SAND2011-3275C

Supercritical CO_2 Brayton Cycle
Program Summary and Development Roadmap

Presented to the
VHTR R&D FY-11 Technical Review Meeting
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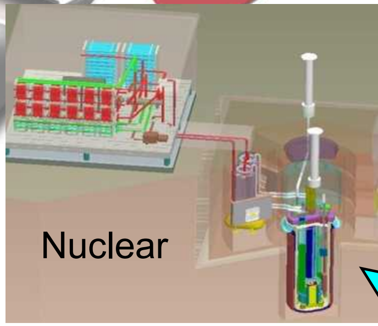
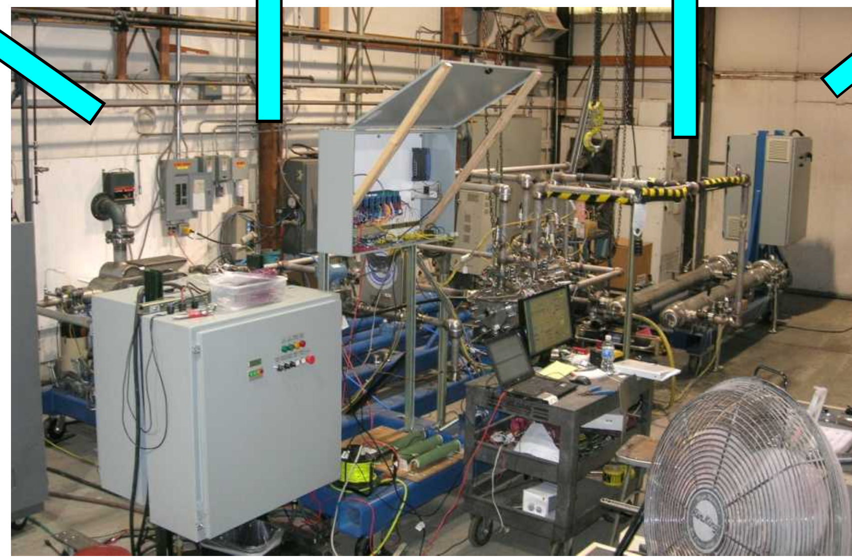


Power Production



Heat Transport and Storage

Turbomachinery

Interested in other applications? – Plan on attending the

Supercritical CO_2 Power Cycle Symposium

The Power Industry's Next Phase Shift

http://sco2powercyclesymposium.eventbrite.com/

May 24-26, 2011
Hosted by the University of Colorado, Boulder CO

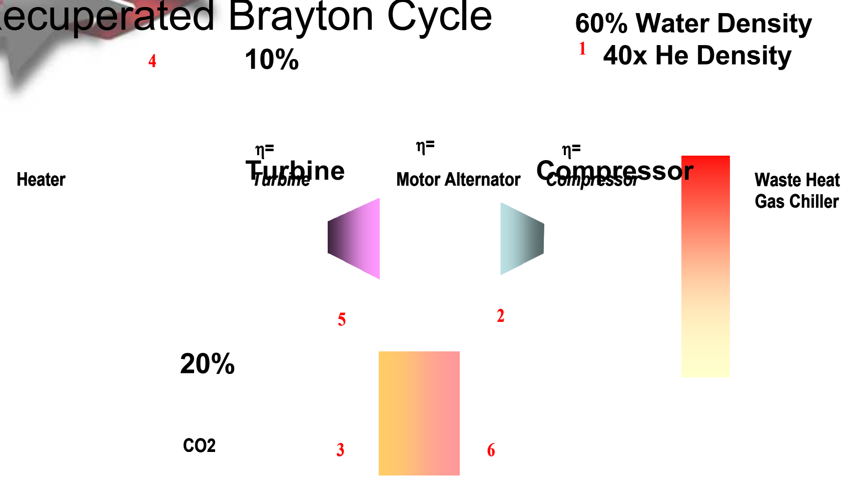
55 papers presented
10 countries attending
Includes a tour of Barber Nichols (Arvada, CO) and the Sandia 1MW split flow PCHE Unit

Outline

- What is a Supercritical CO_2 Brayton Cycle?
- Why is it Important and How is it Used?
- DOE Gen-IV S-CO_2 Program Summary
  – Major Accomplishments
- Strategic Development Plan

What is a Supercritical CO_2 Brayton Cycle?

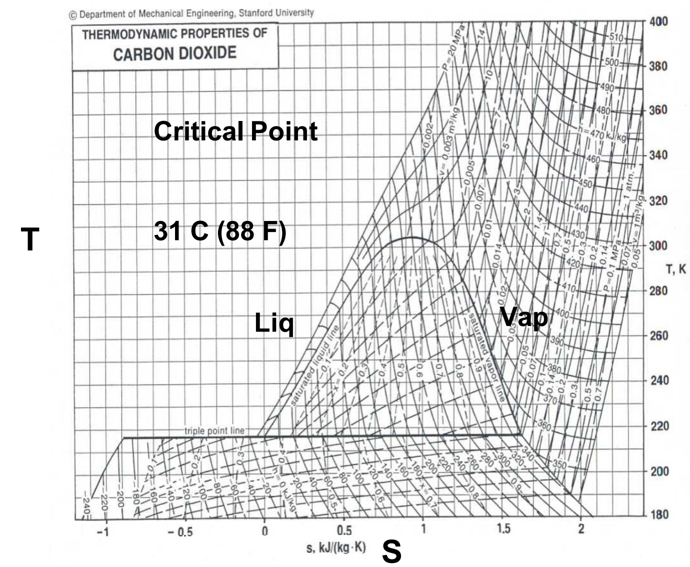
Recuperated Brayton Cycle



Liquid like Densities with CO_2

Very Small Systems,

High Efficiency due to Low Pumping Power



Rejects Heat

Above Critical Point

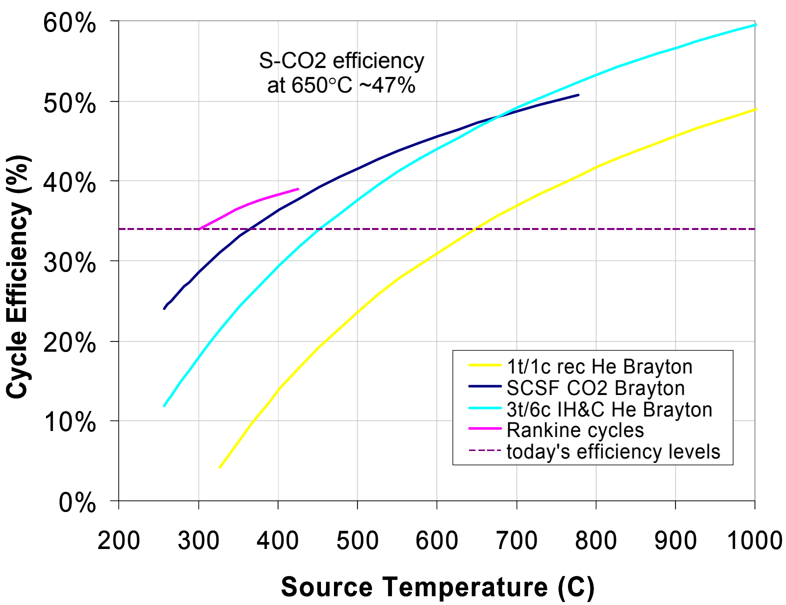
High Efficiency *Non-Ideal Gas*

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)

He Turbine (300 MWe)

