SUPERCRITICAL CO_2 POWER CYCLE DEVELOPMENT SUMMARY AT SANDIA NATIONAL LABORATORIES

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Sandia National Laboratories

Advanced Nuclear Technology

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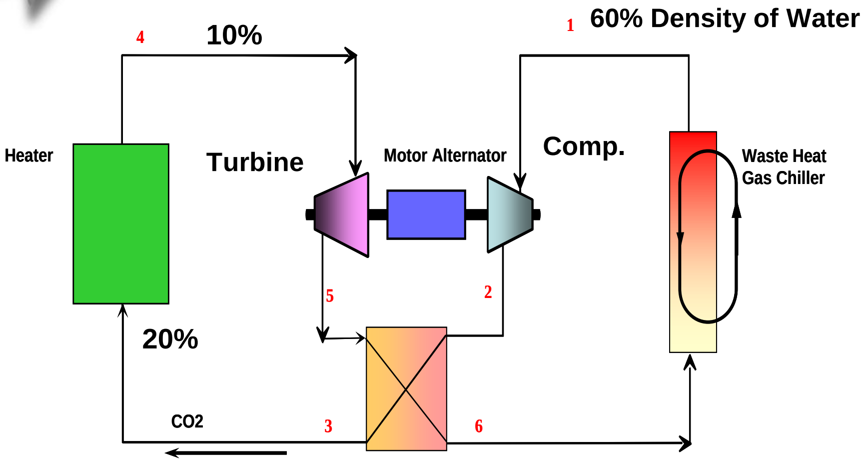
Goals of Presentation

- ***What is a Supercritical CO_2 Brayton Cycle?***
- **Economic and Environmental Benefits of S-CO_2 Power Systems**
  - **Economic and Environmental**
  - **All Heat Sources**
- **Scaling Study Results (10 MWe)**
  - **10 MWe Development and Demonstration Program Status of Development Effort**
  - **Commercial and Government**
- **DOE Gen-IV S-CO_2 Research Program**
- **Summary and Conclusions**

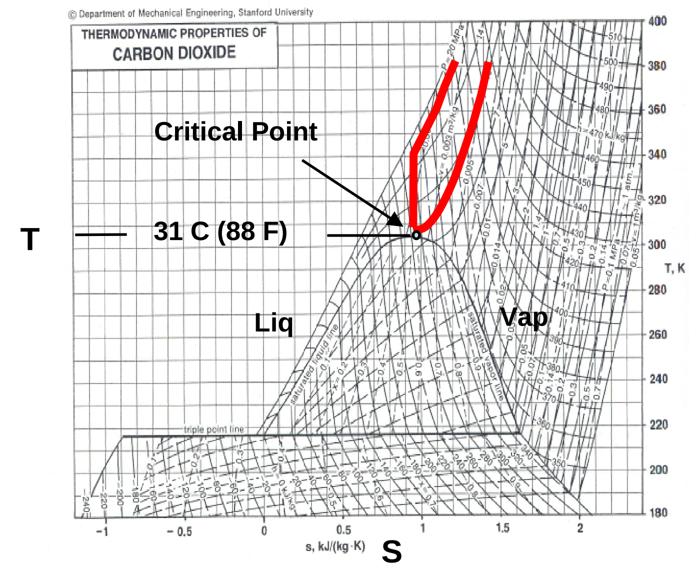
What is a Supercritical CO_2 Brayton Cycle? How does it work?



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***

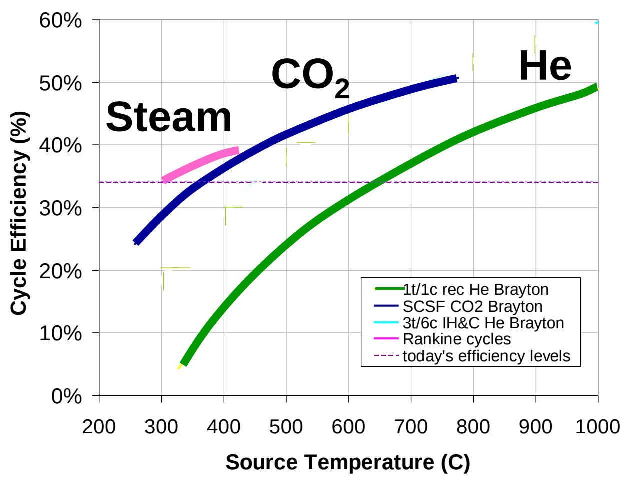
Sufficiently High for Dry Cooling

Critical Point

88 F / 31 C

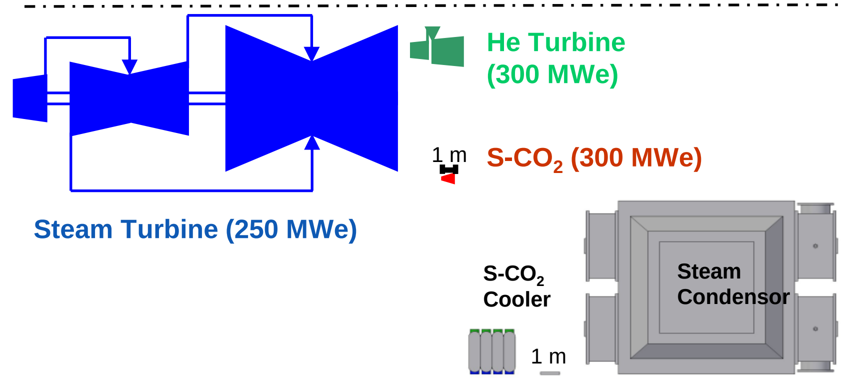
1070 psia / 7.3 MPa

Cycle Efficiencies vs Source Temperature
for fixed component efficiency



High Efficiency at Lower Temp

(Due to Non-Ideal Gas Props)



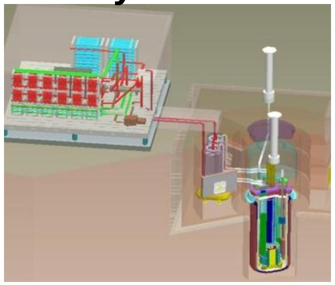
High Density Means Very Small Power Conversion System

Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

Supercritical CO_2 Cycle Applicable to Most Thermal Heat Sources

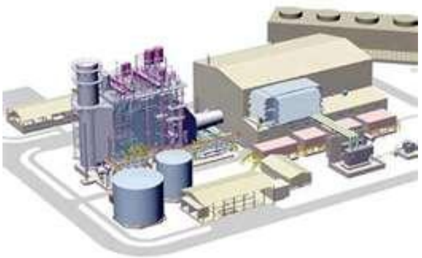
Solar

Military ***Fix Base & Marine***



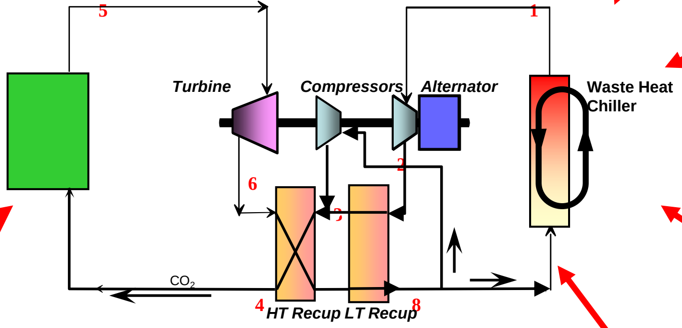
ARRA Geothermal

Waste Heat
Bottoming Cycle to a Gas Turbine

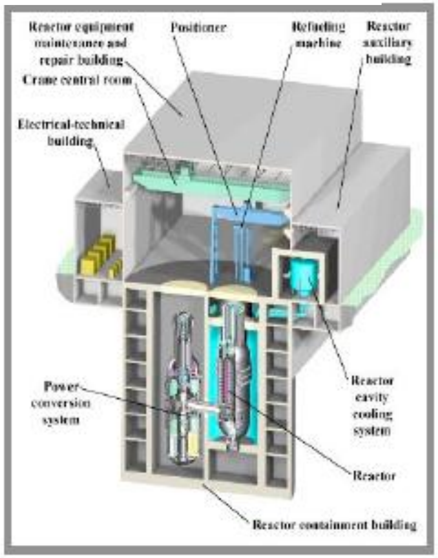


SNL Solar Tower

Supercritical CO_2 Brayton Cycle

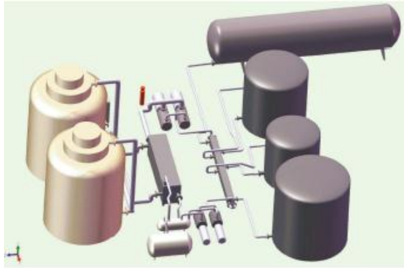


Nuclear (Gas, Sodium, Water)



