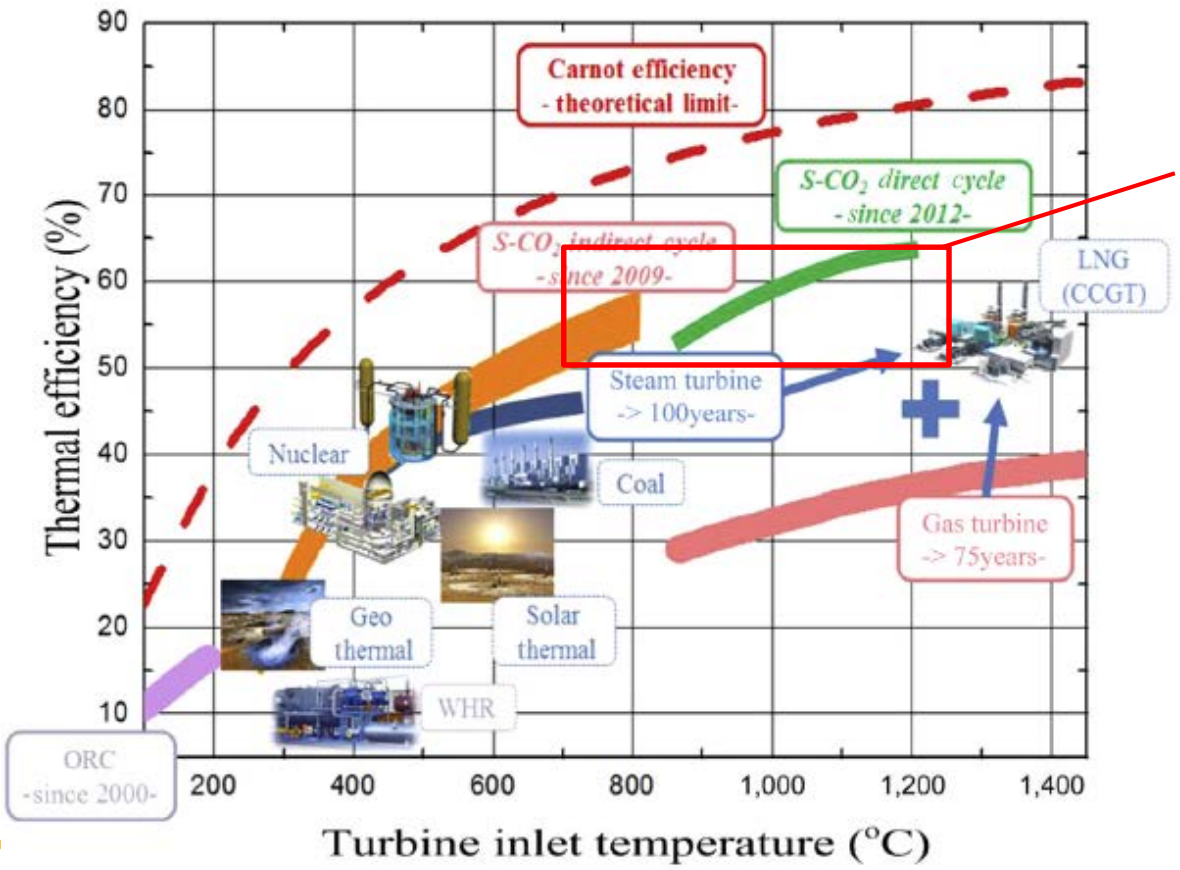


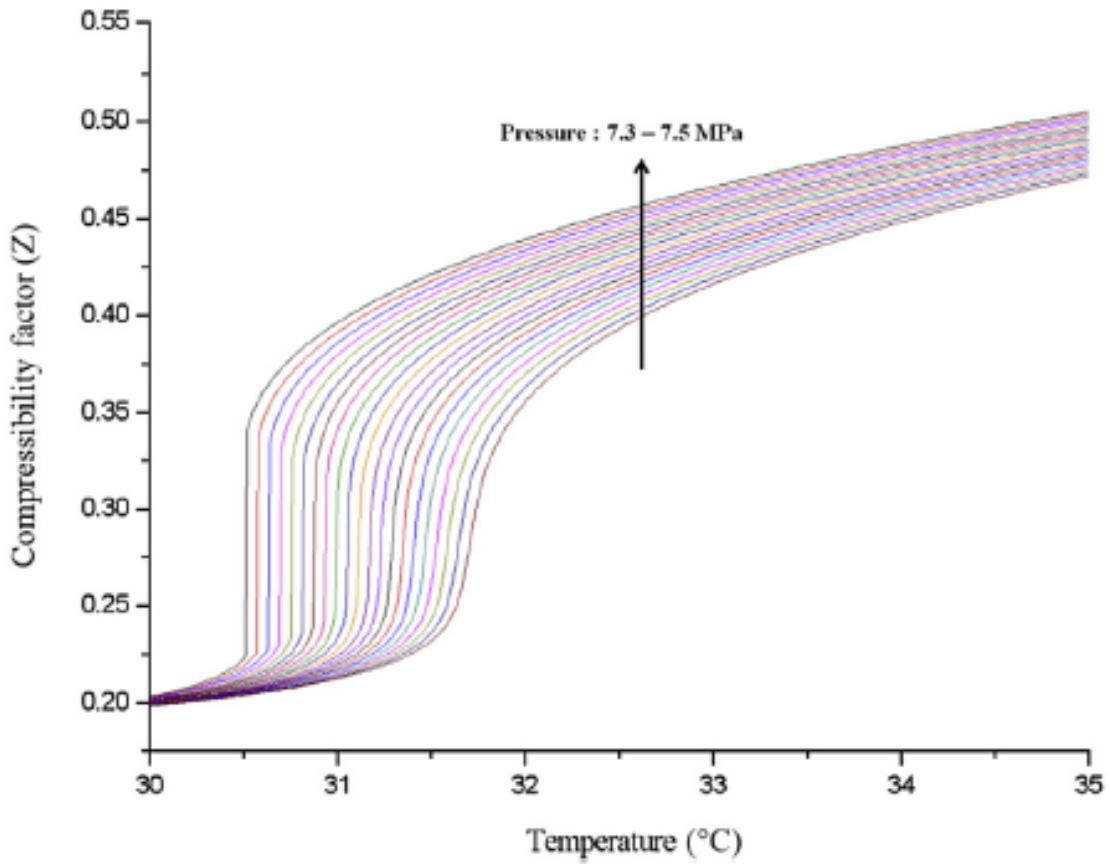
Fig 1: Thermal efficiencies of power conversion systems and applications. CCGT, combined cycle gas turbine [1]