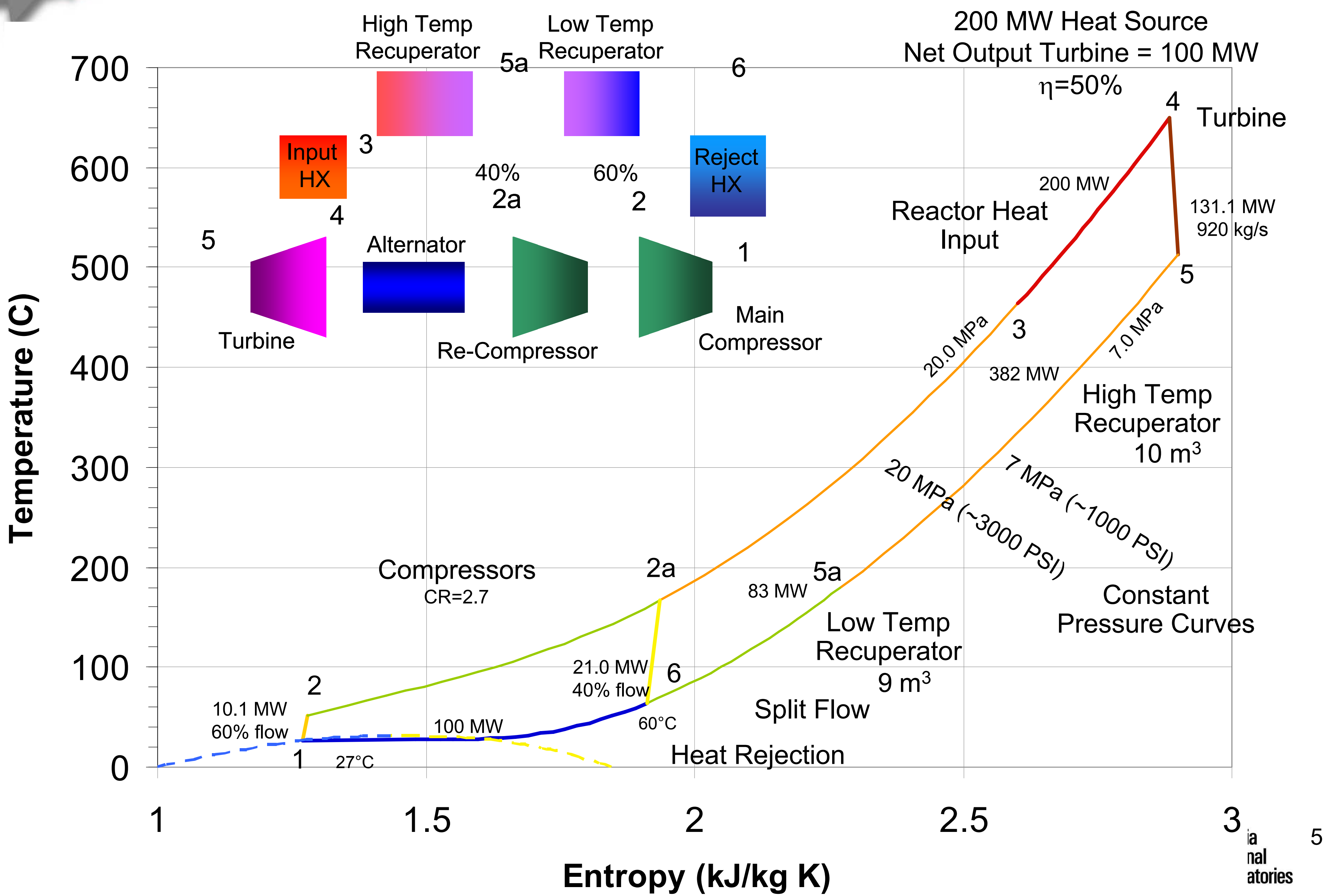
1 m **$S\text{-}CO_2$ (300 MWe)**

Steam Turbine (250 MWe)

High Density Means Very Small Power Conversion System

Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

T-S Diagram – S-CO_2 Brayton Cycle With Split Flow

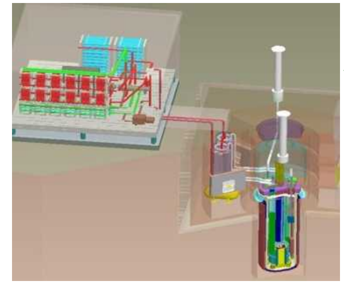


Supercritical CO_2 Cycle Applicable to Most Thermal Sources

Solar

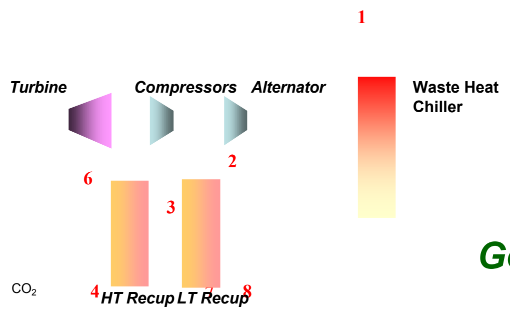
SNL Solar Tower

Military

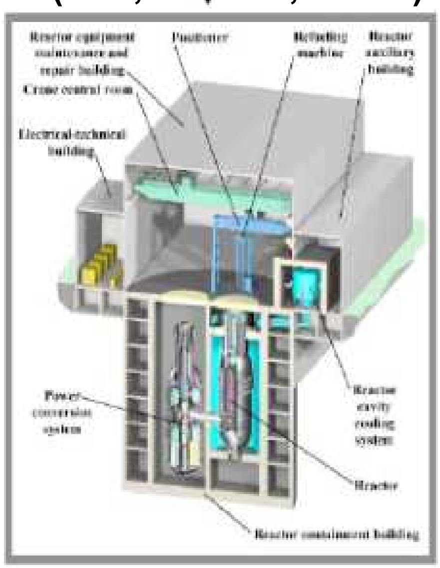


Fix Base Plant
Marine

Supercritical CO_2 Brayton Cycle



Nuclear (Gas, Sodium, Water)



DOE-NE
Gen IV

ARRA
Geothermal

INERI
NRCan CANMET &
SASK Power

Fossil **Sequestration Ready**

SNL has Funding or Research Agreements with Agencies Representing All these Heat Sources

Key Features of 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 MWe Systems
  1000°F (810 K) ~ 538°C Efficiency = 43 %
  1292°F (1565 K) ~ 700°C Efficiency = 50%

- **Standard Materials**

  Steels, Stainless Steels and Inconels

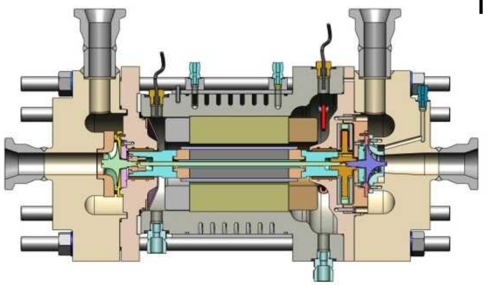
- **High Power Density for Conversion System**

  ~30X smaller than steam or 6X 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)

- **Advanced Systems (Increase Eff 3-5% points)**



1.5” Compressor
70 hp, 52 kW

Steam Turbine

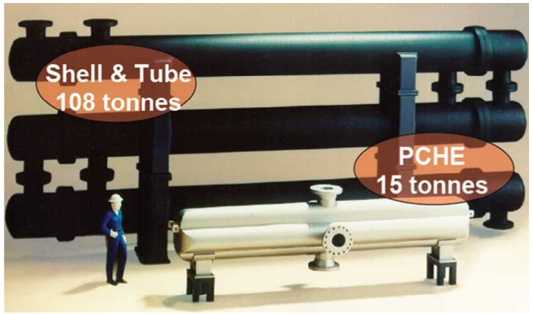
Turbine Building

12’

S-CO_2

High Efficiency – Low Source Temps
Standard Materials
Small Size and Footprint
Modular & Transportable
Load Power Following
Affordable and Fabricable
Potential for Air Cooling Heat Rejection
Natural Convection Flow Cooling

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



Advanced Heat Exchangers Meggit / Heatric Co.

