BRAYTON POWER SYSTEMS FOR FLUORIDE SALT HIGH TEMPERATURE REACTORS

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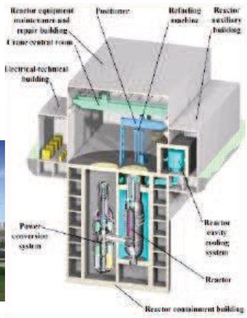
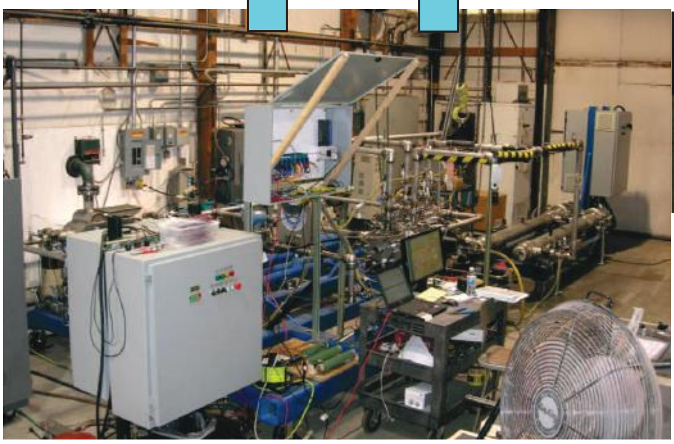


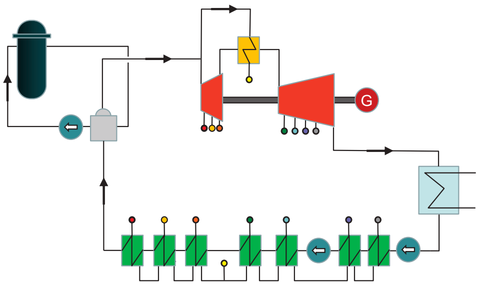


Advanced Power Conversion Systems

- Contrast Differences Between
- Steam Rankine
  - (Superheated, Supercritical, Saturated Vapor)
- Gas Brayton
  - Helium Brayton
  - S-CO2
- S-CO2 Development Status

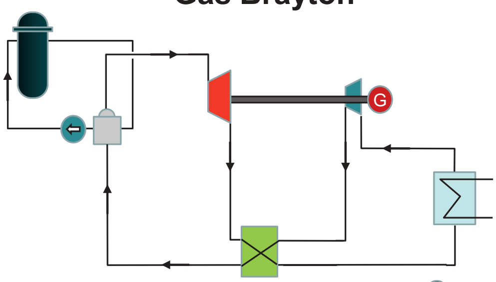
Power Conversion Systems For Advanced Reactors

Steam Rankine

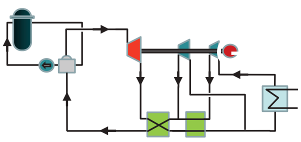


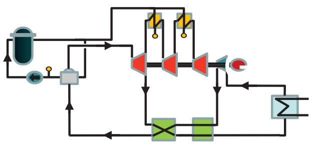
Saturated Vapor	η = 34% at 285C 160 bar P_r= ~1600/1	High Pressure Ratio Means Large Turbines Many Stages Low Density Steam Large Condenser
Superheat	η = 41-43% at 510-525C 200 bar, P_r = 2000 /1	
Supercritical	η = 37.5% at 380C 250 bar P_r= ~1200	
	η = 45% at 500C 250 bar P_r= ~3000/1	

Gas Brayton



	Standard Brayton	Brayton with Reheat
He	η = 43% at 900 C 70 bar P_r =3/1	η = 42% at 650 C 70 bar ***Pr=30/1 IHC***
Supercritical CO_2	η = 42% at 510-525 C 200 bar P_r = 2.6	η = 55% at 650 C 250 bar ***P_r = 4.1*** “Cond & Reheat” CIT=295 K
	η = 48% at 650 C 200 bar P_r = 2.6	





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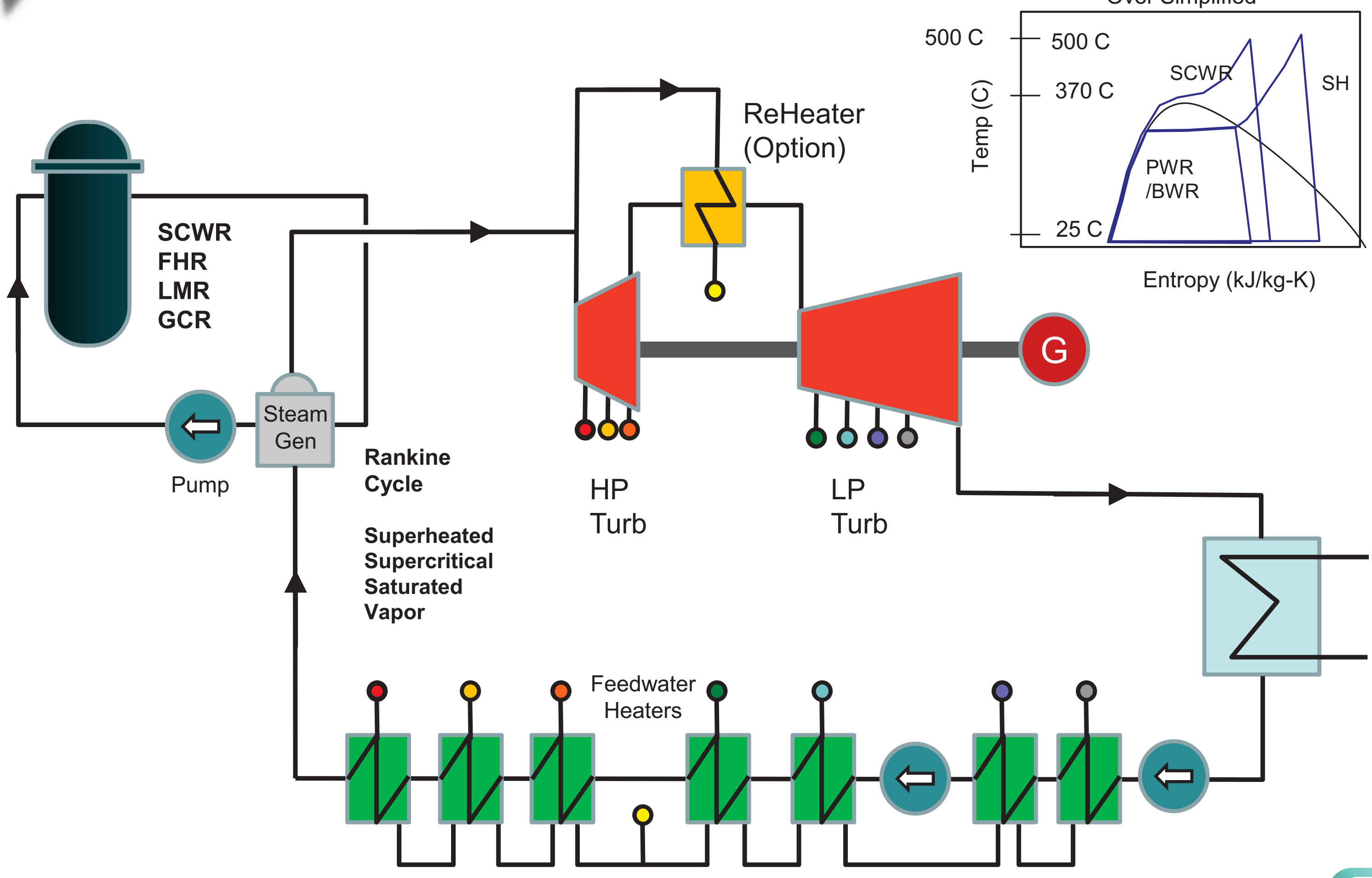
Steam Power Systems