S-CO_2

- ✓ High efficiency
- ✓ Simple layout
- ✓ Compact turbomachinery
- ✓ Different heat sources

CO_2 Properties

- Critical conditions: 30.98°C (87.76 F) and 7.38 MPa



$$Z = \frac{Pv}{RT}$$

- ✓ Compressibility factor smaller than 1
- ✓ reduced compression work in the compressor

Fig 2: CO2 compressibility factor near the critical point [1]

Why Higher Temperatures and Pressures?

- The higher the energy source temperature the higher the net work delivered and the **efficiency**.

- Higher operating pressures allow use of super critical cycles, thus much smaller components/system size

Coal-Air: 2150°C
NG-Air: 1950°C
Coal/NG-Oxygen: 3000°C

Courtesy of Addison Stark, ARPAE 2017

Example Impact

In a typical 1000 MW power plant with every one percent efficiency increase:

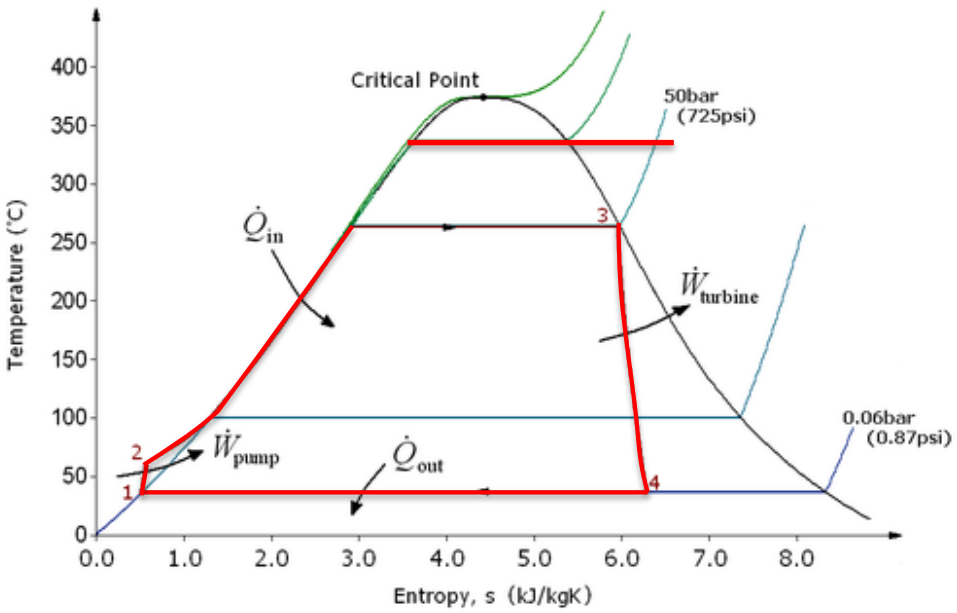
12.65 billion gallons/year water saved

100,000 tons/year CO2 emission reduction

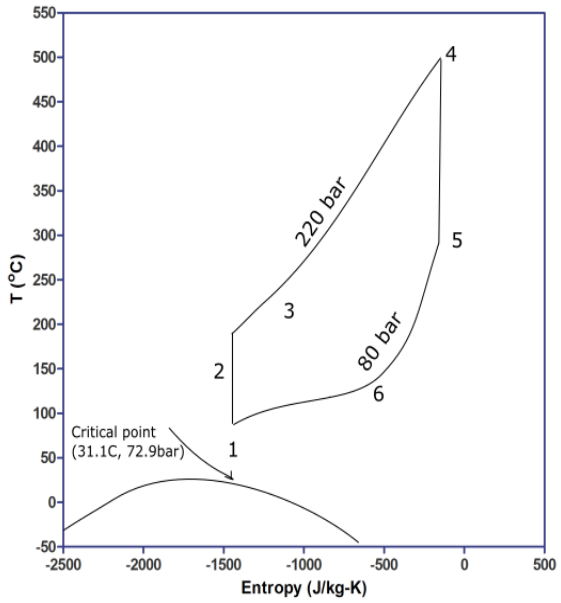
Why Higher Pressures?