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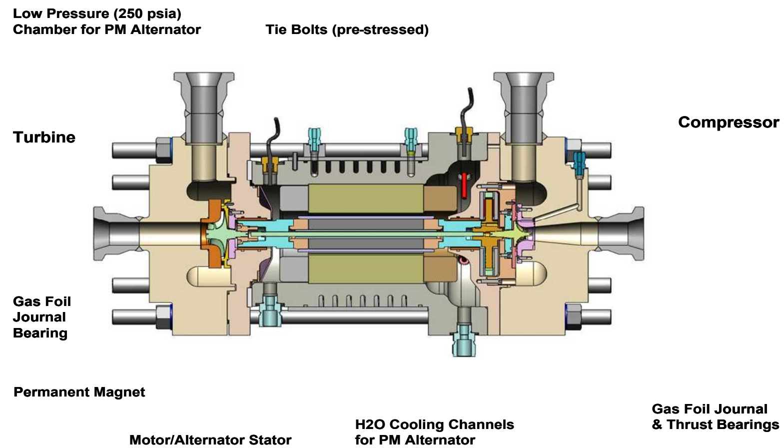
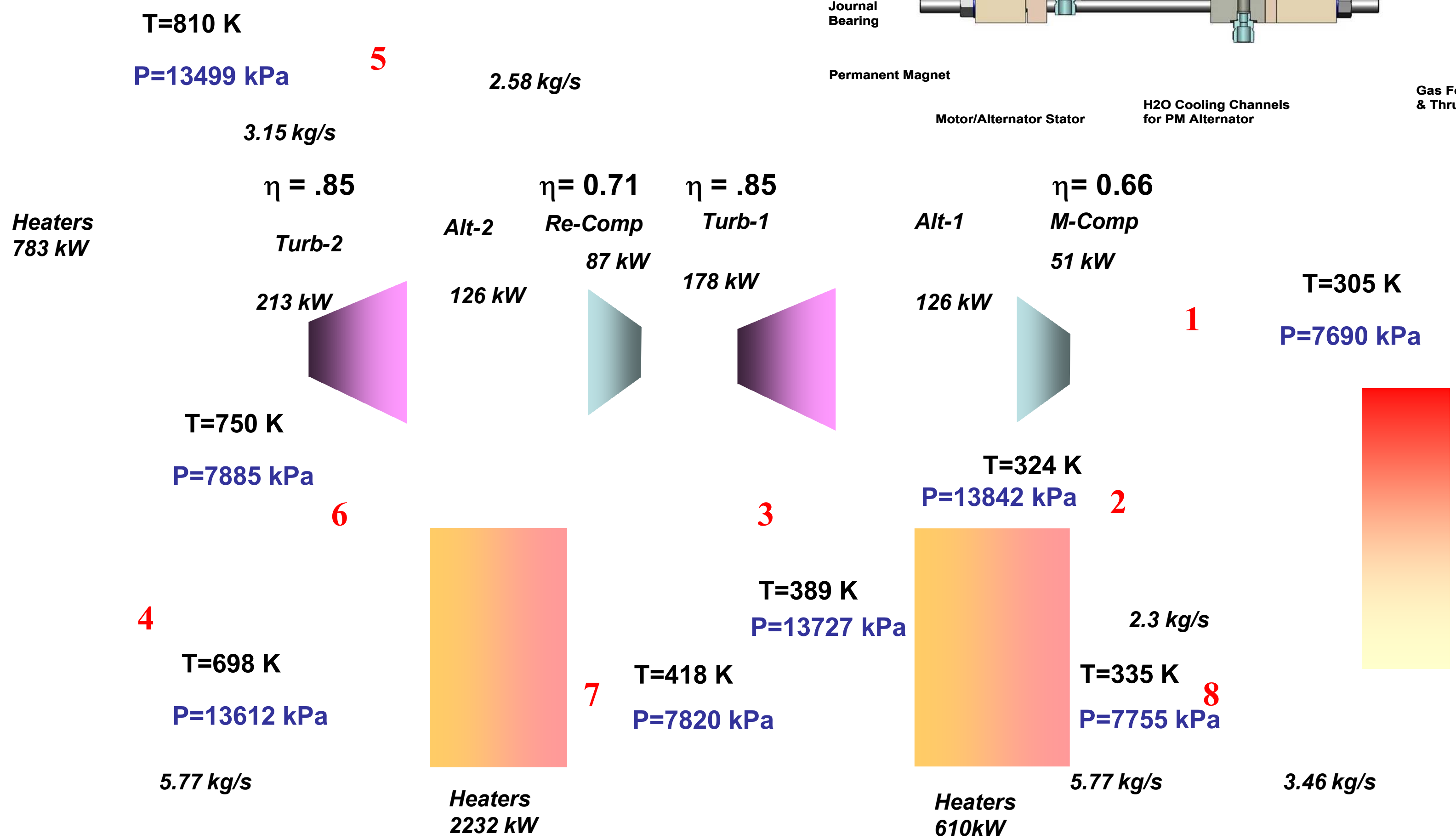
SNL/DOE Design Target for Proof-of-Principle Split-Flow Recompression S-CO_2 Brayton Cycle

Modified Cycle to Enable Scaled
Turbomachinery Development with Lower Risk
Dual Shafts, Lower Pressure Ratio

1 MW Unit at Barber Nichols

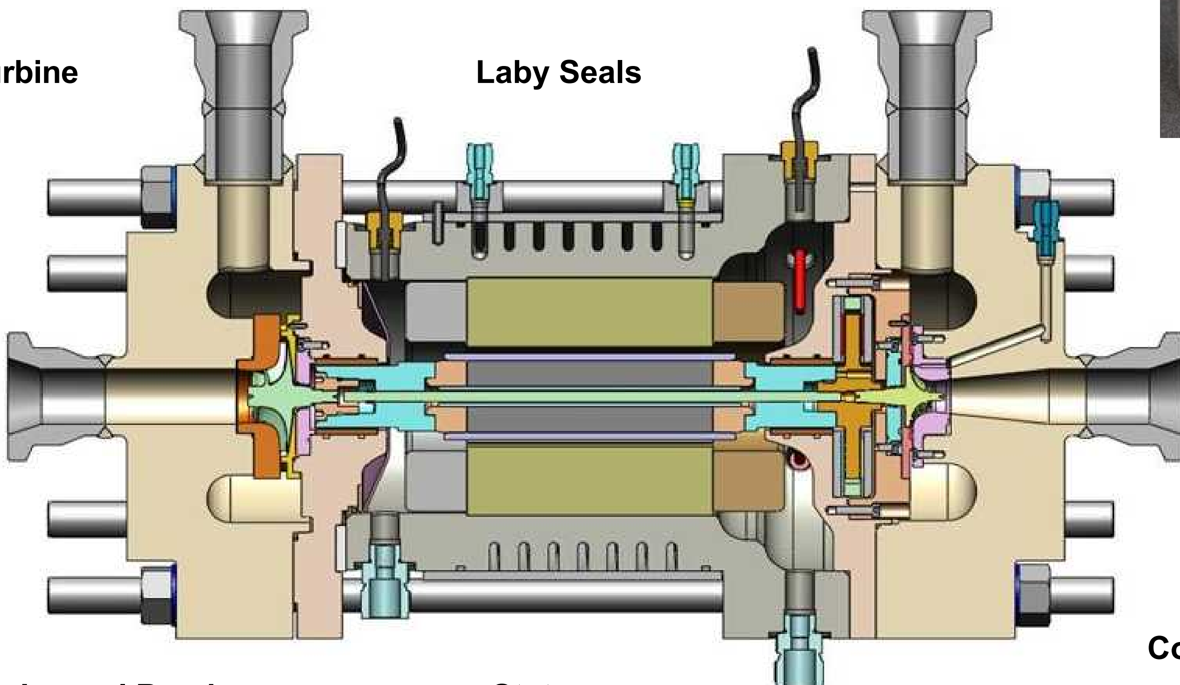




Key Technology

Turbo-Alternator-Compressor Design
with Gas Foil Bearings (~24” long by 12” diameter)

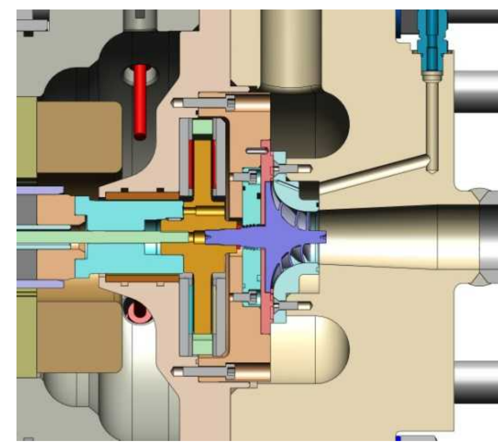
Technology for Small Scale System



Capstone

Gas-Foil Bearings

Compressor



Barber Nichols

Patent Application is in Process for All major Features of this Design

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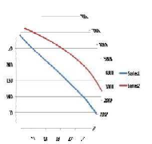
$S\text{-}CO_2$ Development Sequence