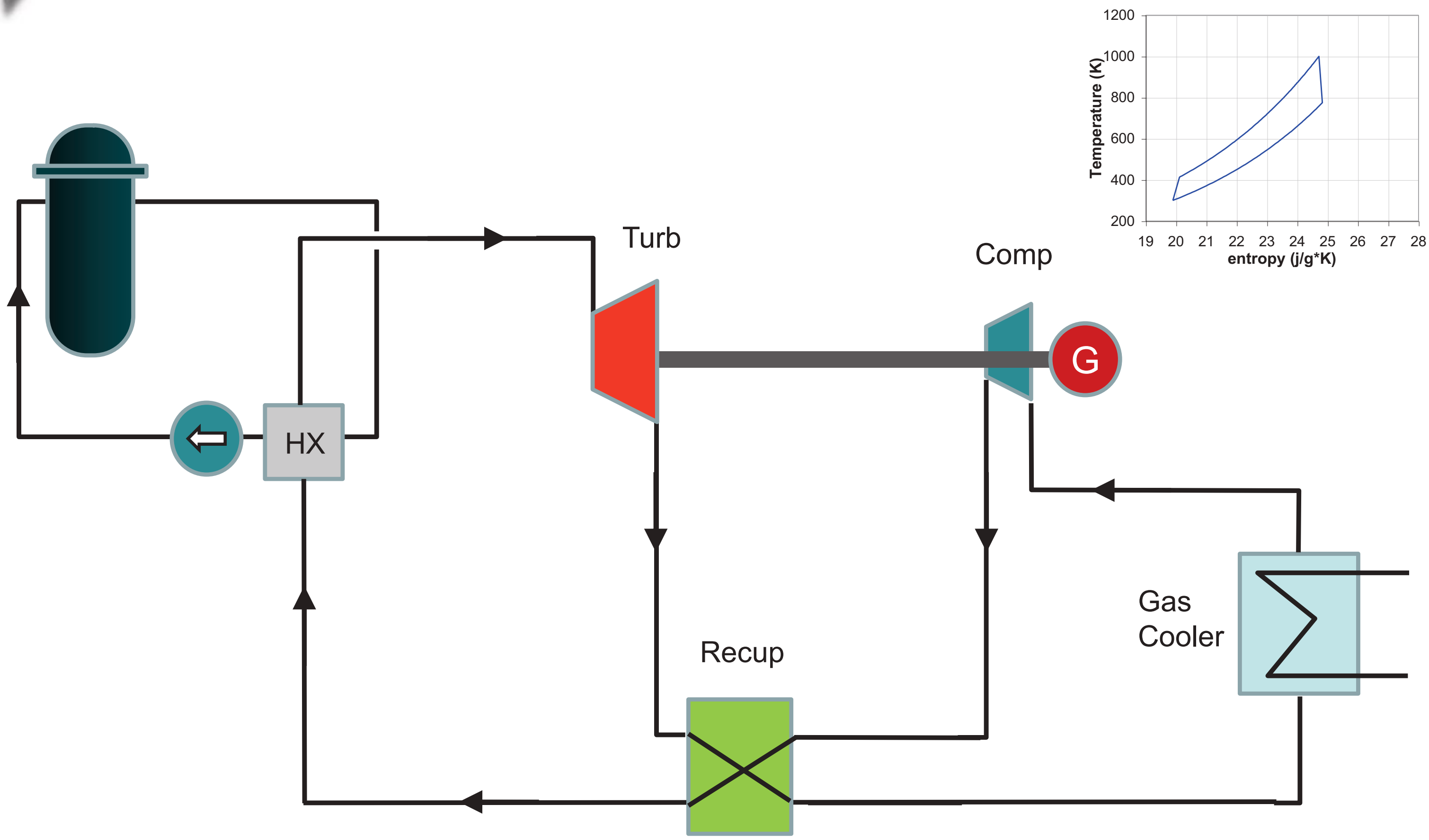
(Saturated, Superheated, & Supercritical)