- Higher operating pressures allow use of super critical cycles, thus higher efficiencies and smaller system size

sCO2 Power Cycle vs. Rankine

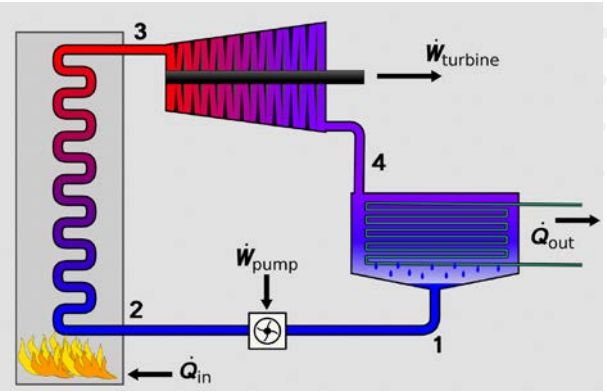


Ideal Steam Cycle

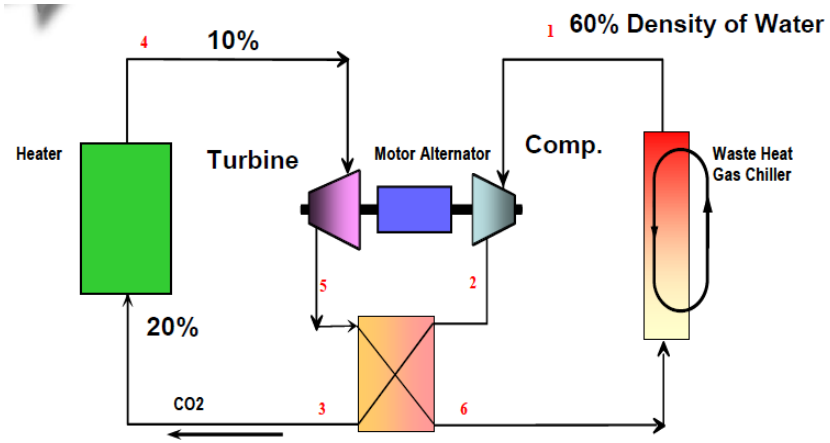


sCO_2

Steam Power Cycle



Supercritical CO2 Brayton cycle



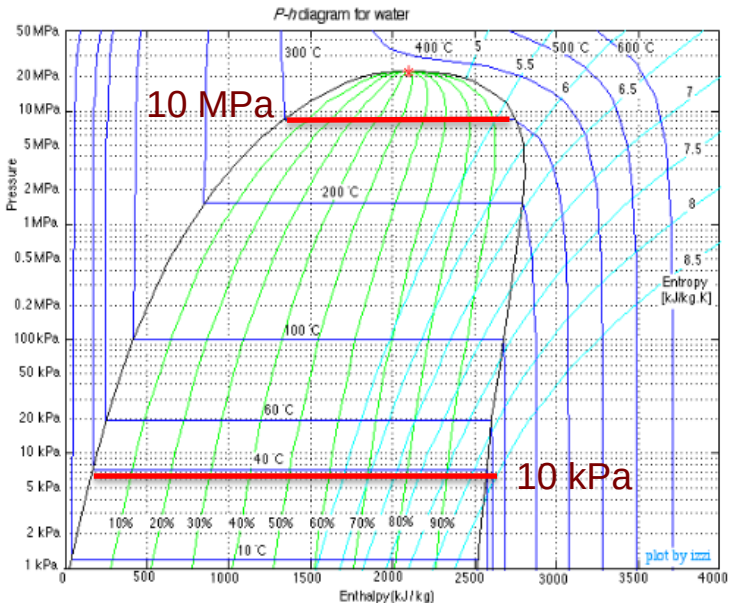
Liquid like Densities with CO_2

sCO2 operates in single phase—thus single-phase heat exchangers

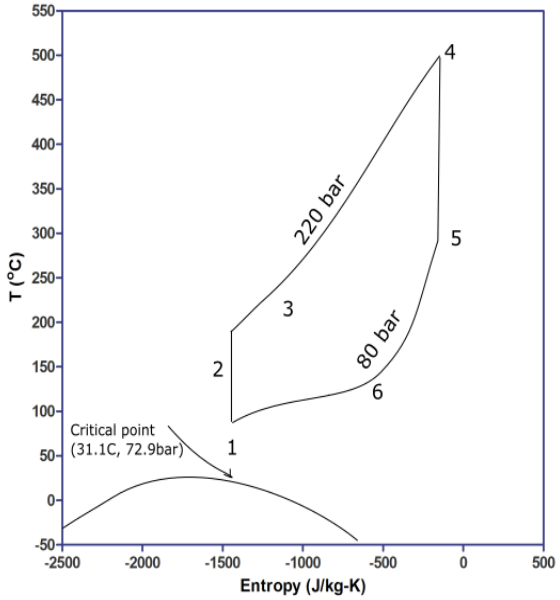
Compression ratio (CR) requirement of ~3 vs > 100 for Rankine cycle