Single Compressor Research Loop
at Sandia

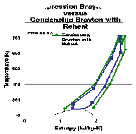
Heated Unrecuperated
Brayton Loop

Split Flow
Recompression Brayton Loop
at Barber Nichols

Other Supercritical Fluids (SF_6)



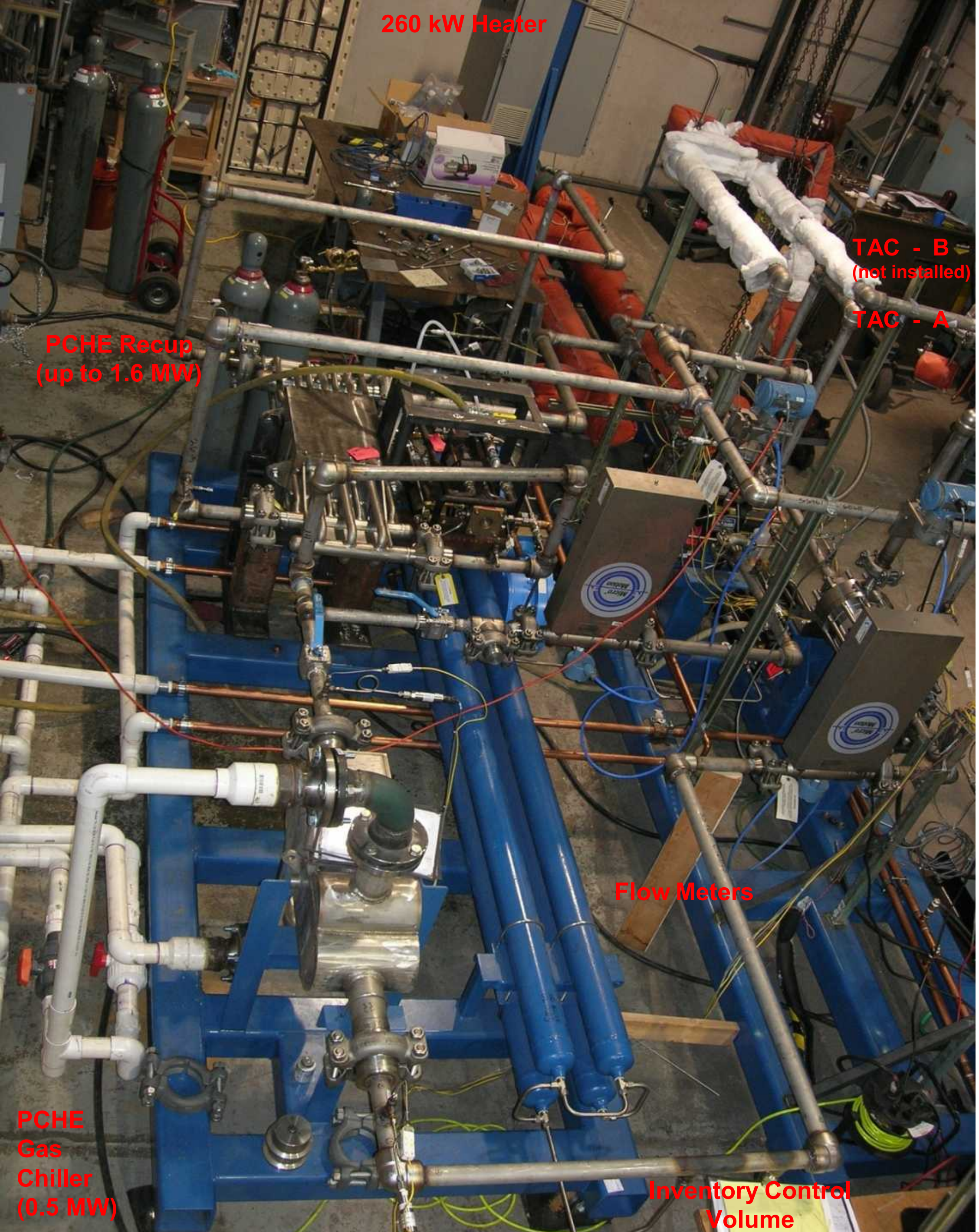
Supercritical Mixtures

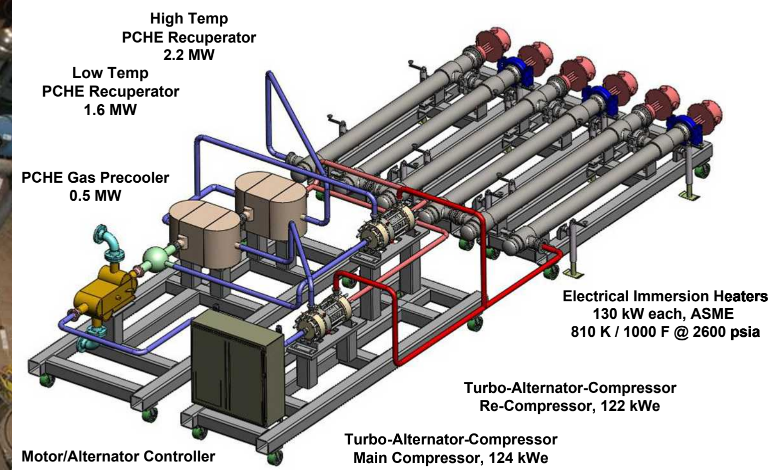


Condensation Cycle

Supercritical CO_2 Recompression Brayton Cycle

DOE-Gen IV





Barber Nichols

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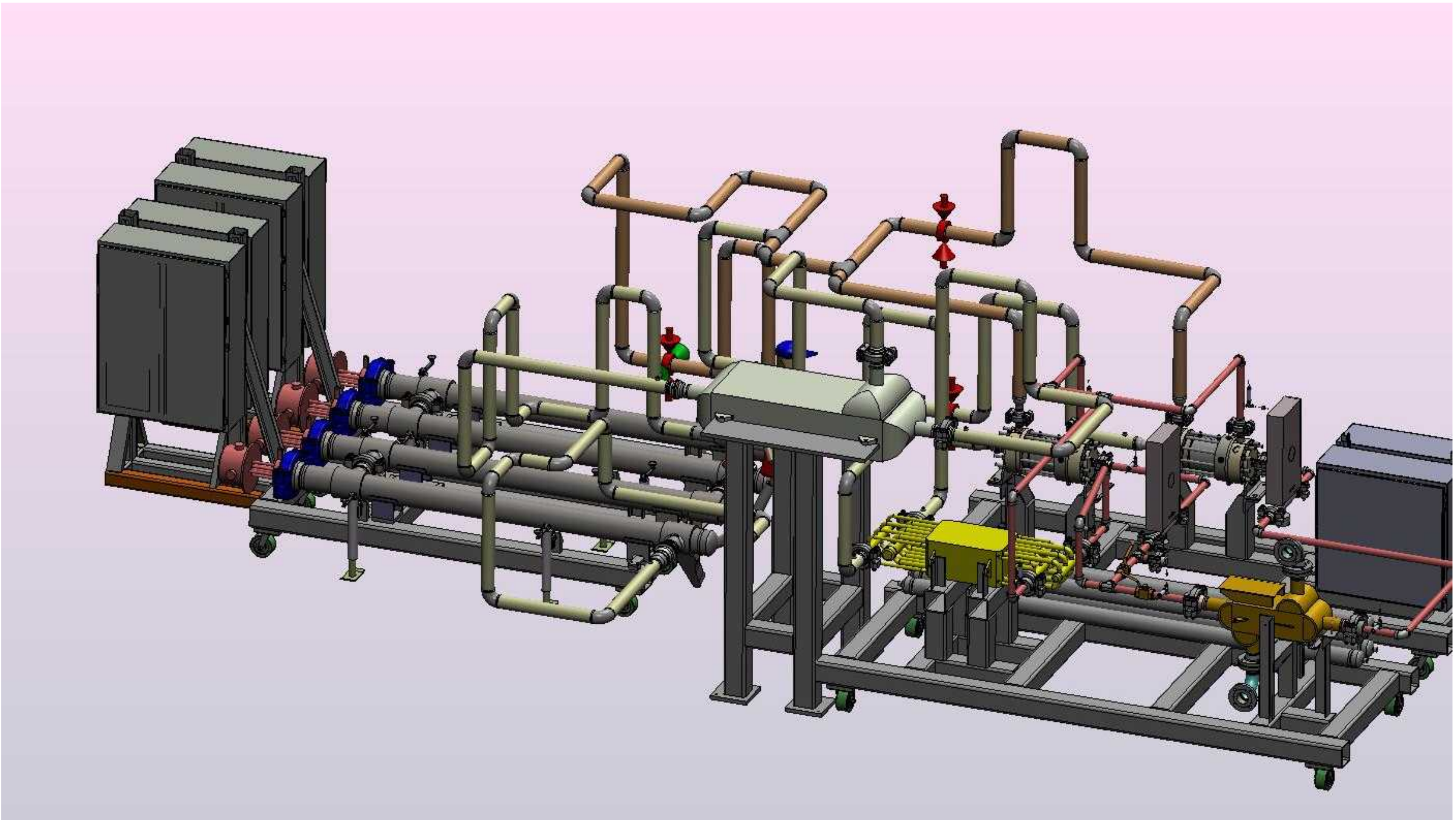
S-CO_2 Recompression Brayton Loop