DOE-NE Gen IV

Carbon Capture & Sequestration
CCS
Fossil



Energy Storage & Heat Transport & CCHE

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

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)
- Advanced Systems (Increase Eff 5-8% points) & Dry

GenIV S-CO2 Brayton Cycle

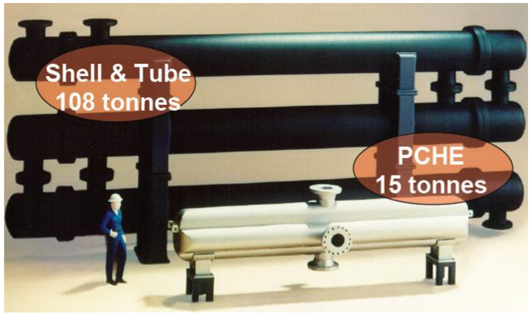
Turbine Building

Steam

S-CO_2

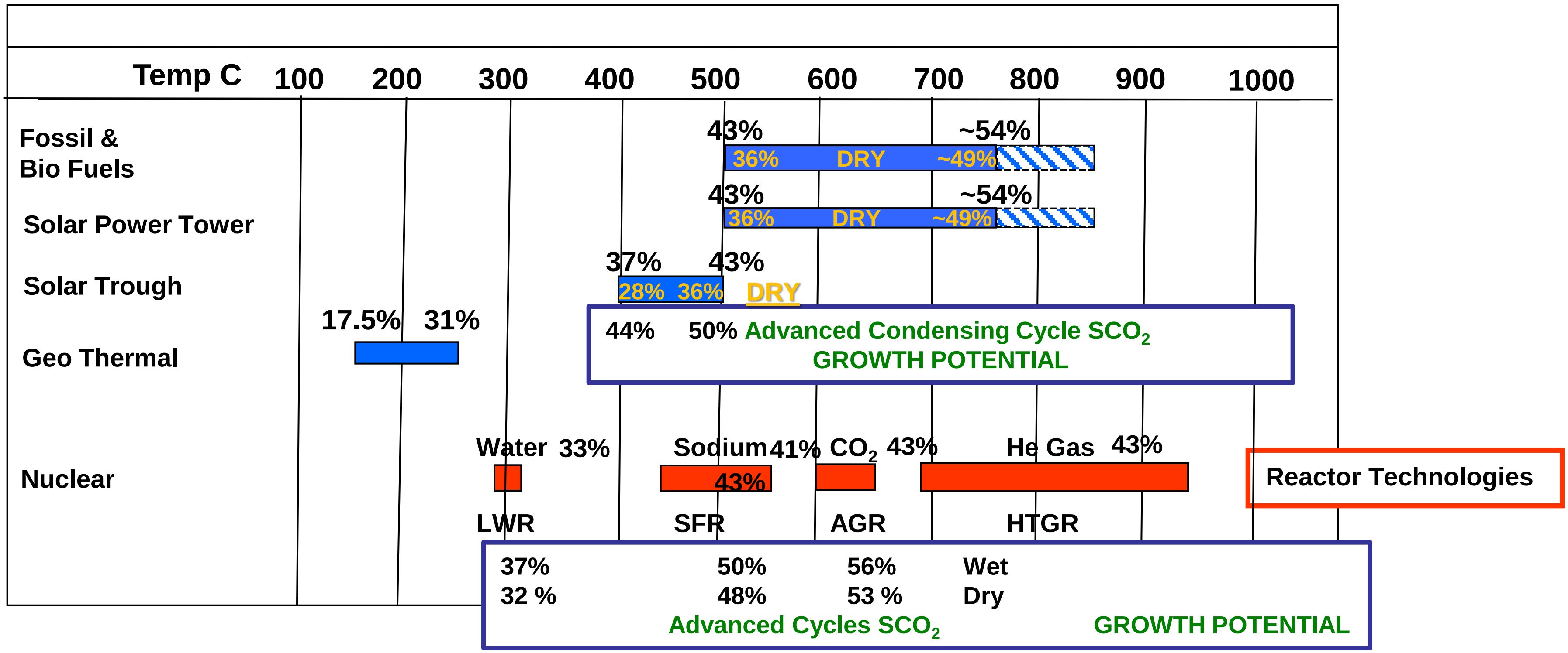
Good Efficiency at Low Operating Temps
Standard Materials, Small Size
Modular & Transportable
AFFORDABLE and FABRICABLE

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



Advanced
Heat Exchangers
Meggit / Heatric Co.

Heat Source Operating Temperature Range & SCO_2 Power Conversion Efficiency for Various Heat Sources



$S\text{-}CO_2$ Power Conversion Operating Temperatures are Applicable for All Heat Sources

Optimum Design Requires Different Approaches for Each Heat Source

Supercritical Fluid Technology has Untapped Growth Potential

Assumptions (Turbomachinery Eff (85%/87%/90% : MC/RC/T), 5 K Approach T, 5% dp/p losses, Hotel Losses Not In Included, Dry Cooling at 120 F)