Source: https://en.wikipedia.org/wiki/Rankine_cycle

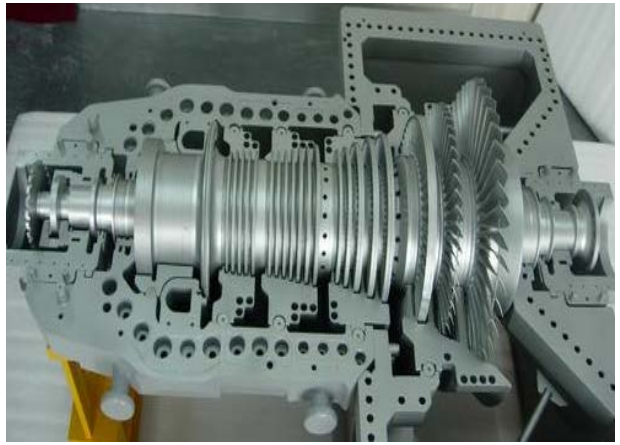
Higher Pressures



Water PR >100



sCO_2 PR ~ 3

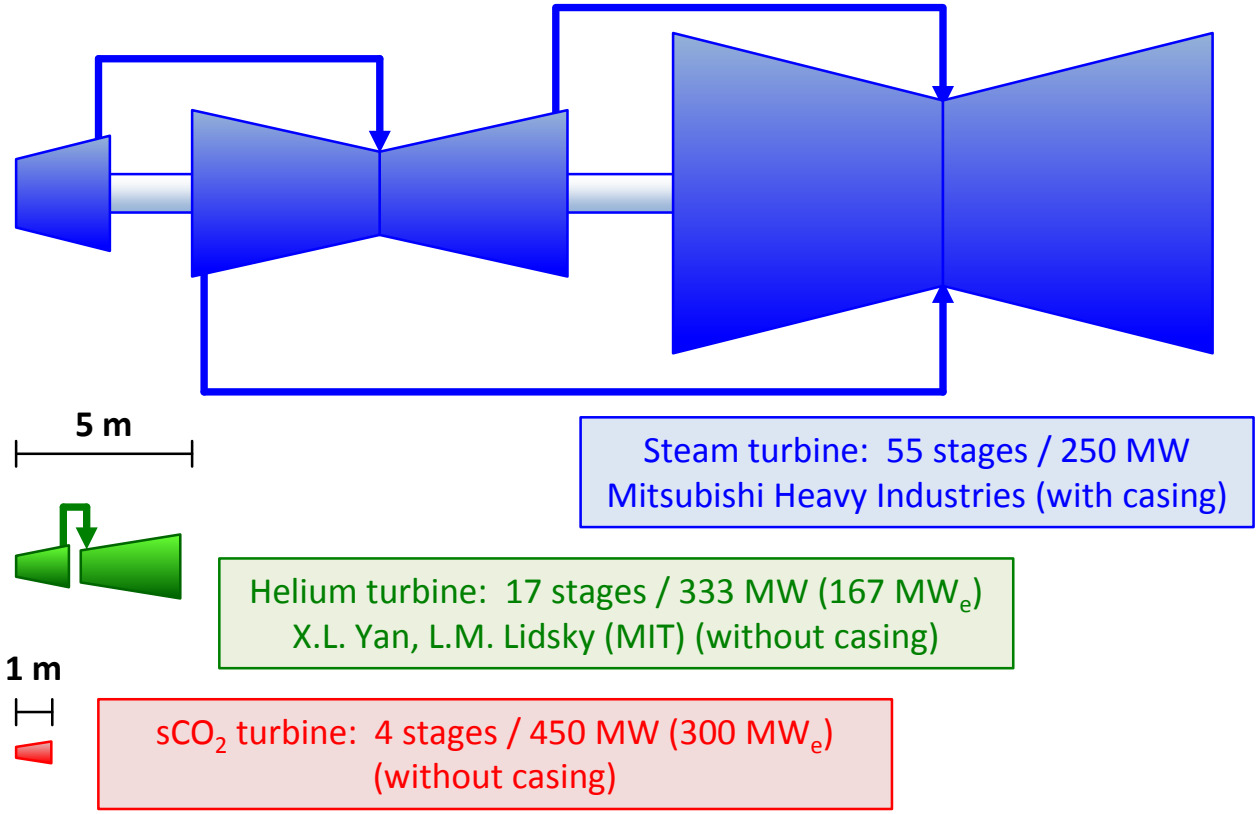


Steam turbine (50kW)

sCO2
(50kW)

Higher Pressures can enable use of super critical fluids and substantially reduce the size

Relative size of components

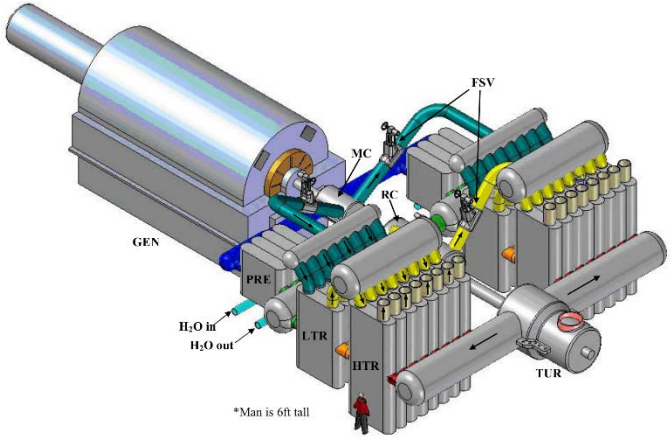


Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)