Engineering Drawing of 520 kW Heater Power Upgrade



Cost of Printed Circuit Heat Exchangers

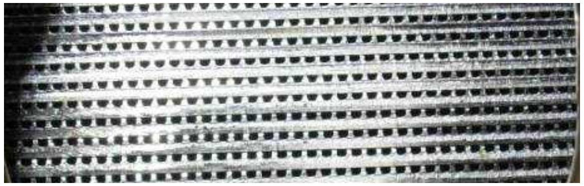
	Actual		Specific Costs		
Cost	kW	lb	lb/kW	$/lb	$/kW$_{th}$
60000	510	492	0.96	122	118
106000	1600	551	0.34	192	66
210000	2300	1410	0.61	149	91
Average			0.64	154	92

~ $ 500/kW$_e$

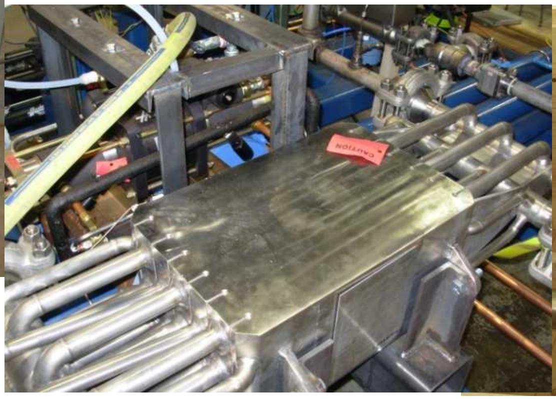
Target is $150-$200/kW$_e$
~ $30/kW$_{th}$

SS316
13-15 $/lb

Gas Chiller Water/CO_2



LT Recup



HT Recup

More Accurate Cost Model = Engineering Design + A*Volcore + B*Length Nozzles

Reduces the costs to = (closer to 250-300 $/kWe)

Volume Production + Materials Selection + Advanced Manufacturing

Will lower costs to 150$/kWe

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$S\text{-}CO_2$ Development Status

- **$S\text{-}CO_2$ Research Compression Loop Summary**
  - First Operation (July 2008)
  - Compressor Performance Maps (Dec 2008)
  - Seal and Bearing Tests (2009)
  - Installed at SNL (March 2010)
  - Condensation & Gas Mixtures 2010 & 2011
- **S-CO2 Brayton Loop Summary**
  - First Operation (July 2009)
  - First Power Production (March 2010)
    - Peak Temperature at 600°F (315°C)
    - Break Even Power at 300°F (150°C)
  - Split Flow with Dual Turbo-Compressors (Dec 2010)
  - Startup Up Issues Resolved for all Systems
- **Future Activities (1 MW Recompression Unit)**
  - Increase Heater Power and Facility Cooling Capabilities (780 kW)
  - Increase Turbine Inlet Temperature - Design 1000°F (540°C)
  - Ship to SNL Facility (July-August 2011)
- **Future Research**
  - Mixed Fluids
  - Condensing Cycle
  - Natural Circulation Flow
  - Gas-Foil Bearings
  - Thrust Loads
  - $S\text{-}CO_2$ Heat Pumps
  - Air Cooling Heat Rejection
  - 10 MW_e Industrial Scale Demonstration Design (FY 2011)

Summary of DOE Program

Sandia/DOE-GenIV S-CO_2 Program has Fabricated/Operated S-CO_2 Turbo-Machinery Test Loops

- Hardware focus with multiple loops and multiple configurations
- Currently among the leading S-CO_2 power production loops in the world
  - Other loops include: Japan TIT, Czech Republic, Echogen)
- Power production in multiple loop configurations

Focus is on Improving Performance in these Loops

- Hardware upgrades include heaters, recuperators, larger evaporative coolers
- Testing focus is on startup, power production, power electronics and controls, higher inlet temp, lowering frictional losses, bearings and seal development/improvements
- There were some unexpected startup behaviors issues (fully resolved)

Multiple “Paying” Customers

- DOE-NE, Geo Thermal, DoD/DOE, Solar, Fossil, (other DOE Agencies)
- Over $10M Invested since 2006 (DOE)

Scaling Study Indicates that 10 MWe uses Industrial Technologies and is Commercially Relevant

- Multiple Interested Industrial Partners

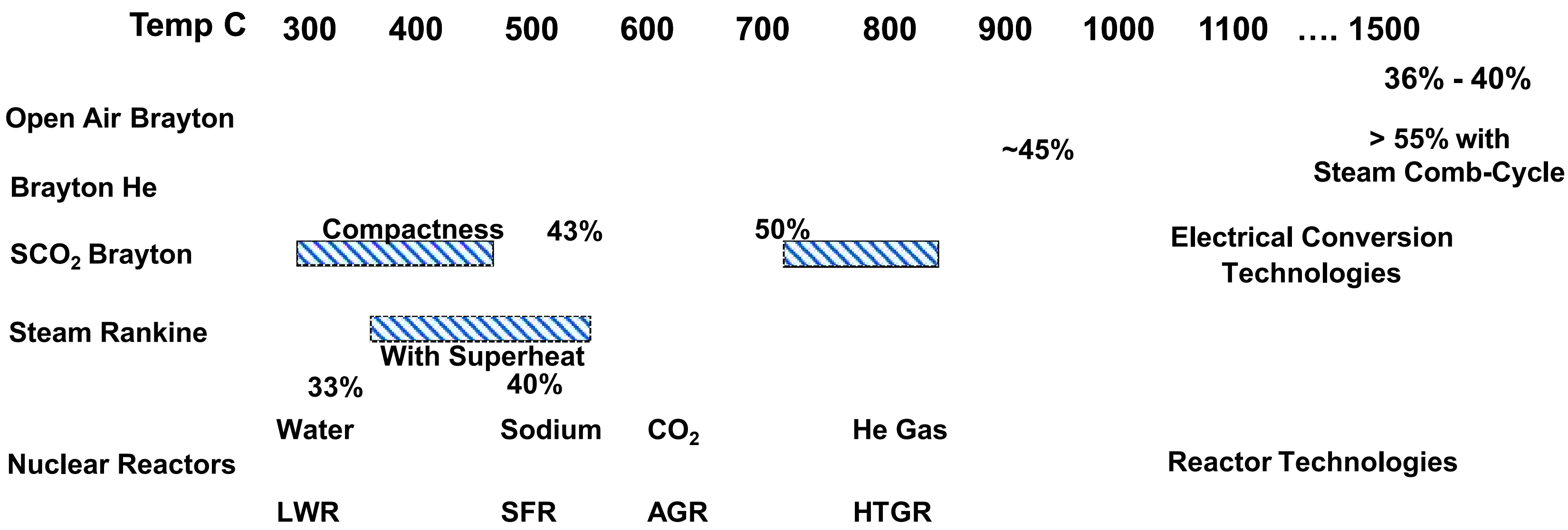
Advanced S-CO_2 Options Look Very Promising

- Condensing, Advanced Cycles, Natural Circulation, Air Heat Rejection

Future Effort

- Complete the Current Small Scale 1 MW_{th} Program
  - Fluid Mixtures, Other Supercritical Fluids, Advanced Cycles and Condensing Cycle
- Begin a Scale-up Demonstration Program to 10 MWe.