$S\text{-}CO_2$ Power Cycle Economic and Environmental Benefits

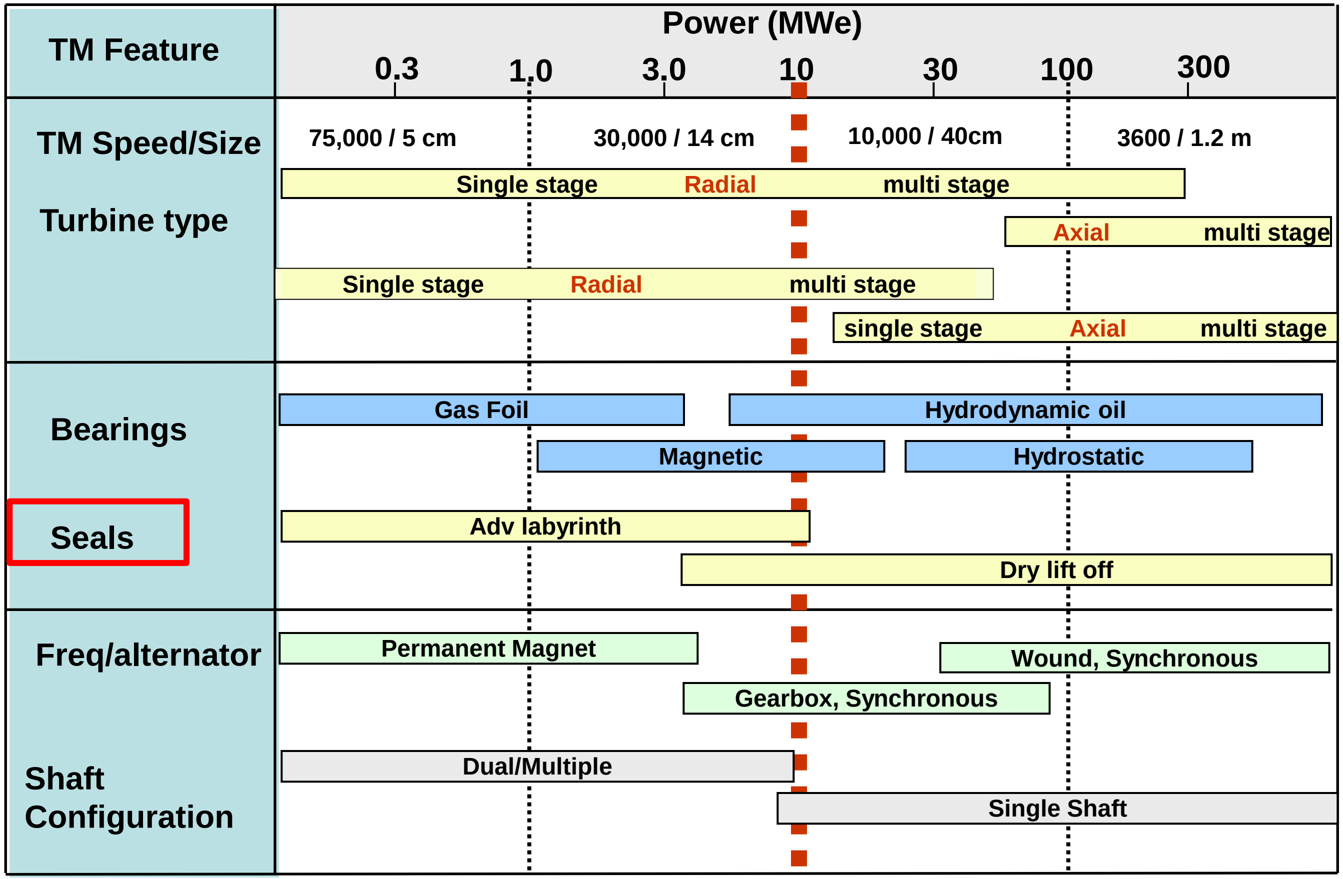
- DOE has invested 5 years and ~ $10-11 M on Proof-of-Principle $S\text{-}CO_2$ Power Systems
- The Potential Economic and Environmental Benefits of $S\text{-}CO_2$ Power Systems are Large
  - Useful with All Heat Sources
  - Wide number of Applications (Bottoming Cycles, Solar , Waste Heate, Marine, Nuclear..)
  - Economic Benefits Mean 100's of Billions of Dollars
  - Environmental Benefits are also Large
    - Increased Efficiency
    - Significant Efficiency improvements for Carbon Capture and Sequestration with Advanced Coal Combustion
    - Dry Cooling is possible for all heat sources
- Development is Still Needed (especially at larger scales)
  - Heat Source and Power Cycle are Linked (Cycle/Design Research)
  - Heat Exchanger Development is Needed
    - Micro-Channel Design Costs, Nuclear Certification, Packaging, Failure Modes, Cost Reductions
  - Commercial Engineering and Demonstration is Needed using Industrial Hardware (~10 MW_e)

Potential Markets

- Pulverized Coal Steam Plant Replacement Efficiency upgrade Efficiency to >50%
  - X100's of plants refurbished
- PC with CCS Demo System
- Solar Power Towers
  - Renewable Portfolio Standard
  - 6 Plants planned (50-100 MW_e each)
- Solar Troughs (Needs cycle optimized for 400 C)
- Integrated Bio-Fuel/SCO_2 Plant (Carbon Reduction Requirements)
- Military Applications (Fixed Base and Marine)
- Commercial Marine (Gas Fired Turbines)
- Geo-Thermal Wells
- Waste Heat Applications
  - Gas Turbine Bottoming Cycle
  - Supercritical Water Oxidation
- Nuclear Reactors
  - (LWR, SFR, GCR, Molten Salt Reactors)

Scaling Study

Scaling Rules and Ranges of Application for Key Brayton Cycle Turbomachinery Components