Helium turbine: 17 stages / 333 MW (167 MW_e)
X.L. Yan, L.M. Lidsky (MIT) (without casing)

sCO_2 turbine: 4 stages / 450 MW (300 MW_e)
(without casing)

Note: Compressors are comparable in size



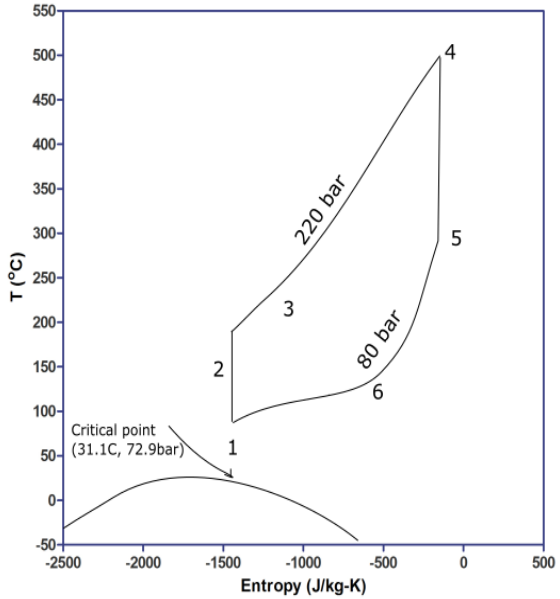
Third Generation 300 MWe S-CO2 Layout from Gibba, Hejzlar, and Driscoll, MIT-GFR-037, 2006

Source: Wright (2011), Adapted from Dostal (2004)

sCO2 vs. Rankine

- Compression ratio (CR) requirement of 3 vs 500 for Rankine cycle
- Rankine cycle requires multistage compressors due to high CR
- Freezing issues with Rankine cycle

- Advanced high temperature sCO2 cycles outperform steam by several points
- Thermally stable, low-hazard, low-cost working fluid
- Simple, direct, single pressure, single-phase heat exchangers
- Flexible cycle, can integrate with wide variety of heat sources without disrupting existing plant operations
- Organic Rankine cycle is feasible but does not go beyond 300°C temperature



Primary technical challenges/Opportunities

1. **Size-induced** challenges - sCO2 cycles in the 100's of kW scale have unique challenges
   - Turbine/expander diameter is on order of cm! Tolerancing on order of microns.
   - High performance, long lasting seals for the scale at hand
   - Very high shaft rotation speed required – bearing wear-out a major issue
   - Power Electronics for precise control of turbo machinery and the cycle

2. **Temperature and pressure-induced** challenges
   - Requires new designs for seals, bearings, etc.
   - Temperature gradients are extreme
   - High temperature materials are difficult and/or costly to fabricate
   - Combination of high temp. and high pressure requires innovative designs for HXs
   - HXs are too large (poor BOP) and costly

What are the program goals?

- **Three sub categories**

Technology Area 1: Cycle Design and Analysis

Technology Area 2: Turbomachinery and Supporting Components/Accessories

Technology Area 3:Component Development—HXs and Balance of Plant

Technology Area 1: Cycle Design and Analysis Possible Metrics

- 60% efficiency
- $2,000/kW$_e$
- [Compactness metric?]
- [Sliding scale of cost if team aims for compactness?]

Work in Progress

Technology Area 2: Turbomachinery and Supporting Components/Accessories Possible Metrics

- Pressures of ~1200 psi on the low side and 4500 psi on the high side
- Leakage <#%?
- Metrics for supporting components?
  - Bearings, Seals: lifetime?
  - Compressor, Expander: efficiency?

Work in Progress

Technology Area 3:Component Development—HXs and Balance of Plant Possible Metrics

Work in Progress

- Cost: $500 – 600/kWe (25 – 30% of system cost)?
- Effectiveness:
- Compactness: (UA, Q/m3, Q/kg, Q/$)?
- Pressure drop:

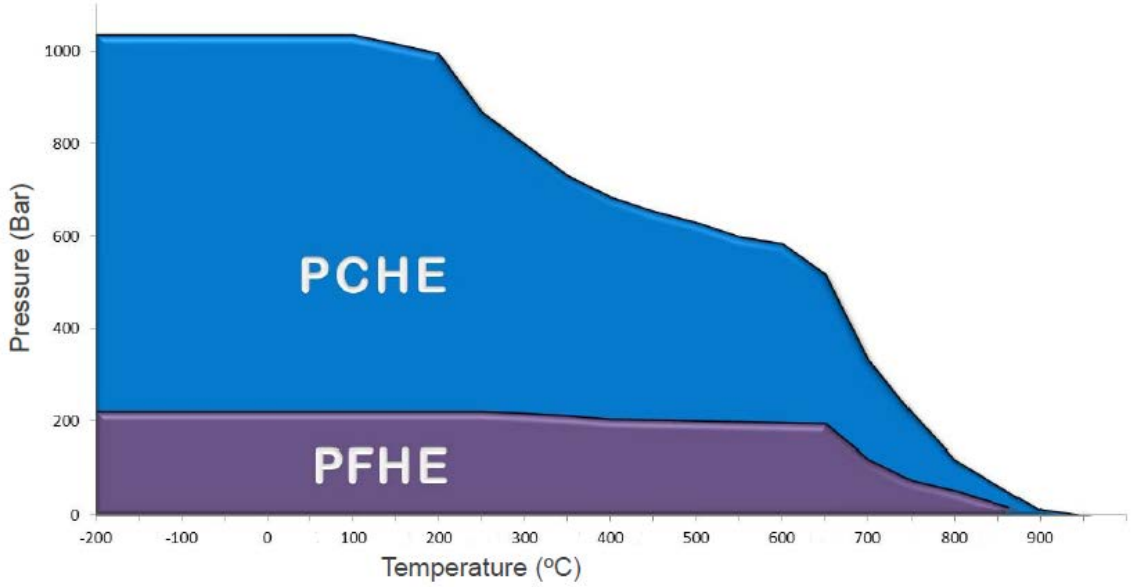
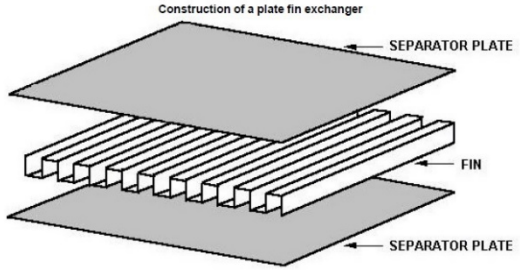
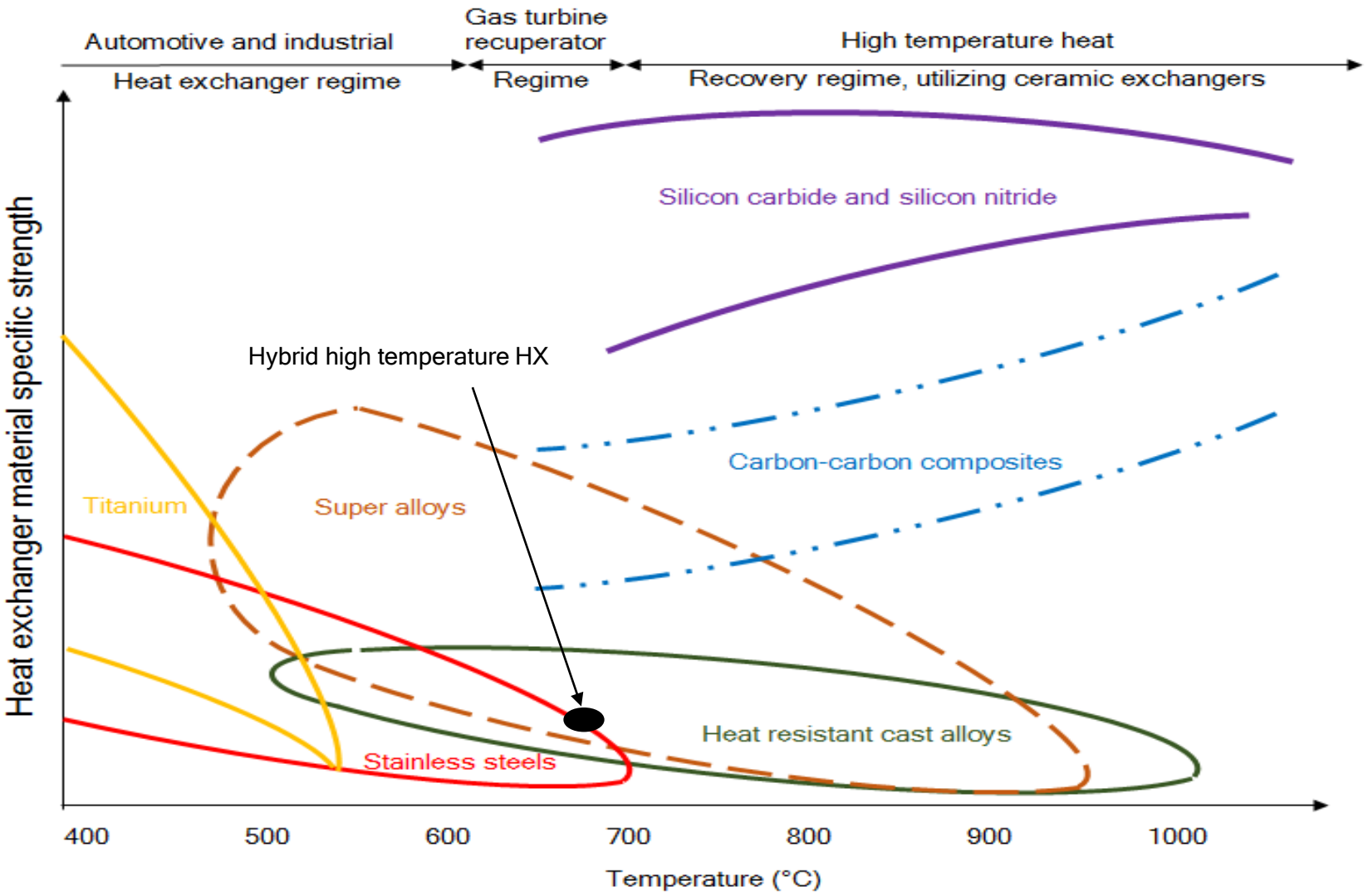