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

Assumptions (Turbomachinery Eff (85%/87%/90% : MC/RC/T), 5 K Approach T, 5% dp/p losses, Hotel Losses Not In Included

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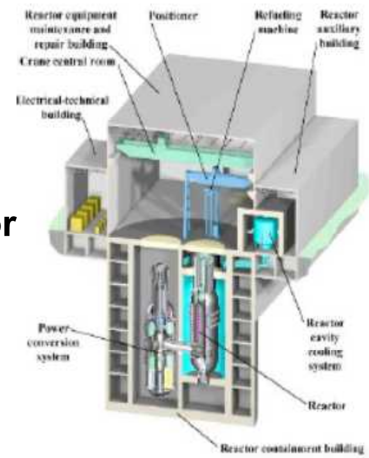
S-CO_2 Power Cycles for Reactors

S-CO_2

NGNP
High Temperature
Gas Cooled Reactor
850-900°C

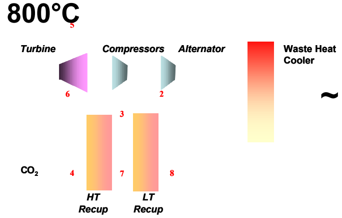


He

850°C

650°C

800°C

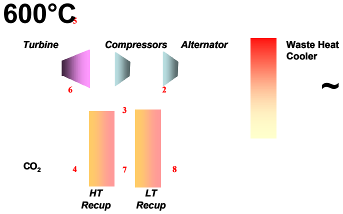


GCRs

~ 54 %

~50% Efficiency
(S-CO_2 Brayton)

600°C

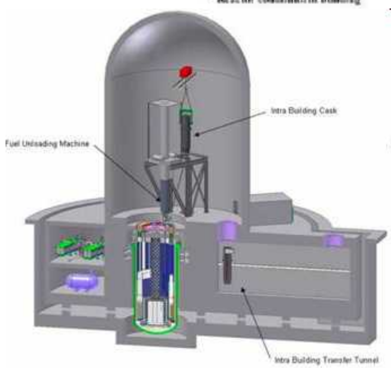


He

450°C

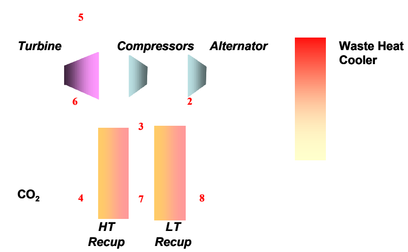
~ 46 %

Sodium Cooled
Reactor
500-550°C



Sodium

525°C

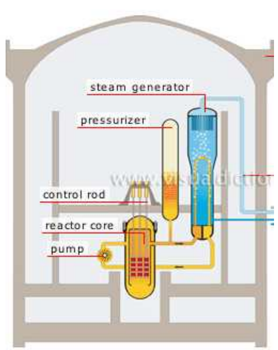


SFRs

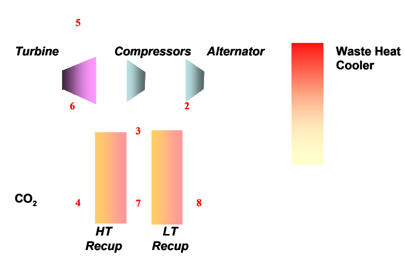
~44% Efficiency
(S-CO_2 Brayton)

LWRs
Pressurized
Water Reactor
330°C

Potential SMR
Applications



315°C



LWRs

~39% Efficiency
(S-CO_2 Recup Rankine
IH+IC Brayton)

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Supercritical CO_2 Power Systems

Advantages:

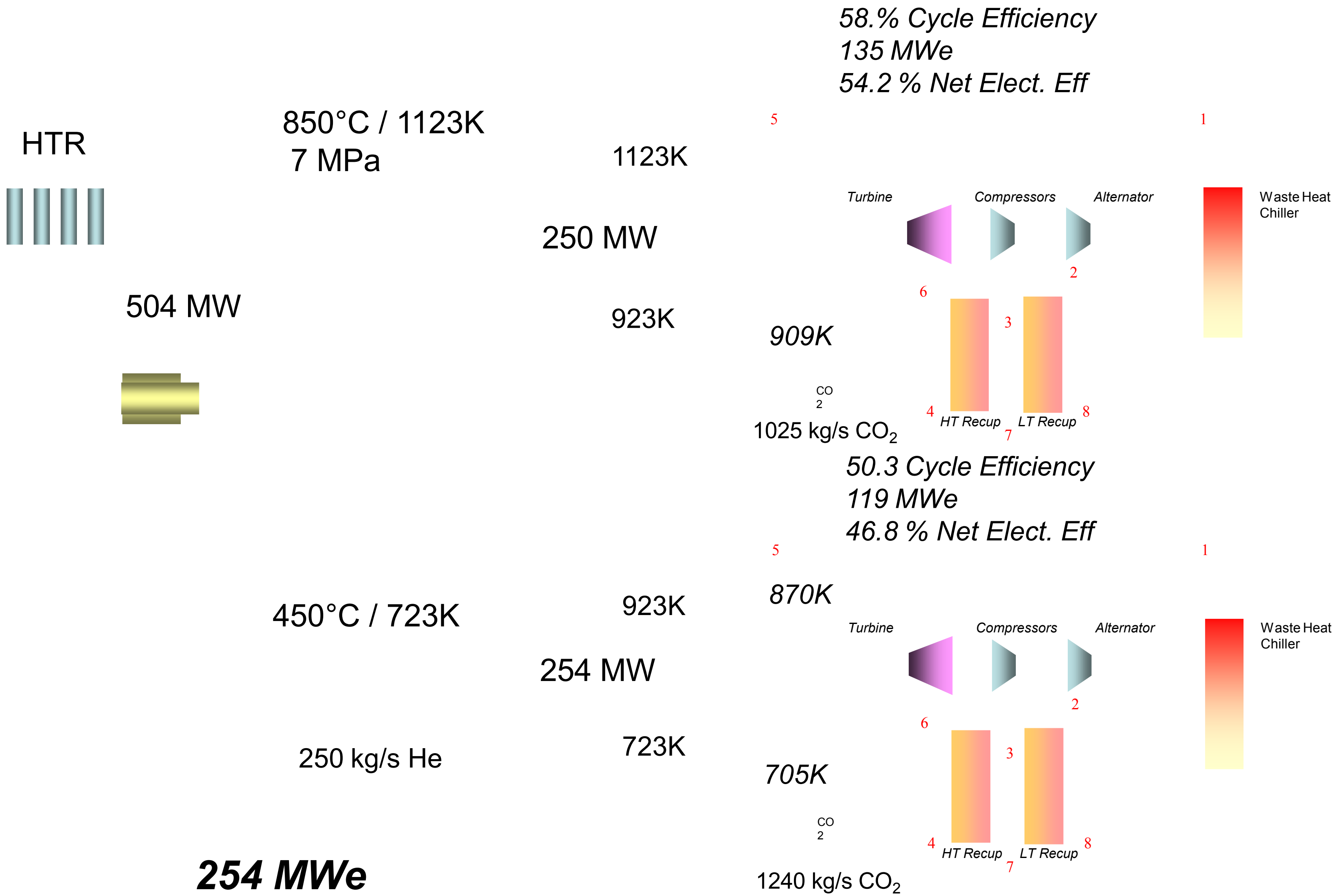
- CO_2 is inexpensive - It doesn't leak easily
- High density - Small loop pressure drop and small size
- Better materials compatibility at > 500°C (compared to steam)
- High thermal efficiency at modest temperatures > 400°C
  - (better than steam > 400°C)
- Pressures are on par with steam (up to 3500 psia)
- Potential for dry air cooling
- Potential for load following
- Many growth options are available