Large, Two-Phases, Well known, Work Well, and Commercially Available

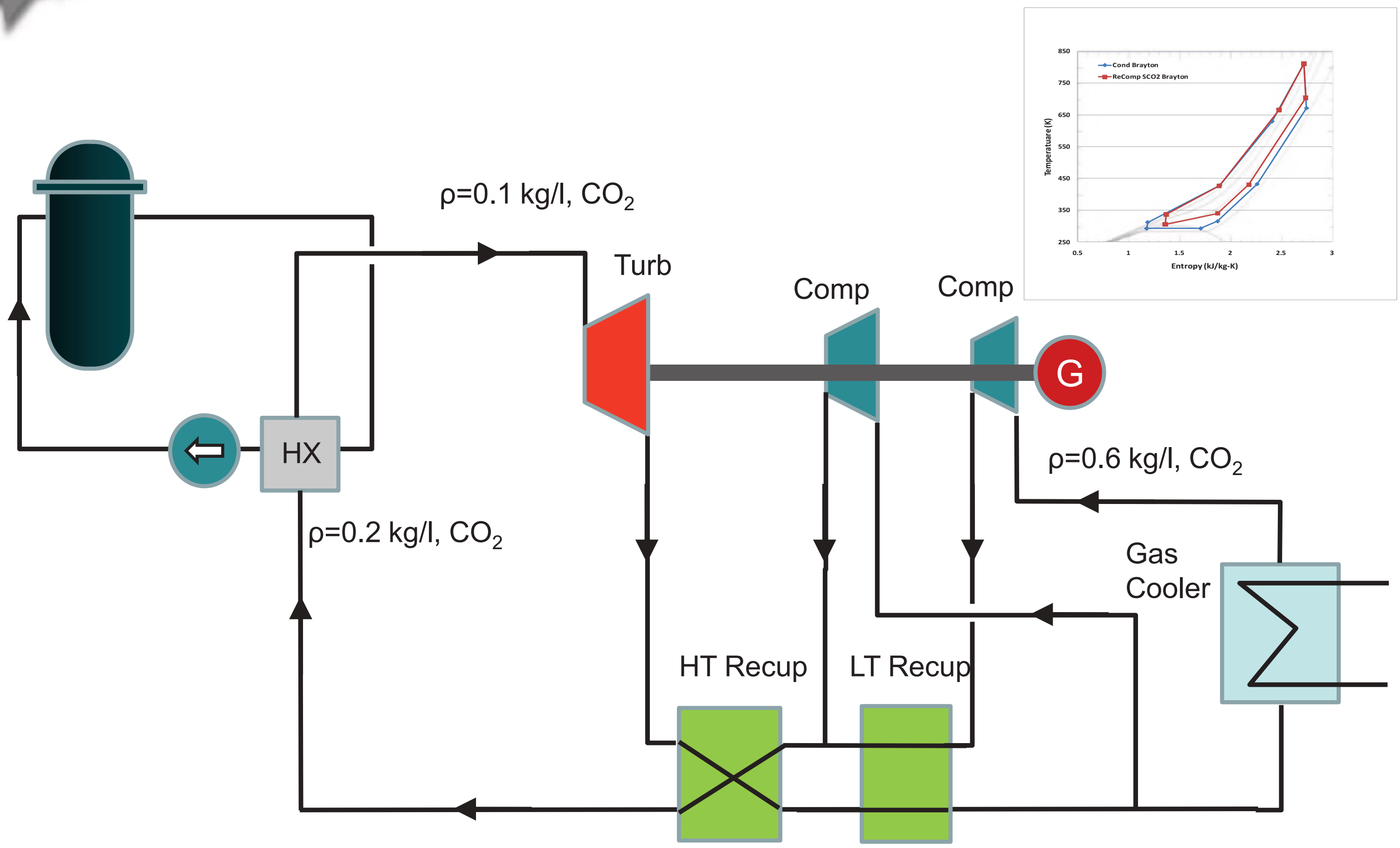
Simple Brayton Cycle

Helium, Air, other Gases



Simple, Small, Single Phase, Known Technology for Air, Immature Industry

Supercritical CO_2 Brayton Cycle

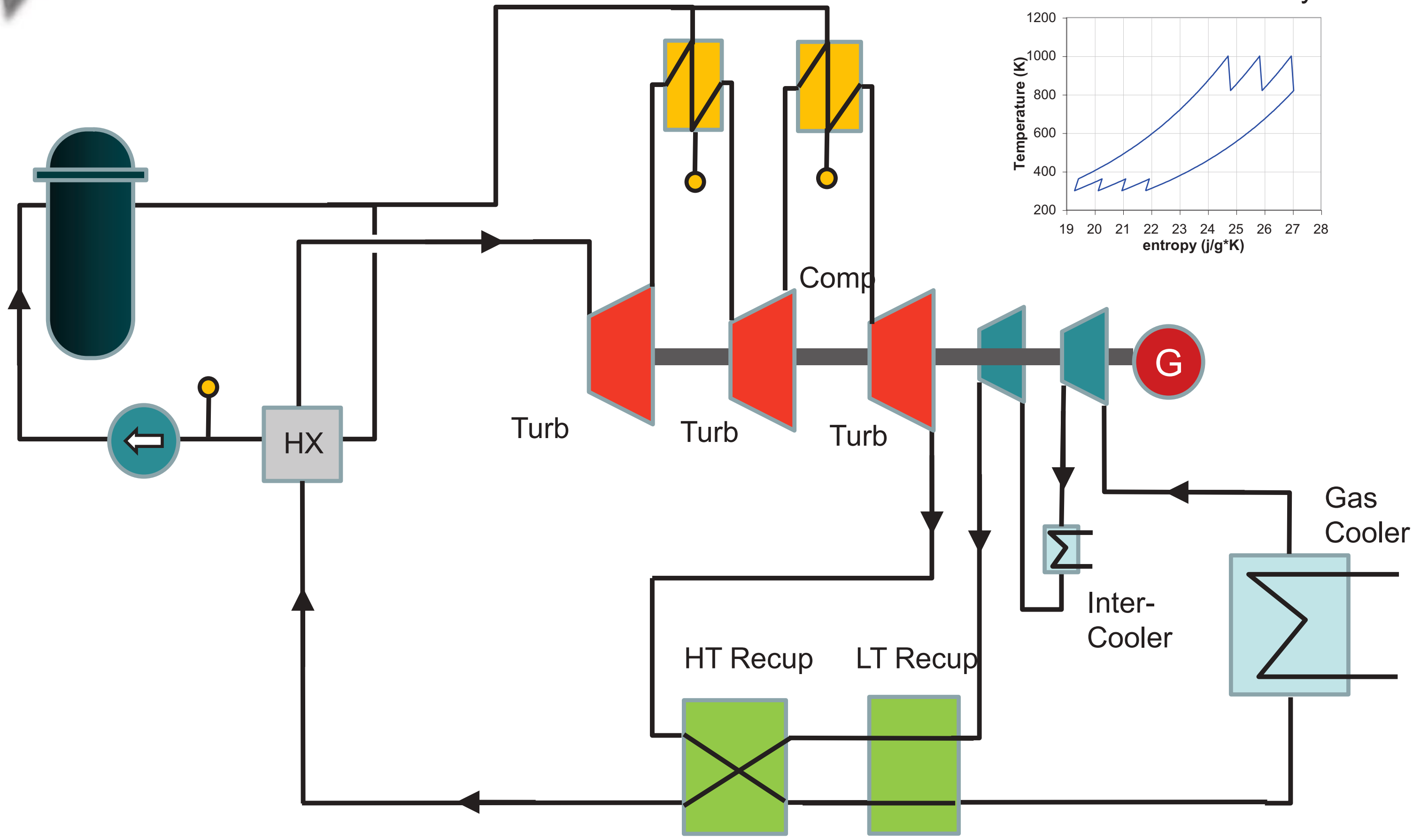


Simple, Very Small, Likely More Efficient, Single Phase, Industrial Development Needed

All Brayton Cycles

can use Reheat and Interstage Cooling

High Pressure Ratio
To Gain Efficiency



Advanced S-CO2 Systems, Very Small, Highly Efficient, Single or Two-Phase,
Future Growth Path Industrial Development Needed

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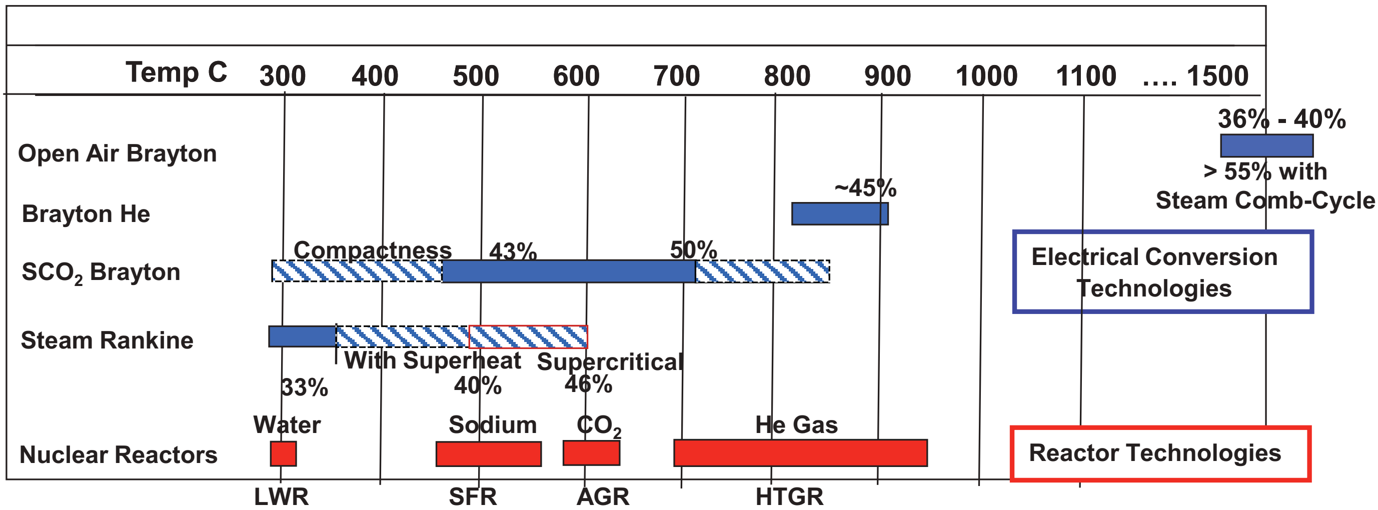