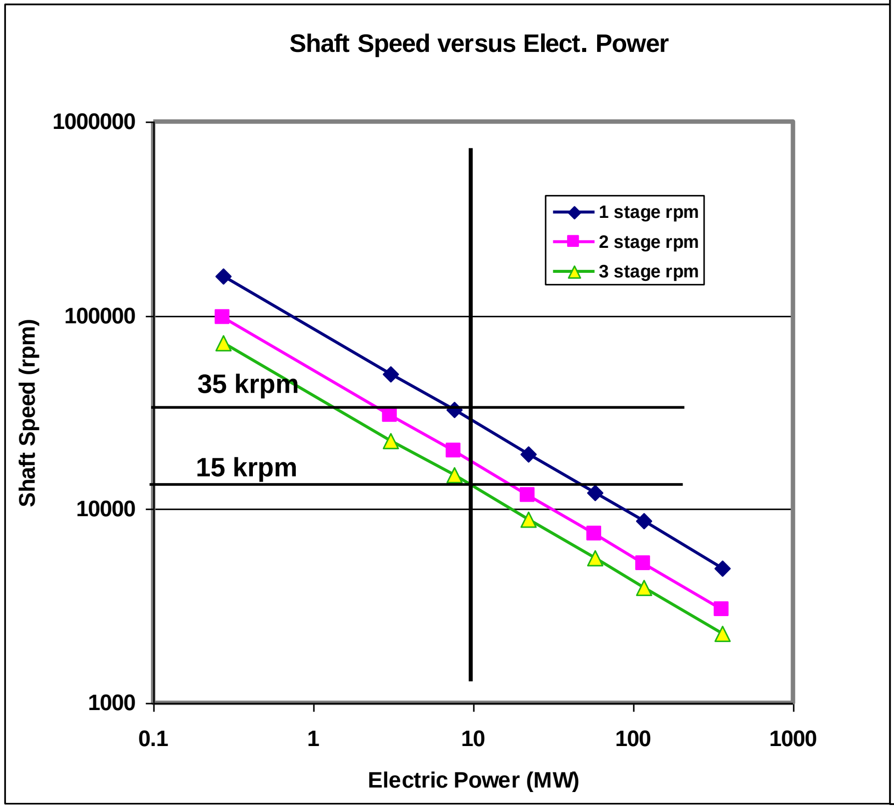


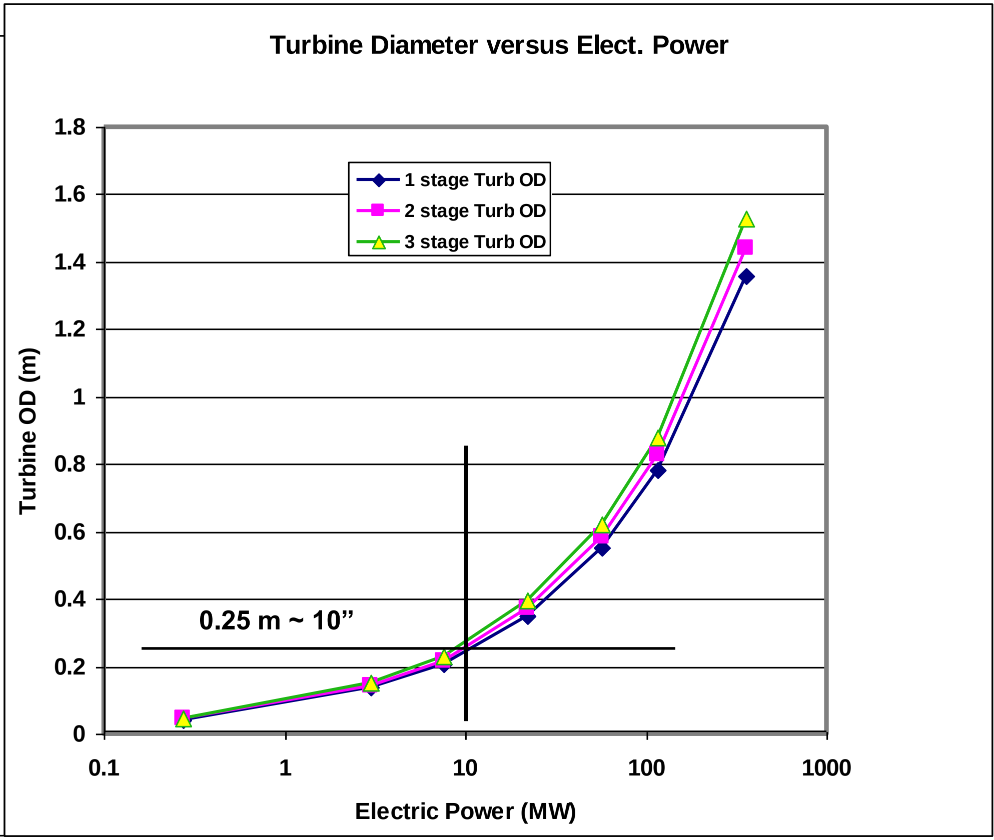
High Technology
High $/kWe

Commercial Technology
Lower $/kWe

- 10 MWe allows use of Commercial Technologies

Approximate Shaft Speed and Turbine Wheel Diameter

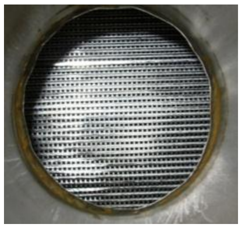




Printed Circuit Heat Exchanger Scaling Rules

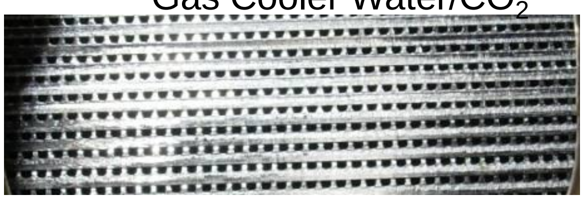
	Actual			Specific Costs	
Cost	kW	lb	lb/kW	$/lb	$/kW$_{th}$
60000	510	492	0.96	122	118
106000	1600	551	0.34	192	66
210000	2300	1410	0.61	149	91
Average			0.64	154	92

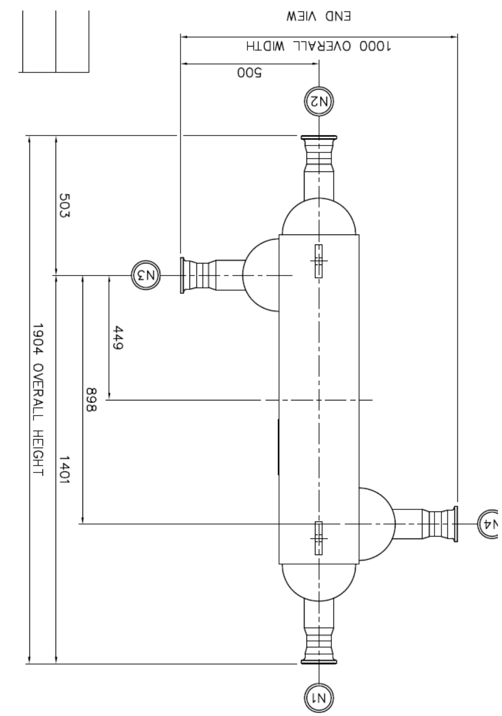
= $ 600/kW$_e$



Gas Cooler Water/CO_2

LT Recup





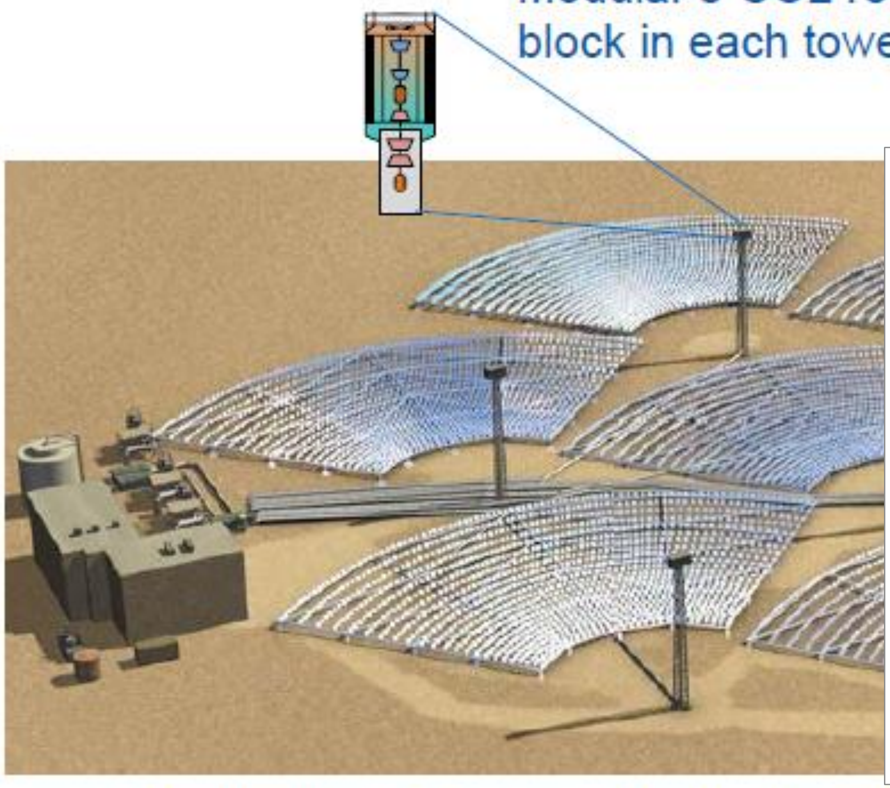
Need 50% reduction (Materials, Scale, & Advanced Manuf.) to reach 200$/ kWe

Concentrated Solar Applications

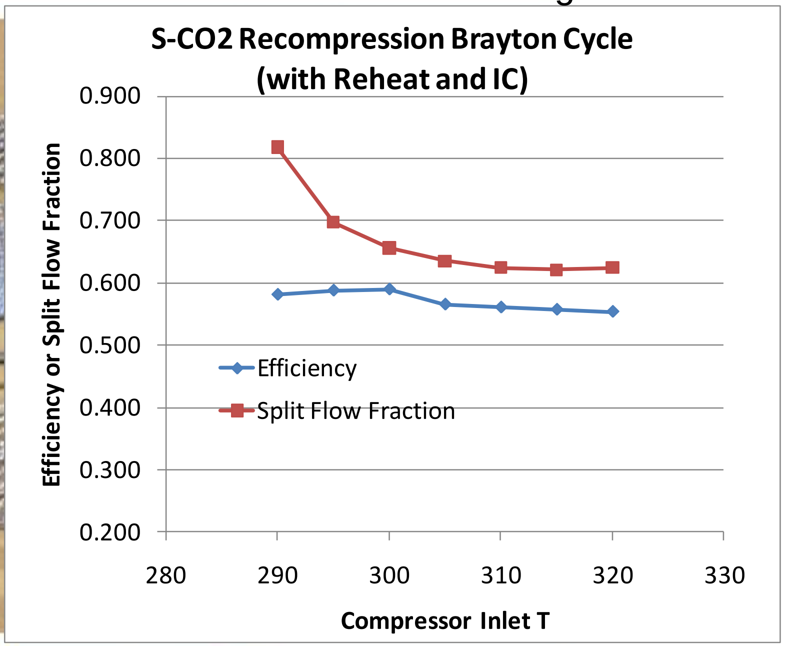
Small or Big ?