Fig XX: Design capabilities and maximum rated exchange in operation [2]



Material vs. Temperature Chart



Approximate temperature range for various heat exchanger materials (adapted from Heat Exchanger Design Handbook, Second Edition[6])

Phase 1: Parameters to optimize

- SLM printing parameters
  - Laser power
  - Scanning speed
  - Hatch angle (angle between laser scanning directions of consecutive layers)
  - Hatch distance (distance between consecutive scan lines)
  - Layer thickness
  - Building directions and orientation (angles between the axis and the component printed)
  - Overlap rate (percentage of area affected by repeated melting with energy beam)

- Powder parameters
  - Size of the powder
  - Percentage of ODS-Y_2O_3 in the composition

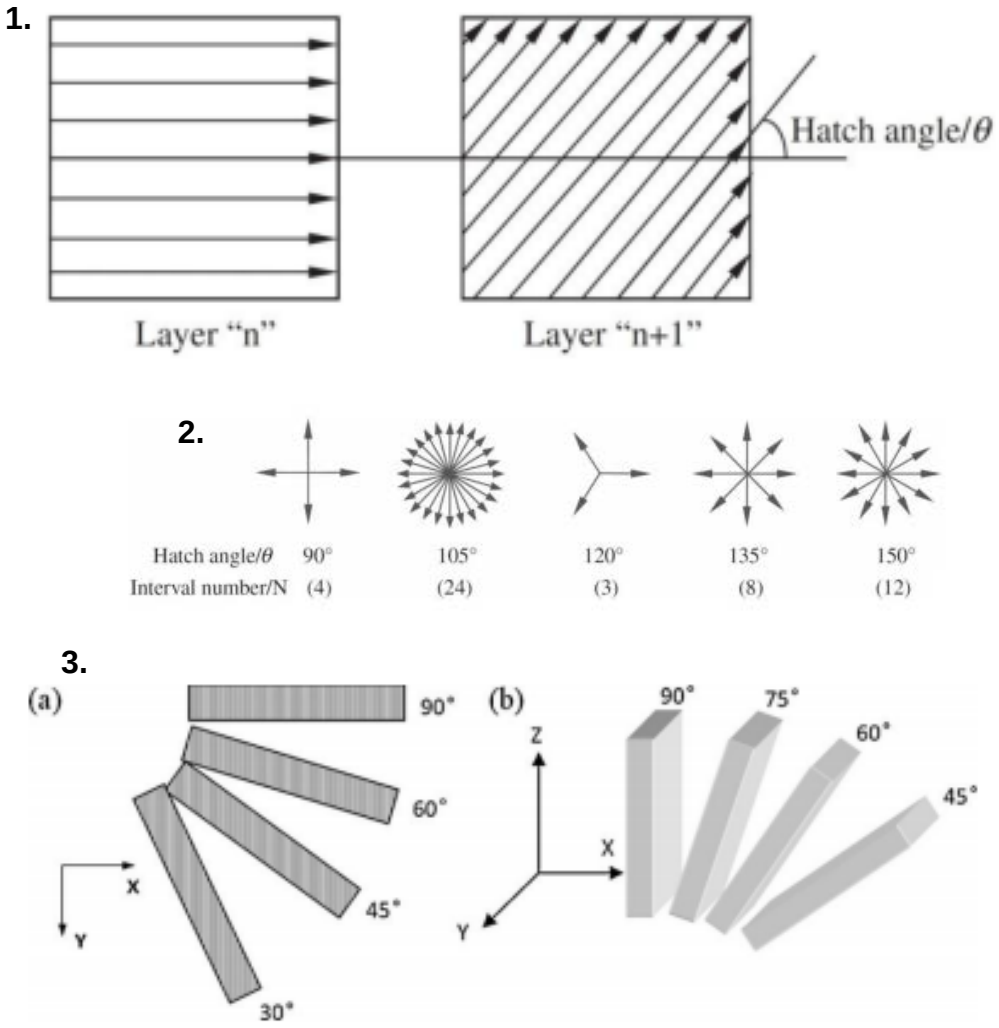


Fig 9: 1) Rotations in lines in neighboring planes. 2) diagram of intervals under different hatch angles 3. Manufacturing strategy of tensile samples (a) horizontal, (b) vertical [9]

Acknowledgements

ARAPE Management and the support staff

Dr. Geoff Short

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Dr. Pat McGrath

Dr. Addison Stark

Dr. Chris Atkinson

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Day I: Thursday, 10/19: Oaks Ballroom