Power Conversion and Nuclear Reactor Outlet Temperature Ranges

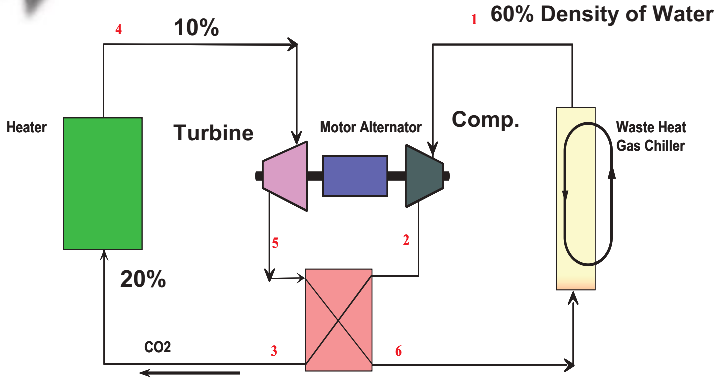


S-CO_2 Power Conversion Operating Temperatures Matches all Advanced Reactor Concepts
LWR – compactness, condensing cycle appear promising
LWR- highly efficient with S-CO2 Condensing Power Cycles

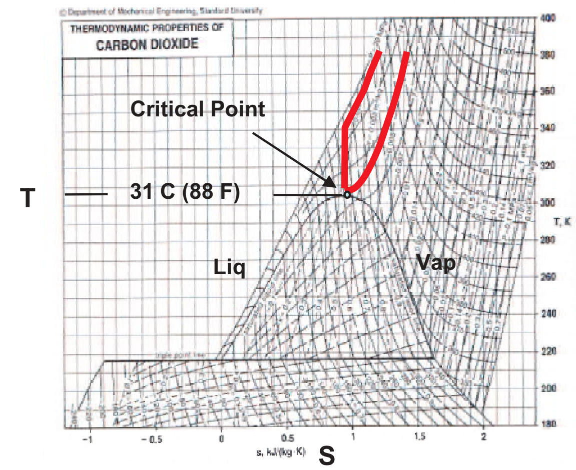
Supercritical CO2 Brayton Cycles

- What is a Supercritical CO_2 Brayton Cycle?
- Why is it Important and How is it Used?
- DOE Gen-IV S-CO_2 Program
- Major Accomplishments
- ~~Power Generation Example~~
- Summary & Conclusions
- ~~Problems and Failures~~
- ~~Unusual Behavior~~
- ~~Advanced Cycles~~

What is a Supercritical CO_2 Brayton Cycle? How does it work?