1-10 MWe or 100 MWe

Modular s-CO2 receiver / power block in each tower…



Advanced S-CO_2 Power System
Reheat and Inter-Cooling   TIT=700C



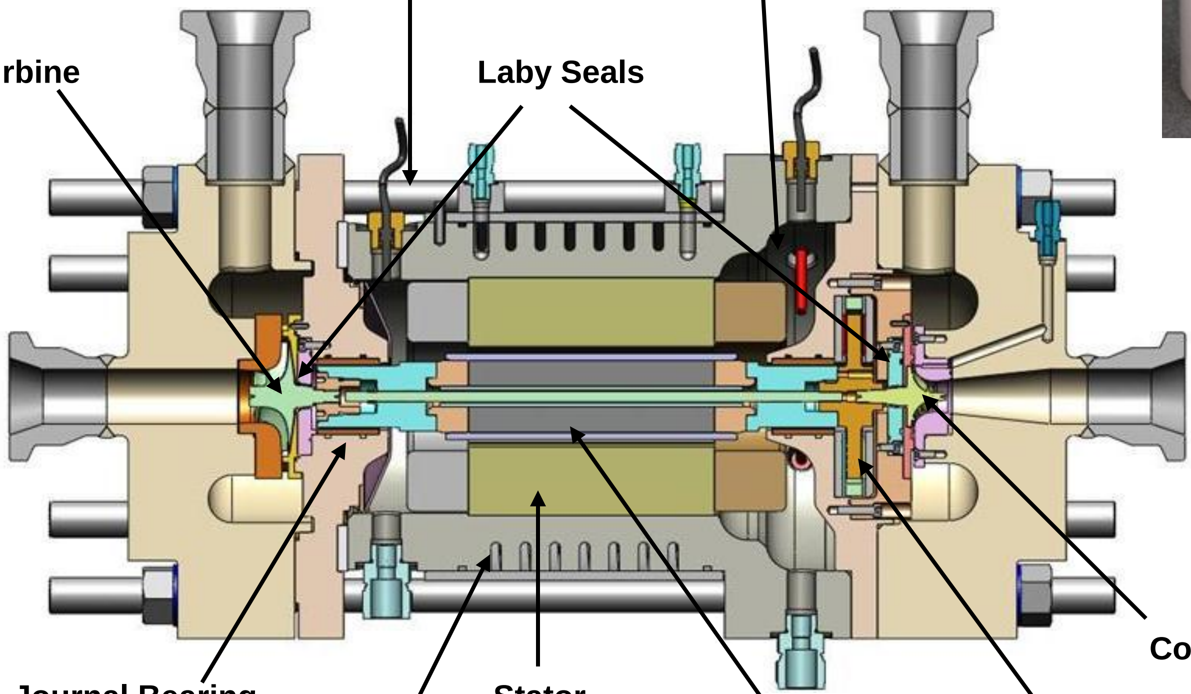
or centralized s-CO2 power block with salt receivers?

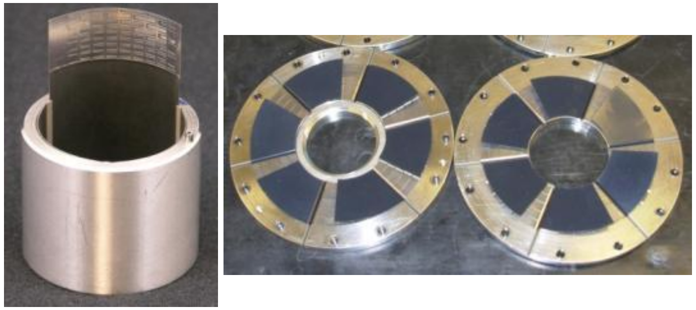
DOE Supercritical CO_2 Program Description

- **DOE Gen-IV S-CO_2 Research Program**
  - **Testing**
    - **Brayton and Compression Loop Descriptions**
    - Compressor Performance Mapping
    - **Power Generation in Simple Heated Brayton Cycle**
    - Mixtures
    - Condensation Cycles
    - Thrust Bearing Heating
    - Sealing Technology
  - Modeling
  - Ability of Sandia S-CO_2 Brayton Loop to Reproduce Other Cycles
  - **Summary and Conclusions**

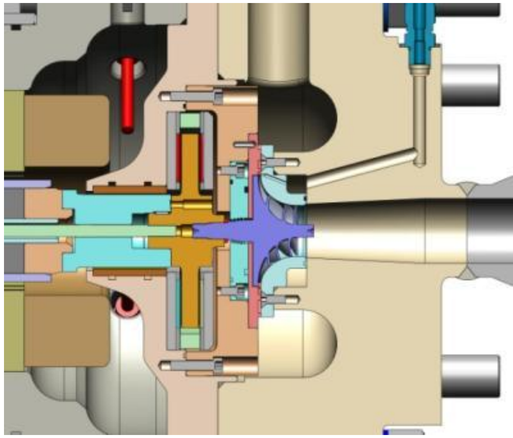
Key Technology

Turbo- Alternator Compressor Design
Permanent Magnet Generator with Gas Foil Bearings
~24” Long by 12” diameter