Disadvantages:

- Lacks development - DOE-NE is currently funding this effort at SNL in the 1 MW (heater class) S-CO_2 development program
- High pressure (same as steam up to 3500 psia)

Allows for Phased/Staged Commissioning in NGNP

Tandem S-CO_2 Brayton Cycles



254 MWe
50.4 % Net Elect. Eff.
850°C

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Phase I

- 50% Power
- Full Flow
- 450°C Inlet Temp
- 650°C Outlet Temp

- Benefits
  - Early Operations at Low Temp
  - Develop, Test, and Validate IHX Design
  - Validate System Operation

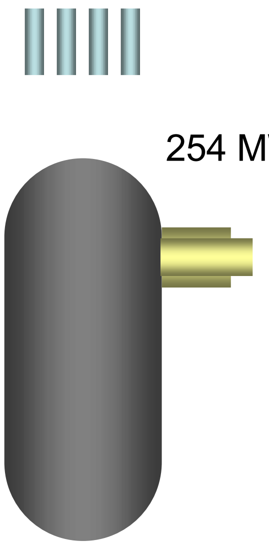
Increased Operational Margin

46.8 % Net Electricity Efficiency at 650°C

HTR

650°C / 923K
7 MPa

254 MW



450°C / 723K

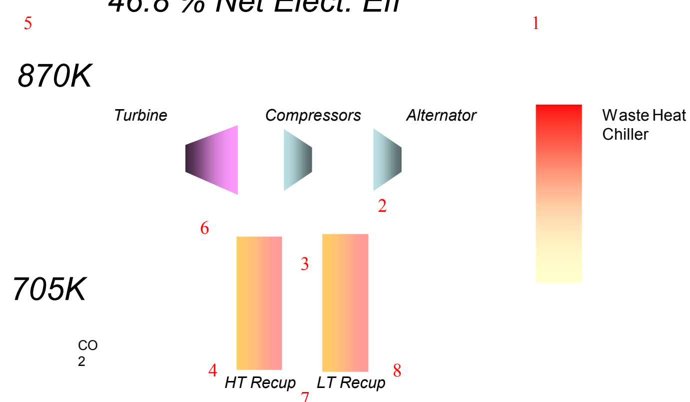
923K

254 MW

723K

250 kg/s He

50.3 Cycle Efficiency
119 MWe
46.8 % Net Elect. Eff



1240 kg/s CO_2

119 MWe
46.8 % Net Elect. Eff.
650°C

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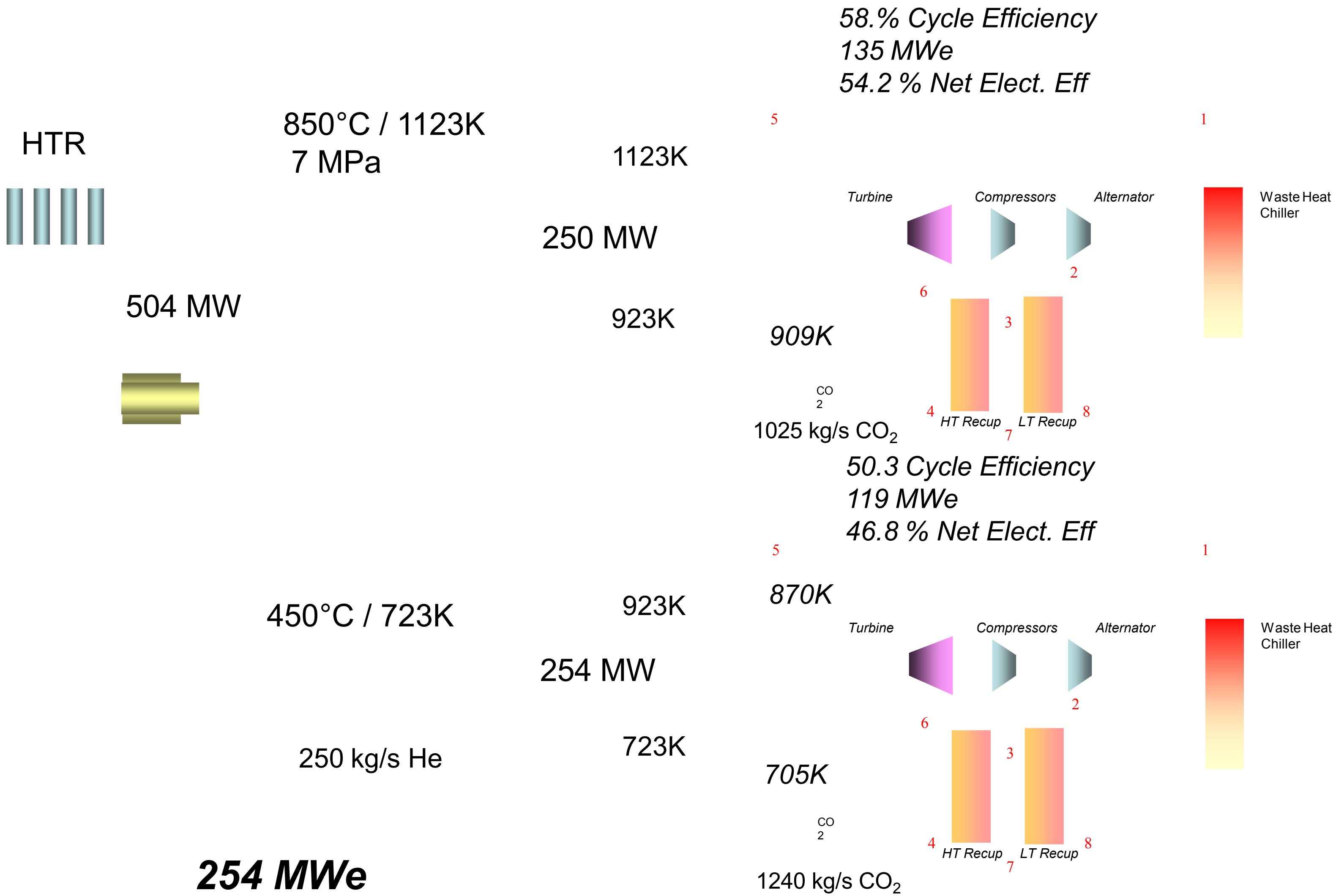
Phase II



254 MWe
50.4 % Net Elect. Eff.
850°C

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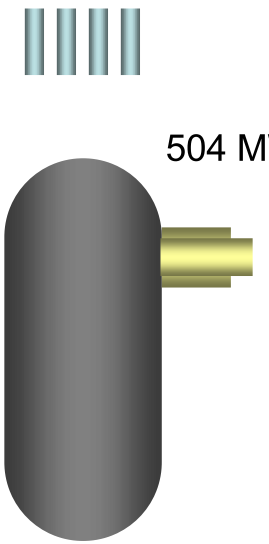
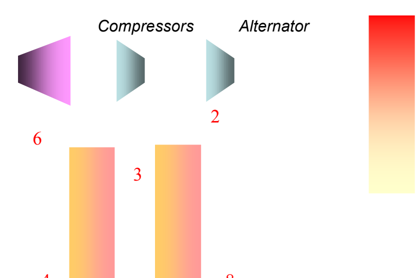
Phase II Options

Thermal Chemistry for Industrial Processing + Electrical Power Generation



High Temperature Industrial Heat (e.g., Hydrogen)