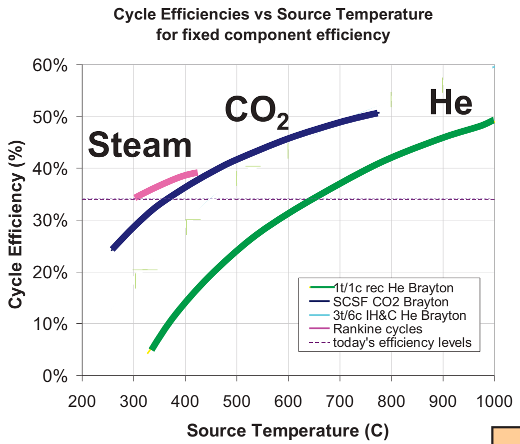


Liquid like Densities with CO_2
Very Small Systems,
High Efficiency due to Low Pumping Power

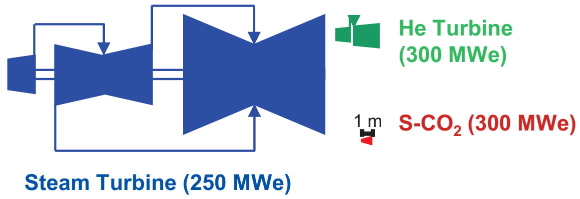


Rejects Heat
Above Critical Point
High Efficiency *Non-Ideal Gas*
Sufficiently High for Dry Cooling

Critical Point
88 F / 31 C
1070 psia / 7.3 MPa



High Efficiency at Lower Temp
(Due to Non-Ideal Gas Props)

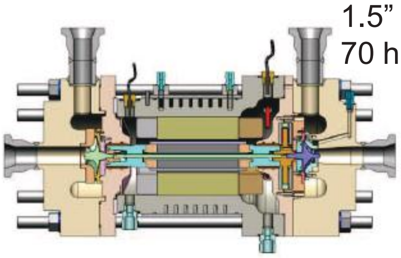


High Density Means Very Small Power Conversion System
Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

Key Features to a Supercritical Brayton Cycle

- **Peak Turbine Inlet Temp is well matched to a Variety of Heat Sources (Nuclear, Solar, Gas, Coal, Syn-Gas, Geo)**
- **Efficient ~43% - 50% for 10 - 300 MW_e Systems**
  - **1000 F (810 K) ~ 538 C Efficiency = 43 %**
  - **1292 F (1565 K) ~ 700 C Efficiency =50%**
- **Standard Materials (Stainless Steels and Inconels)**
- **High Power Density for Conversion System**
  - **~30 X smaller than Steam or 6 X for Helium or Air**
  - **Transportability (Unique or Enabling Capability)**
  - **HX's Use Advanced Printed Circuit Board Heat Exchanger (PCHE) Technology**
- **Modular Capability at ~10-20 MWe**
  - **Factory Manufacturable (10 MW ~ 2.5m x 8m)**

Fabricated and Testing
1.5" Compressor
70 hp



Steam Turbine

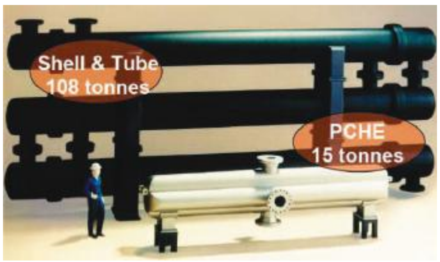
Turbine Building

12'

S-CO_2

Efficiency at Lower Operating Temps
Standard Materials, Small Size
Modular & Transportable
AFFORDABLE and FABRICABLE

Modular & Self Contained
Power Conversion Systems
~ 1.5 m x 8 m



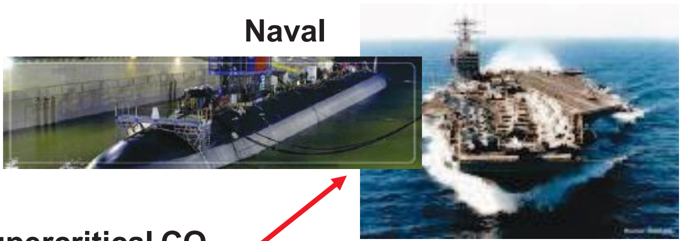
Advanced
Heat Exchangers
Meggit / Heatric Co.

Supercritical CO_2 Cycle Applicable to Most Thermal Sources

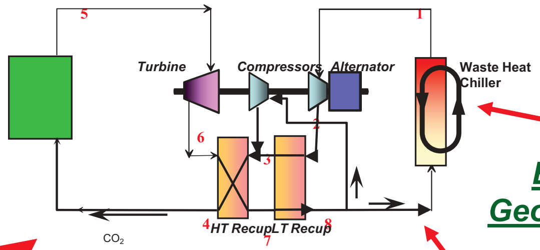
Solar

SNL Solar Tower

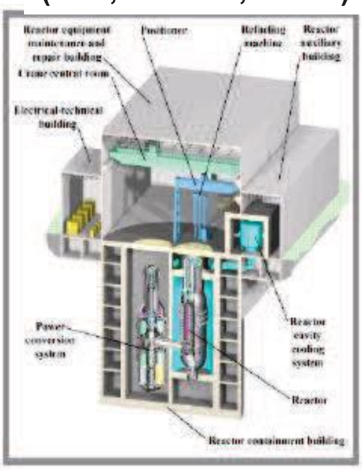
Naval



Supercritical CO_2 Brayton Cycle



Nuclear (Gas, Sodium, Water)