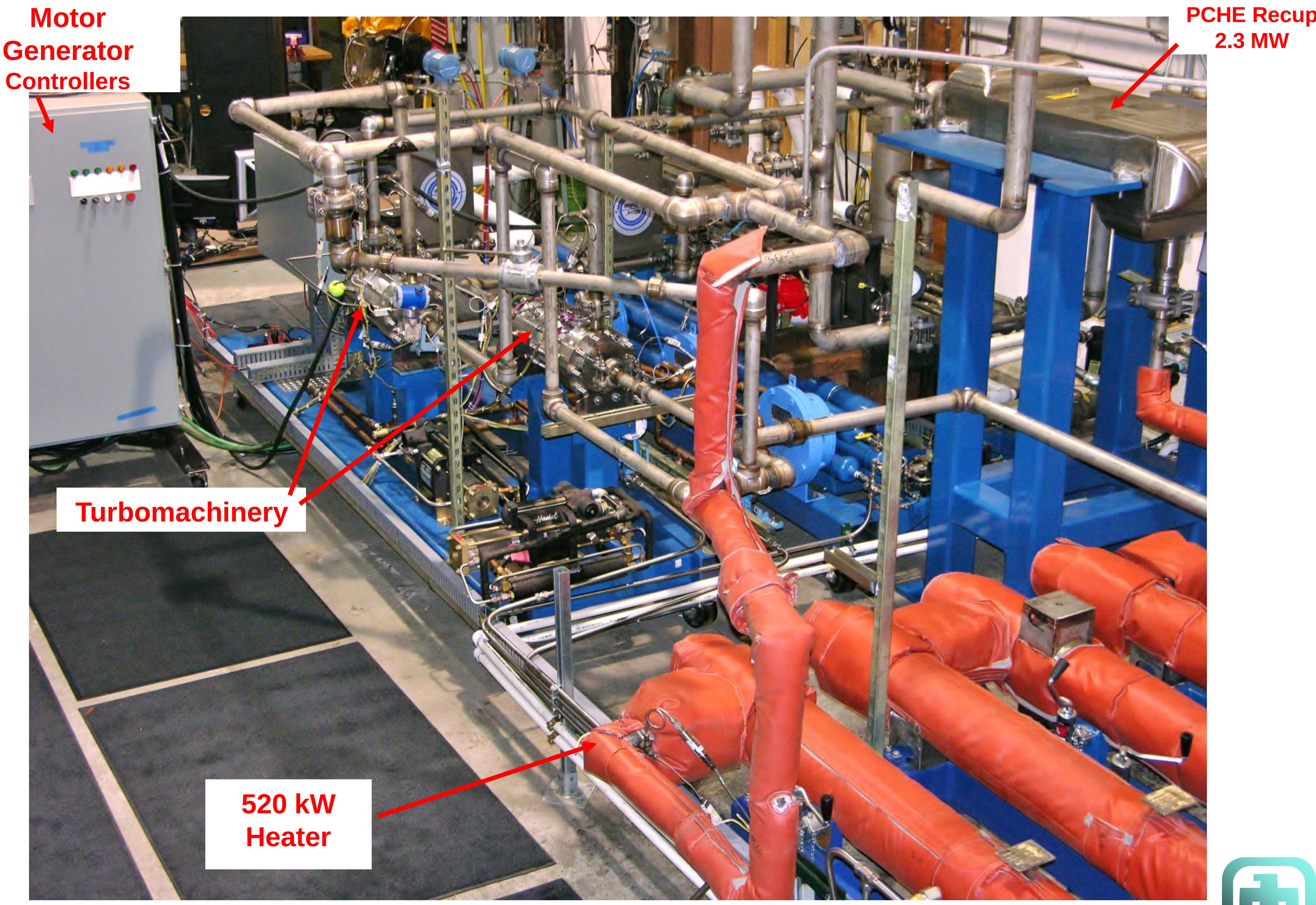


Gas-Foil Bearings

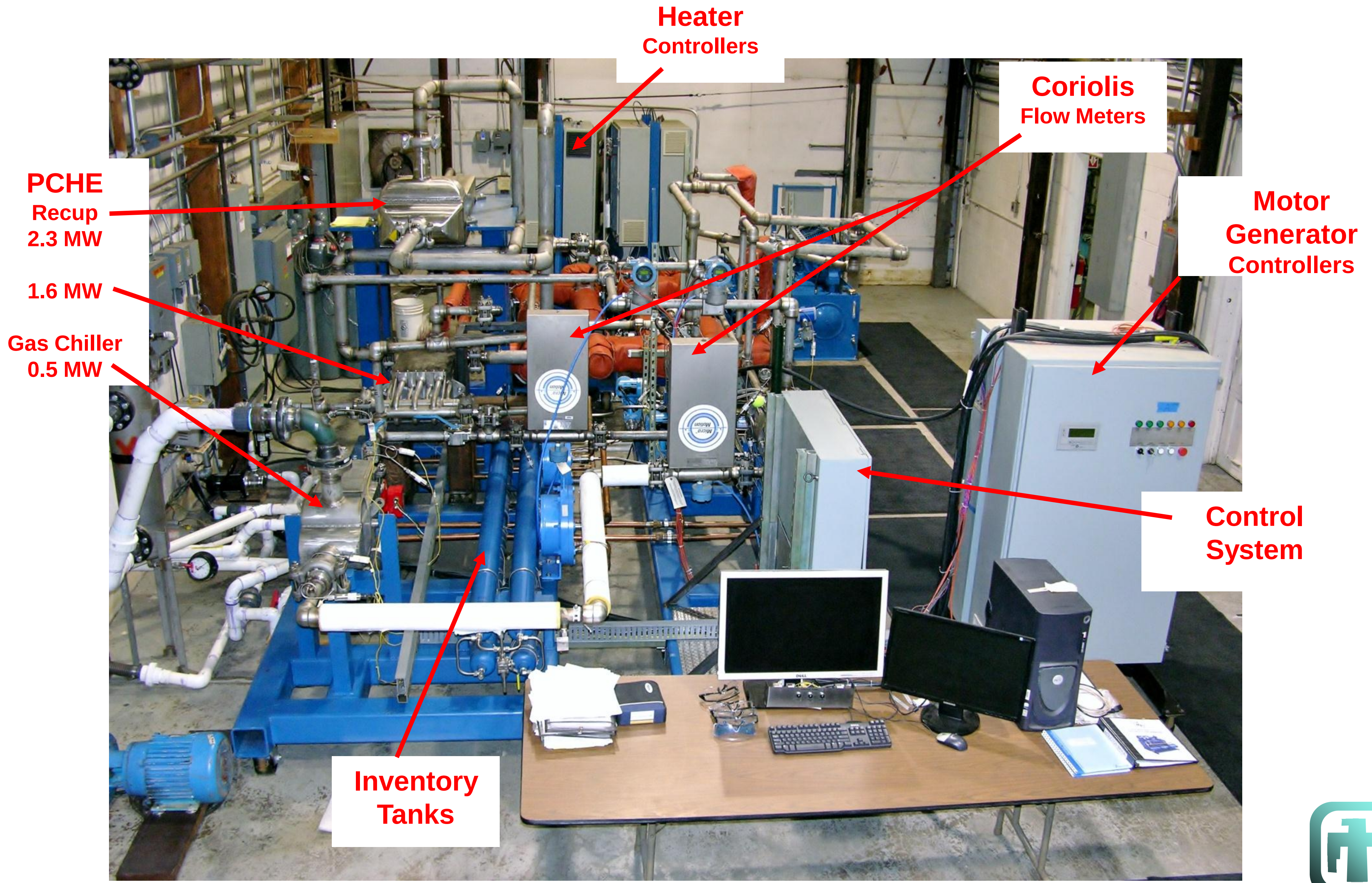


125 kWe at 75,000 rpm

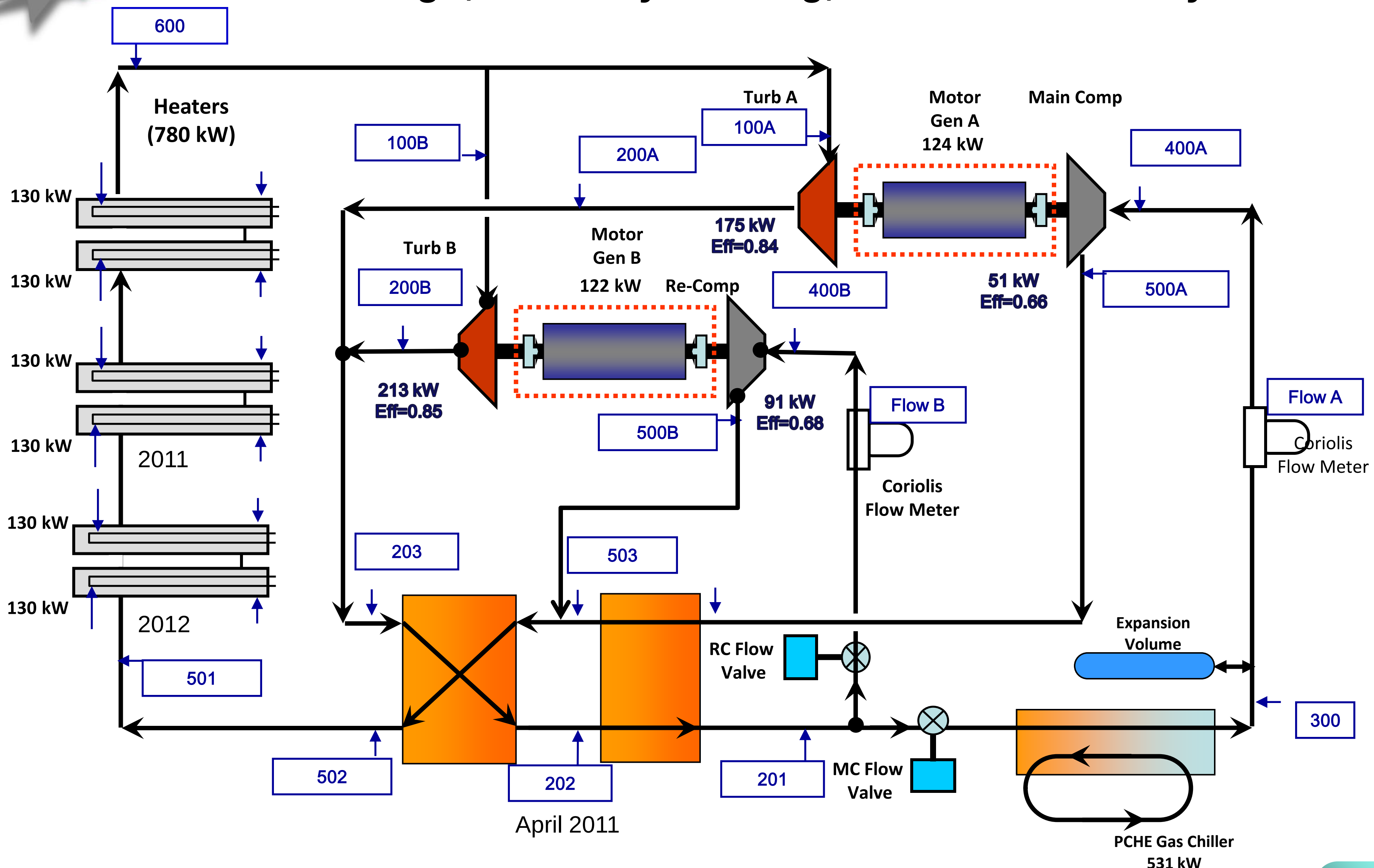
GenIV-Supercritcal CO_2 Brayton Cycle Loop