50.3 Cycle Efficiency
119 MWe
46.8 % Net Elect. Eff



119 MWe
46.8 % Net Elect. Eff.
650°C

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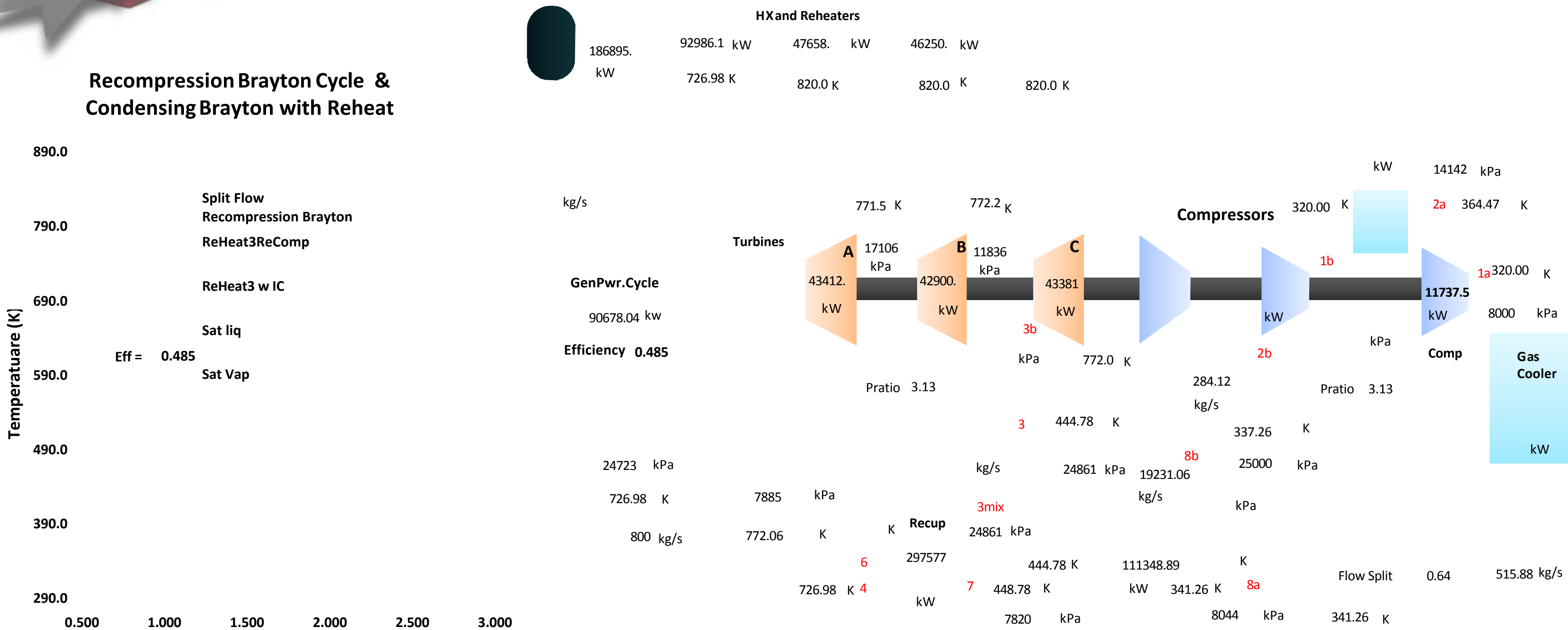
Supercritical CO_2 Role in in High Temperature Gas Reactors

Benefits Of Phased Commissioning

- Early operations at low temperature with full flow
- Develop, test, and validate IHX design
- Validate system operation
- Increased operating margin
- 46.8% net electrical efficiency at 650°C in first system
- Gradual/natural growth to full temperature and power
- Allows for phased-in use with thermal chemical industry
- Allows for simultaneous electrical power and industrial heat

NGNP Potential with S-CO_2

Low Temperature Interstage Heating and Cooling Cycle With Dry Air Cooling Example Shown



Inlet Values	Variable Name	Units	Value	Value	Value	Value
Turbine Inlet T	T.5	K	820	820	1070	1070
Fractional Pressure drop	f.dp		0.0056	0.0056	0.0056	0.0056
Compressor Pressure Ratio	r.c		3.13	3.25	3.13	3.25
Compressor Inlet Pressure	p.1	kPa	8000	7690	8000	7690
Compressor Inllet Temperature	T.1	K	320	305	320	305
Mass flow rate	mdot	kg/s	800	800	800	800
Split flow frac thru chiller	f.split		0.64	0.68	0.64	0.68
Recup Approach Temp	dT.appr	K	4.00	4.00	4.00	4.00
Compressor Isentropic Eff	*0.9*	*0.9*	*0.948683298*	*0.948683298*	*0.948683298*	*0.948683298*
Re Comp Isen Efficiency	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*
Turbine Isen Effic	*0.93*	*0.93*	*0.965489385*	*0.965489385*	*0.965489385*	*0.965489385*
Rx Pwr	**P.Rx**	**kW**	186895.03	203753.60	229029.91	247340.08
Eff Cycle			0.485	0.521	0.580	0.605

48.5% Efficiency, 547°C / 820K, 47°C / 320K

60.5% Efficiency, 797°C /1070K, 47°C / 320K

Scope of Current Program

Multiple "Paying" Customers

- DOE-NE ($1.2M – $1.5M per year)
- SNL-LDRD (Completed) ($1.5m)
- DOE-NE Transformational Reactor (0.2-0.5 M$)
- DOE $1.8M
- Geo Thermal (ORNL) (ARRA) $205k
- Solar SNL (~$200k)

Over $10M Invested since 2006 (DOE)

Scaling Study Indicates That 10 MWe Uses Industrial Technologies and is Commercially Relevant

- Multiple Interested Industrial Partners

Potential S-CO_2 Power System Markets

Sodium, Water, and Gas Cooled Reactors

Concentrated Solar Power

- Solar Power Towers
- Solar Troughs

Gas Turbine Competitor (50% efficiency, Needs Efficient “boilers”)

Carbon Capture and Sequestration Demonstration
(CCS- With Advanced Combustion)

Bottoming Cycle in a Combined Cycle Gas Turbine

Integrated Bio-Fuel/S-CO_2 Plant (Carbon Reduction Requirements)

Commercial Marine (Gas Fired Turbines)

Geo-Thermal Wells (Land and Ocean based)

Heat Transport (Industrial Scale) and Storage (Chemical Plants)

Waste Heat Applications

Military Applications (Fixed Base with SMRs and Marine Propulsion)

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Rough Commercialization Plan for a 10 MWe Demo Power Plant

Phase 1: Year 1 +

- Design (Conceptual, Preliminary, and Final)

Phase 2: Year 2 +

- Purchase, Manufacture, Assemble
  - Delivery schedule for some components may be limiting

Phase 3: Year 3+

- Assemble, Commission Power Unit
- Upgrades and Improvements
- Make Electricity

Phase 4: Year 4+

- Operations and Testing and Upgrades
- Electricity Sales to Grid
- Product Development (Fossil, Solar, Geothermal, Nuclear, Military)
- Redesign for Modularization

Deliverables

- Operating S-CO_2 power system Year 3
- Product Line Year 4+

Sandia National Laboratories

Commercialization Strategy Summary

10 MWe Demonstration Program

3 Year Development Effort (Making Electricity) , 4th Year S-CO_2 Power Products

S-CO_2 Power Conversion Systems

- Smaller, simpler, plus as/more efficient than existing gas or steam power plants in the (500-525°C) temperature range
- Better materials compatibility than steam at high temperatures
- Can be built with existing technologies
- Potential for load following
- Potential for dry air heat rejection
- Growth potential (performance exceeds existing technologies)
  - Higher Temperatures (700°C) >50% Efficiency
  - Alternative and Advanced Cycles extends applicability
    - Fossil, CCS, Bottoming Cycles, LWRs, Geothermal, Solar
  - Condensing Cycles with Re-heat
  - Interstage heating and cooling with higher pressure ratios
  - Higher pressure systems increase efficiency
  - Fluid mixtures to modify supercritical properties to higher or lower temperatures
- Cost estimates appear competitive
- Useful for all heat sources (Nuclear, Solar, Fossil, Geothermal)
- Numerous early non-nuclear products (Fossil, Solar, Heat Pumps, and Marine)
- May improve the economics of coal CCS systems and nuclear systems

Questions?