DOE-NE Gen IV

EERE Geothermal

INERI NRCan CANMET & SASK Power

Fossil

Sequestration Ready

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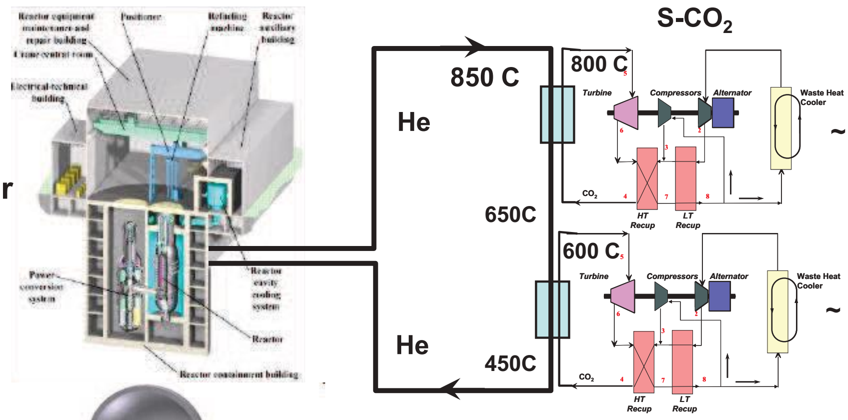
S-CO_2 Power Cycles for Reactors

NGNP
High Temperature
Gas Cooled Reactor
850-900 C



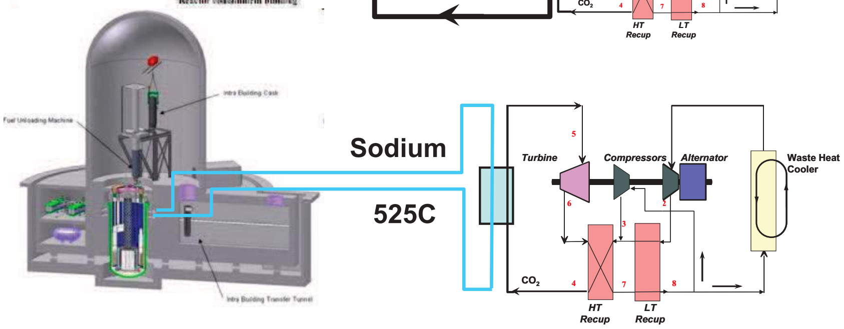
GCRs

~ 54 %

~ 50 % Efficiency (S-CO_2 Brayton)

~ 46 %

Sodium Cooled Reactor 500-550 C

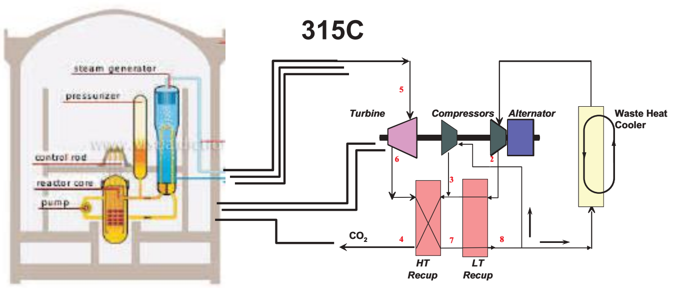


SFRs

~ 44 % Efficiency (S-CO_2 Brayton)

LWRs
Pressurized Water Reactor
330 C

Potential SMR Applications



LWRs

~ 40 % Efficiency (S-CO_2 Recup Rankine Condensing Brayton)

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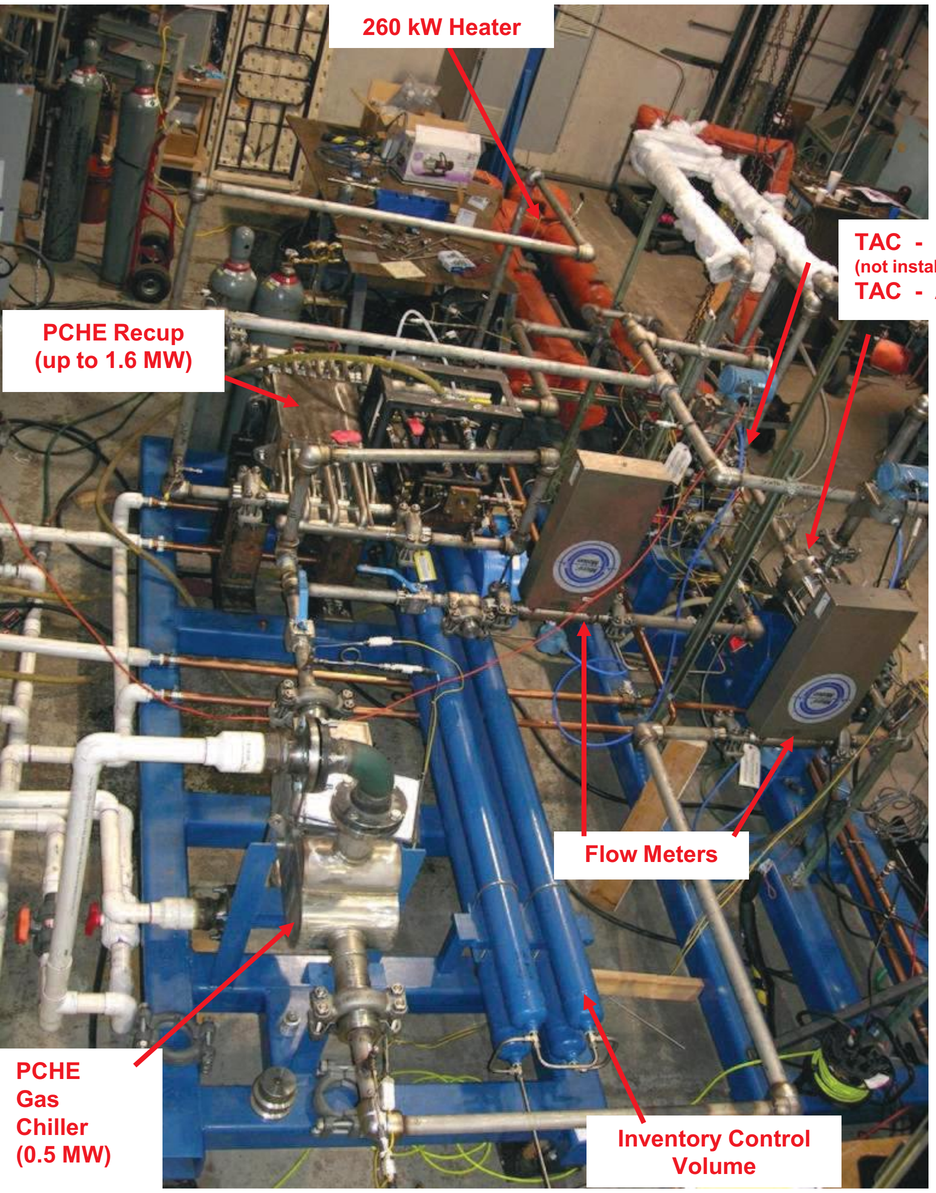
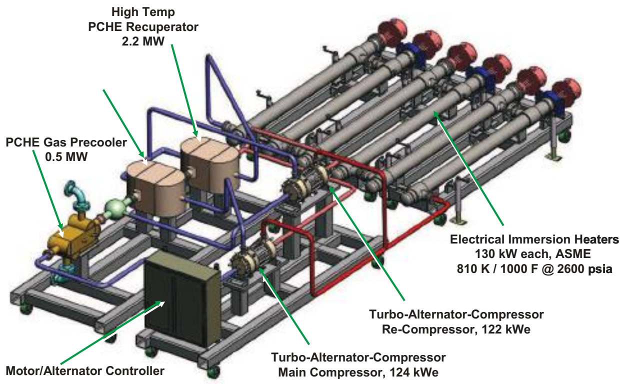
Supercritical S-CO_2 Brayton Cycle