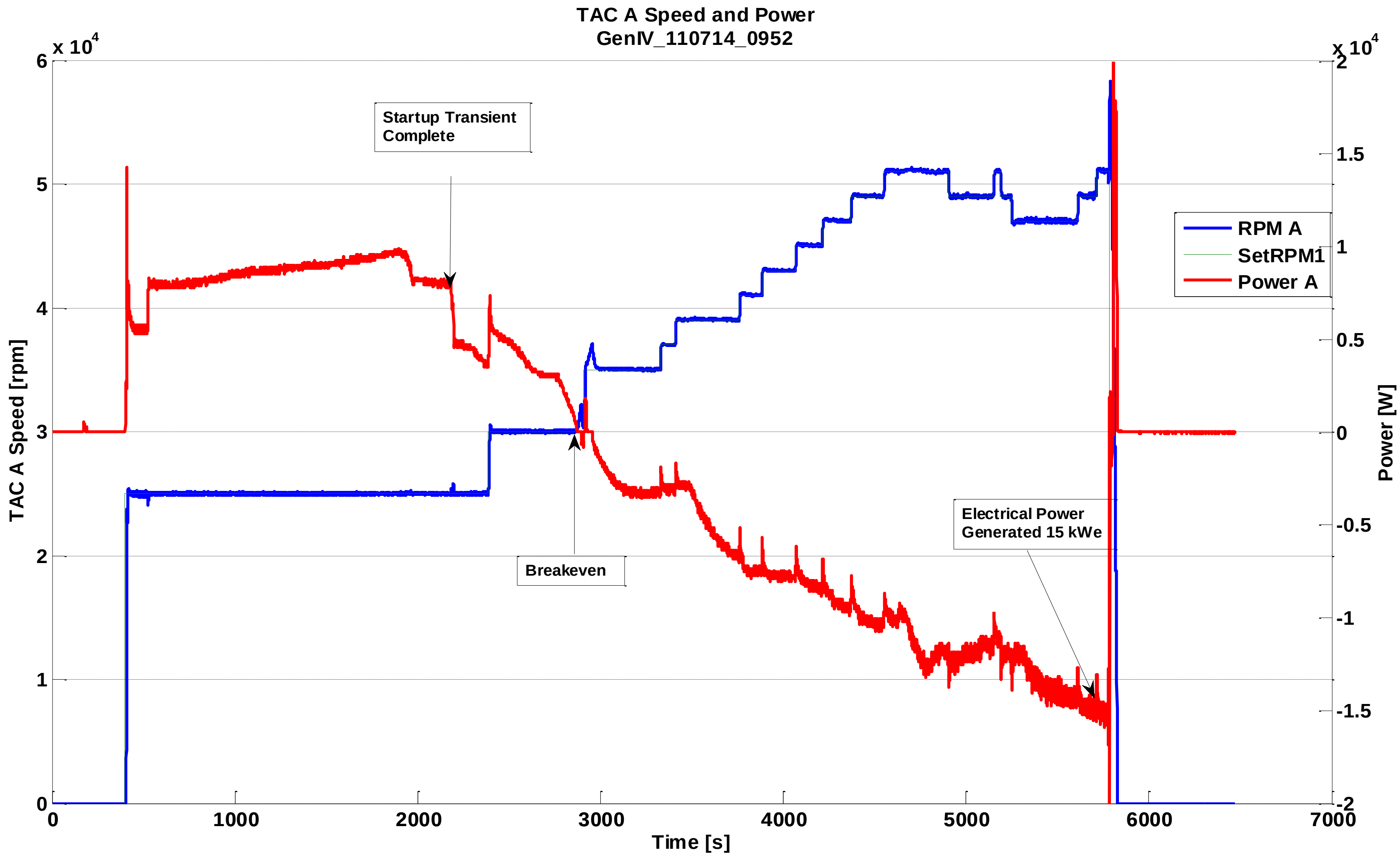
Supercritical S-CO_2 Brayton Cycle DOE-Gen IV



Supercritical CO_2 Brayton Loop
Final Design, Currently Existing, and Alternative Layouts