Time	Event
10:00 - 11:30 AM	Individual meetings with Dr. Mike Ohadi & his technical team (The Pines Room)
11:00 AM – 12:00 PM	Registration Opens
11:30 AM – 12:30 PM	Lunch Served
12:00 PM – 12:15 PM	**Welcome and Introduction to ARPA-E** *Dr. Eric Rohlfing, Acting Director, ARPA-E*
12:15 - 12:45 PM	**High Efficiency High Temperature Modular Power Utilizing Innovative Designs, Materials, and Manufacturing Techniques** *Dr. Mike Ohadi, Program Director ARPA-E*
12:45 - 1:15 PM	**Workshop participant introductions** *All participants to give short (30 sec max) introductions, one-by-one*
1:20 – 1:45 PM	**Dept. of Energy Fossil Energy's Supercritical Carbon Dioxide Power Cycle Technology Program for Large Stationary Power** *Guest Speaker 1: Richard Dennis, National Energy Technology Laboratory*
1:45 – 2:10 PM	**Opportunities and Challenges for sub Megawatt Modular Supercritical Cycles** *Guest Speaker 2: Marc Portnoff, Thar Energy, LLC.*
2:10 – 2:35 PM	**Advanced Materials and Manufacturing Methods for High Temperature Thermal Management Applications** *Guest Speaker 3: Dr. Ali Yousefani, Boeing Aerospace*
2:35 – 2:40 PM	**Breakout 1 Overview** *Dr. Mike Ohadi, ARPA-E*
2:40 – 3:00 PM	**Break/Networking**
3:00– 4:30 PM	**Breakout Session 1: Performance Metrics and Technical Opportunities**
4:30 PM – 6:30 PM	Individual meetings with Dr. Mike Ohadi & his technical team (The Pines Room)

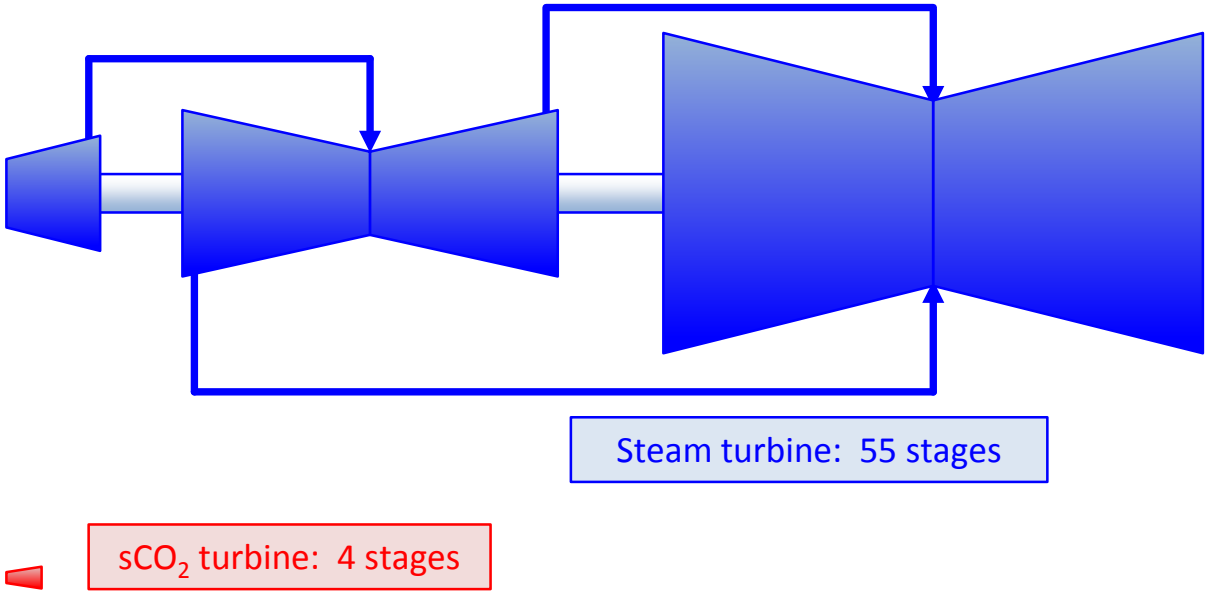
Day 2 Agenda

Time	Event
7:30 – 8:30 AM	Breakfast
8:30 - 8:45 AM	**Day 1 Summary/Readout, Group Feedback, and Day 2 Objectives** *Dr. Mike Ohadi, ARPA-E*
8:45 – 9:10 AM	**High-Temperature Heat Exchangers for Aerospace Applications** *Guest Speaker 4: Dr. Hal Strumpf, Honeywell Aerospace*
9:10 – 9:35 AM	**Experience with <1MW Supercritical Power Generation Technology Development (Including Turbomachinery, Seals, Bearings)** *Guest Speaker 5: Darryn Fleming, Sandia*
9:35 – 10:00 AM	**Progress in 3D Printing of Metals, Including Superalloys** *Guest Speaker 6:* Frederick Claus, Stratasys
10:00 – 10:15 AM	**Waste Heat Recovery in Military Applications** *Guest Speaker 7: Dr. Mark Spector, Office of Naval Research*
10:15 – 10:20 AM	**Breakout 2 Overview** *Dr. Mike Ohadi, ARPA-E*
10:20 – 10:40 AM	Break/Networking
10:40 – 12:00 PM	**Breakout Session 2: Metrics Refinements and Risk Assessment/Mitigation**
12:00 PM	Wrap-up
12:00 – 1:30 PM	Individual meetings with Dr. Mike Ohadi & his technical team (The Pines Room)

Thank You!

Size-induced challenges: smaller scale turbomachinery will introduce new technical challenges and risk

Relative size of steam turbine and sCO2 turbine of equal power rating



Source: Wright (2011), Adapted from Dostal (2004)

Unique challenges with small turbomachinery:

- Turbine blades are very small – wall effects dominate
- Seals
- Fabrication of designs involving small feature sizes with materials that have been difficult to work with

Takeaway: This scale will likely require very different designs than traditional, 10+MW scale sCO2 systems