DOE-Gen IV





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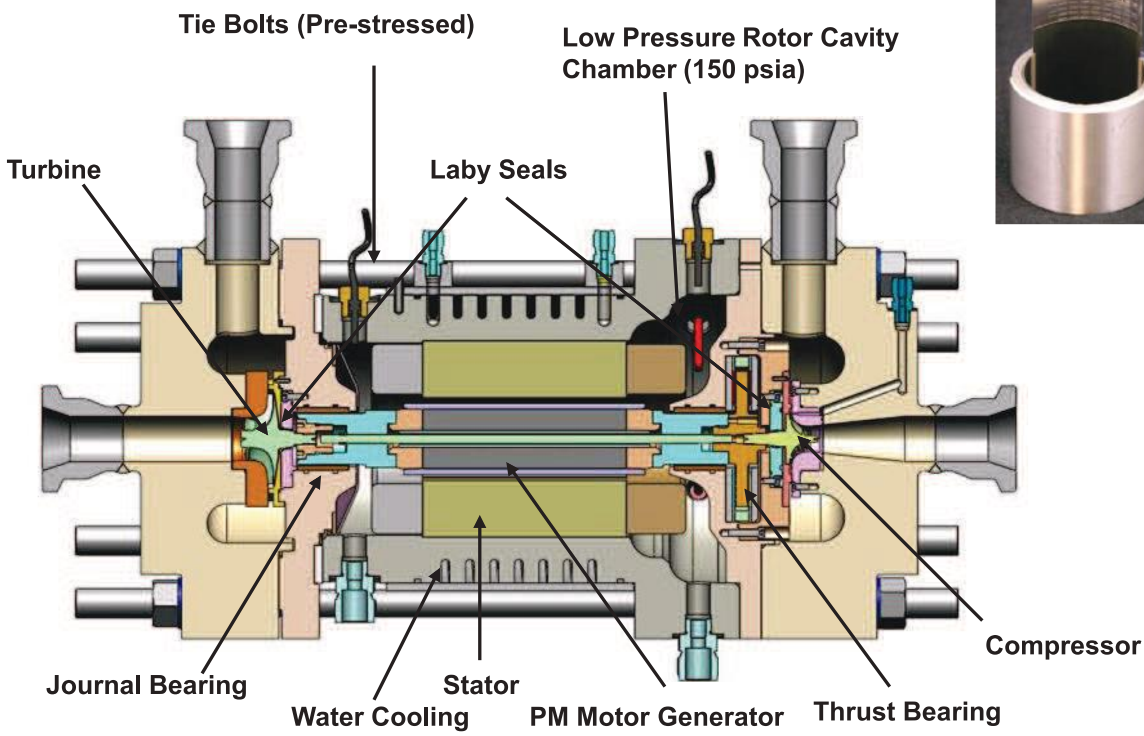
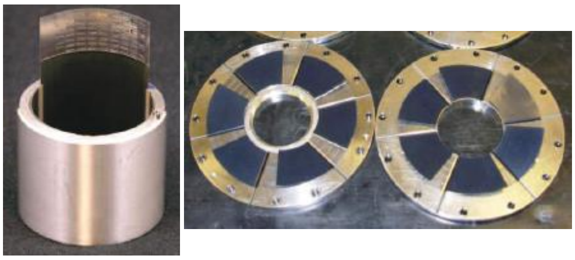
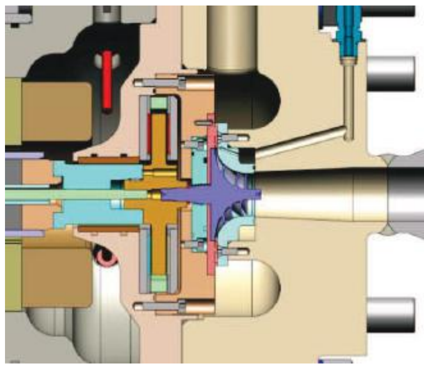
Key Technology
Turbo- Alternator Compressor Design with Gas Foil Bearings

(24” Long by 12” diameter)