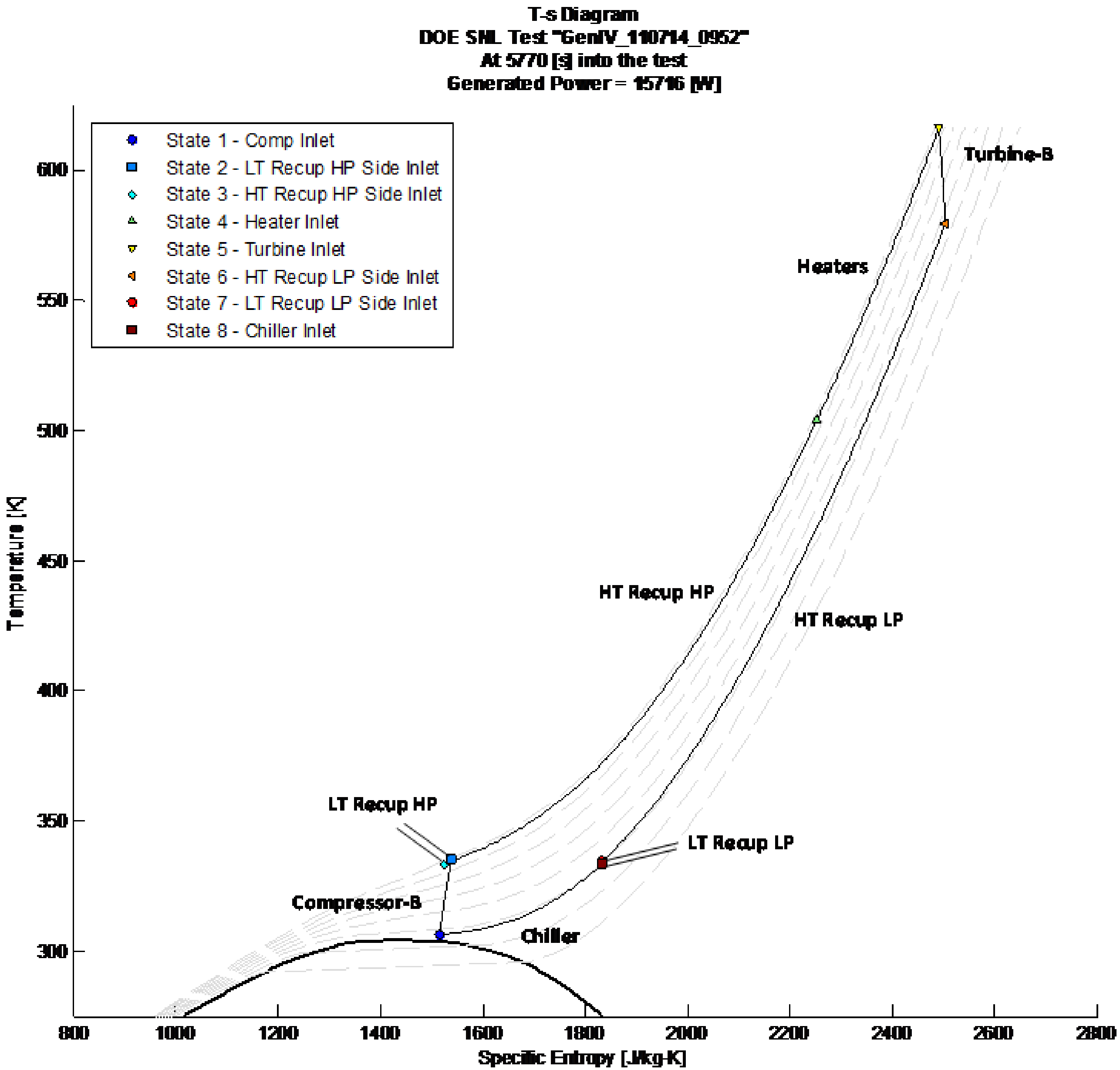


Power Generation in Upgraded S-CO2 Simple Heated Recuperated Brayton Loop



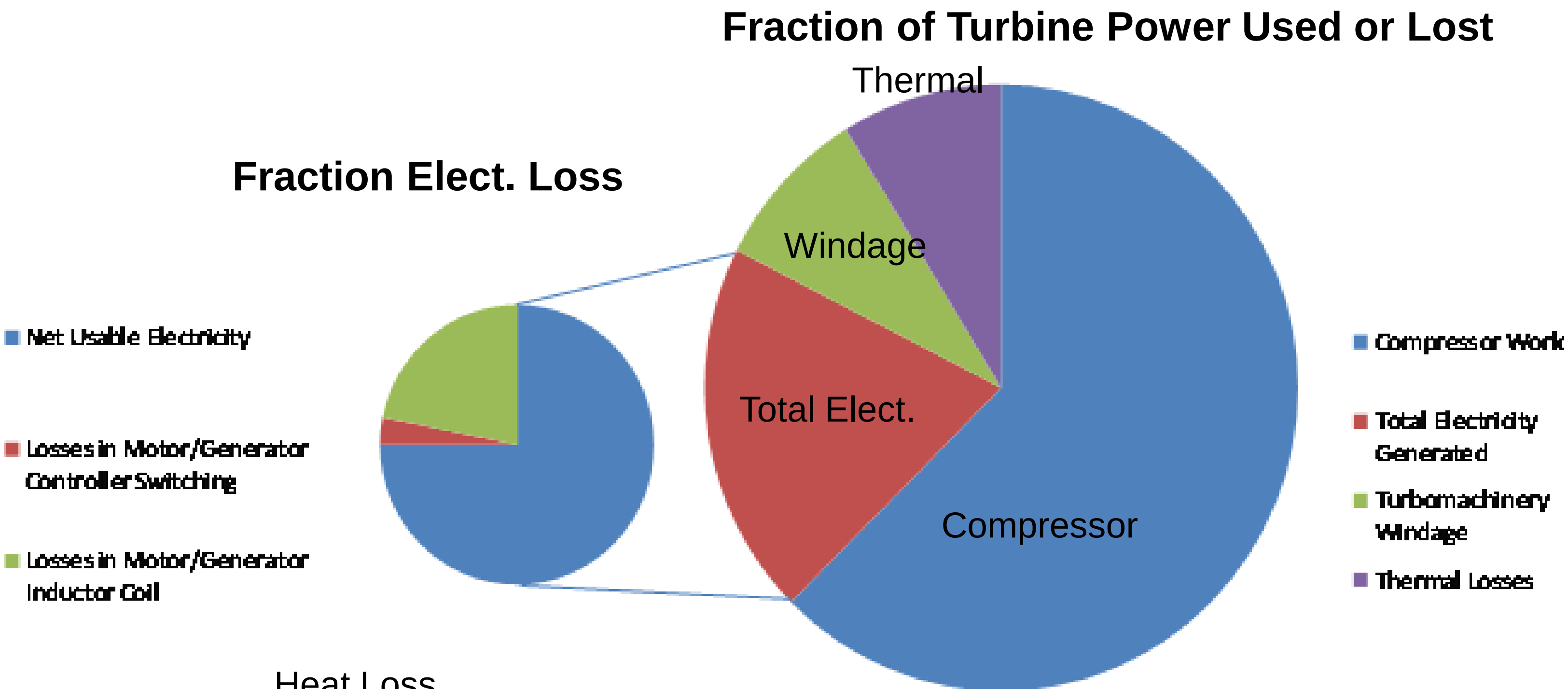
Measured T-S Diagram

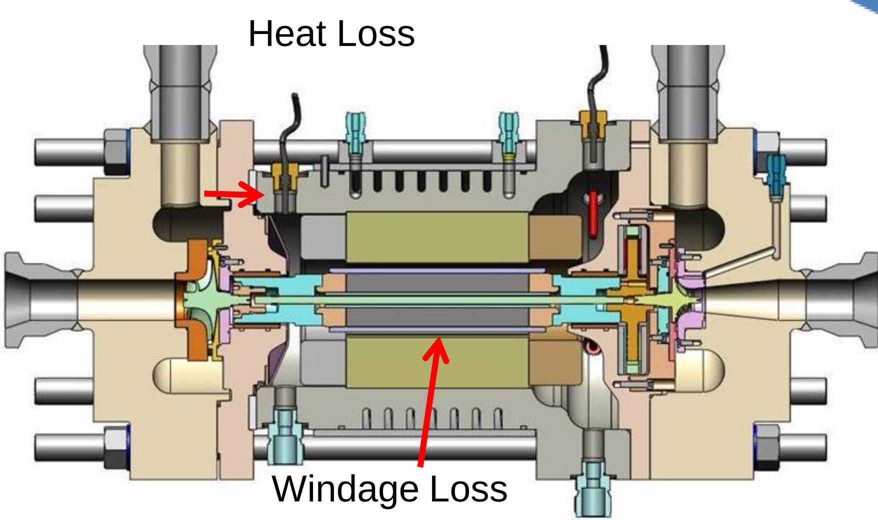
GenIV_110714_0952



Loss Measurements

C-2 Compressor T-2 Turbine





S-$CO_{2:}$ Summary and Conclusions

Potential for S-CO_2 Power Conversion Systems to Improve Economics and Environmental Issues on a Large Scale

1) *Dry Cooling*
2) *CCS*
3) *Improved Efficiency*

For All Types of Heat Sources

Sandia Research Program Summary

- Sandia/DOE have two operating S-CO_2 test loops
  - Research Compression Loop
  - Reconfigurable Brayton Loop
- Measured Main Compressor Flow Maps
  - Overall Good Agreement with Mean-Line Predictions of the Performance Maps
  - Over a wide range of operating Temperature, pressure, and density
- Using Brayton loop Configuration available in FY2010
    - Heater power was limited to 520/390 kW
    - Produced Power in simple heated recuperated Brayton loops (Main TAC and Re-Comp TAC)
    - Cold Startup, Breakeven, Power Production (6% efficiency and 20 kWe), Power/RPM Operation Maps
- Condensation in Tube and Shell and PCHE heat exchangers
  - Improved Efficiency
- Test (critical point) were performed with mixtures of CO_2, CO_2-Neon, CO_2 SF_6, CO_2-Butane
  - Can Increase or decrease T_{crit}
  - Improved Efficiency (especially for low temperature applications)
- Thrust Gas Foil Bearing Tests and Modeling
  - Goal : higher thrust load capability and lower frictional power
- Natural Circulation
  - S-CO_2 Gas Fast Reactor
  - C3D CFD Model development
- Collaborations with Industry + Larger Scale System Development

Path Forward

- **Path Forward**
  - **Continue Testing of Proof-of-Principle Small Loop**
  - **Work/Collaborate with industry to develop S-CO_2 System for any heat source at the 10 MW_e sized system**
  - **Propose for First Nuclear Applications**
    - **Use with LWRs**
    - **Wet and Dry Cooling**
    - **37% and 30% Efficiencies**
    - **Develop S-CO2 Systems for Nuclear Technology**
- **Begin Seeking Gov. Funded 10 MWe S-CO2 power system development to support FE, EERE, NE, others**
  - **Useful for all heat sources (Nuclear, Solar, Fossil, Geothermal)**
  - **Numerous early non-nuclear Products (Marine, Fossil, Solar, Geo, Waste Heat, Heat Storage and Transport)**
  - **Improved the economic and environmental benefits for all systems**
  - **Dry Cooling is Possible**
    - **Required for some heat sources**
    - **Power Cycle modifications are required**