Gas-Foil Bearings



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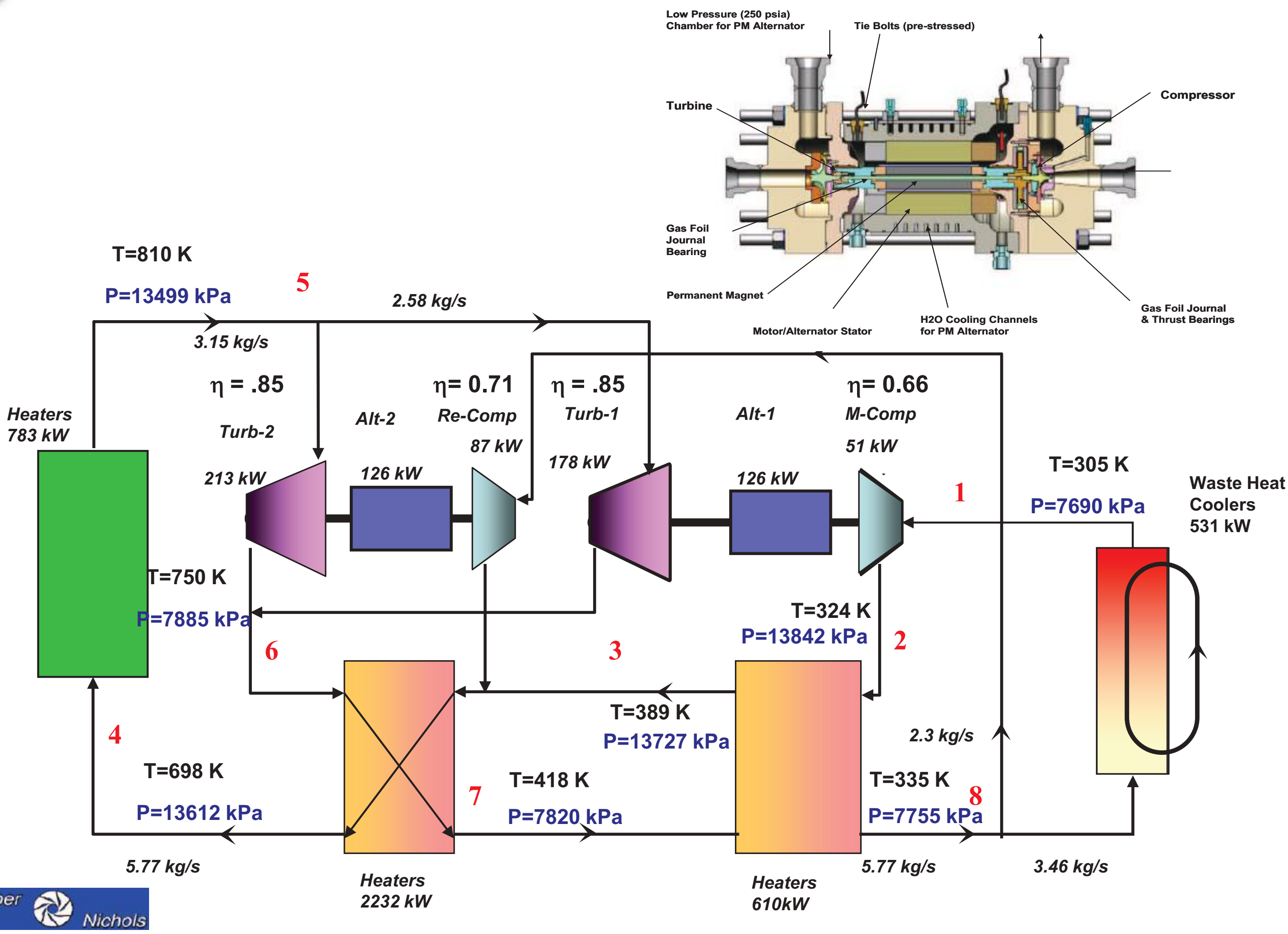
Gen IV Split-Flow Re-compression $S\text{-}CO_2$ Brayton Cycle Design Goal



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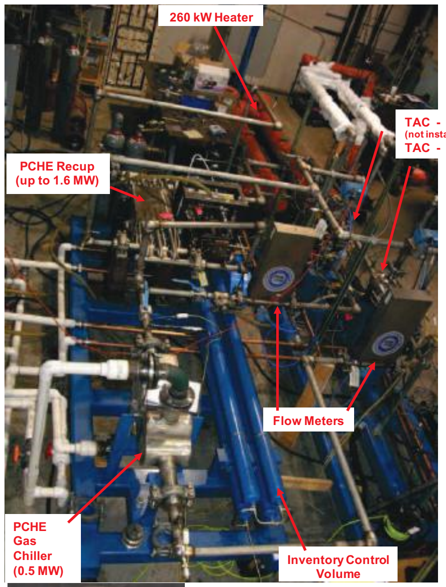
$S\text{-}CO_2$ Development Status

(Brayton Loop)



- **$S\text{-}CO_2$ Brayton Loop Summary**
  - First Operations (July 2009)
  - Split Flow with Dual Turbo-Compressors (Dec. 2010)
  - Recuperator Installed in February 2010
  - First Power Production (March 2010, 430 F)
  - Startup Up Issues Due to Low Temperature High Density Fluids
    - Startup Procedures and Methods Developed and Successful
  - Two Heaters added (total of 0.52 MW) (Oct-Dec 2010
  - High Temperature Recuperated Added (Oct-Dec 2010)
  - Commercialization Strategy for 10 MW Demo System Development Initiated
- **Future Activities**
  - Increase Heater Power and Facility Cooling Capabilities
  - Increase Turbine Inlet Temperature (Design 1000 F)
  - Ship to SNL Facility (Sep 2011)
  - 10 MWe demonstration, Concept Design and Funding Path Developed
  - Research on Mixed Fluids
  - Research on Condensing Cycle

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Summary and Conclusions

- Steam Rankine Power Systems Can be Directly Applied to FHR Reactors
  - Commercially Available (Now)
  - Efficiency up to ~ 45% at 500 C
  - Corrosion Issues
  - Fluoride Salt Steam Compatibility Issues?
  - Superheated are Larger than Supercritical which are larger than S-CO2 power systems
- S-CO2 Brayton Cycles
  - S-CO2 Appears Most Suited to Advanced Reactors
  - Very Good Efficiency (400C -650 C) Temperature Range (43-48% at 500C and 650 C)
  - Peak Temperatures (750-800 C)
  - Small due to low pressure ratio and high fluid density
  - Advanced S-CO2 Systems have very high efficiency (up to 55%)
    - Condensing, CO2-Gas Mixtures change Critical T, Interstage Heating with Condensing
  - Remain Small
  - Very Good Materials Compatibility
  - Reactor Experience in AGRs and MagNox Rx in Great Britain
  - Inexpensive fluid
  - Single Phase
  - Power Systems are Simple (due single phase nature)
  - Less Sensitive to Pressure Drop
  - Need Development and Not Proven on Commercial Industrial Scale
- Helium Brayton
  - Commercial Testing in 1950s, Didn't meet efficiency Goals
  - Potential for High Efficiency at High T (> 900 C) , 48%
    - But pressure drop, gas costs, leakage, generally reduce efficiency to 43%
  - IHC Lowers Improves efficiency at Lower Temp (650 C) eff~43%
    - But complexity and Size make Economics questionable