

SUPERCRITICAL CO₂ POWER CYCLE DEVELOPMENT SUMMARY AT SANDIA NATIONAL LABORATORIES

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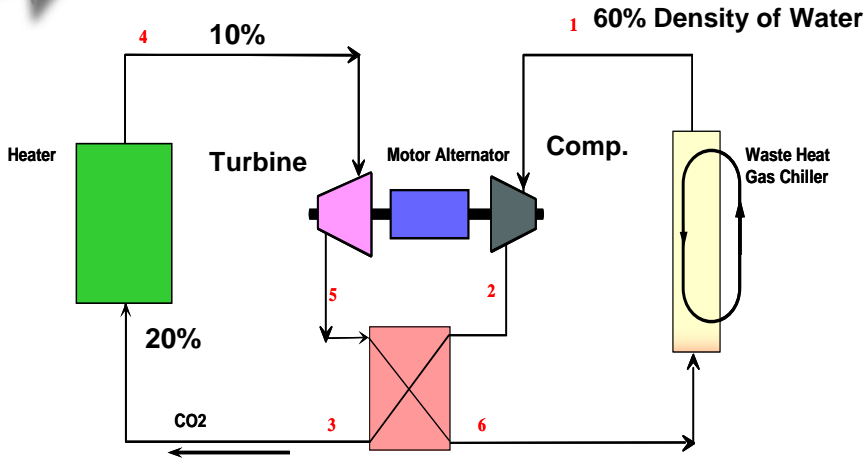


Goals of Presentation

- ***What is a Supercritical CO₂ Brayton Cycle?***
- **Economic and Environmental Benefits of S-CO₂ Power Systems**
 - Economic and Environmental
 - All Heat Sources
- **DOE Gen-IV S-CO₂ Research Program**
- **Scaling Study Results (10 MWe)**
- **10 MWe Development and Demonstration Program Plans and Cost**
- **Status of Development Effort**
 - Commercial and Government
- **Proposed Development Plan/Path for Nuclear Deployment**
 - **Overall Plan, First Steps, Alternative Development**



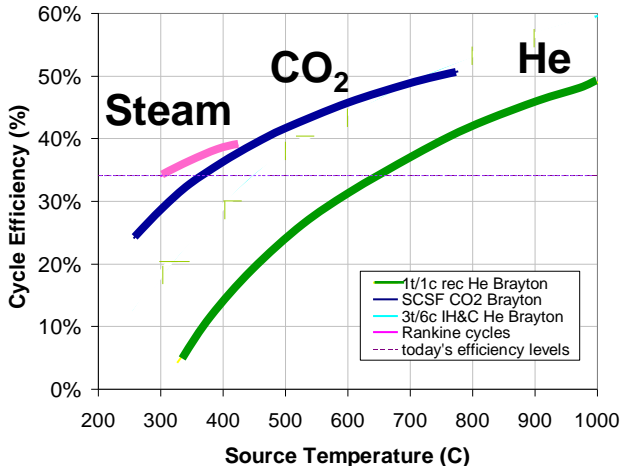
What is a Supercritical CO₂ Brayton Cycle? How does it work?



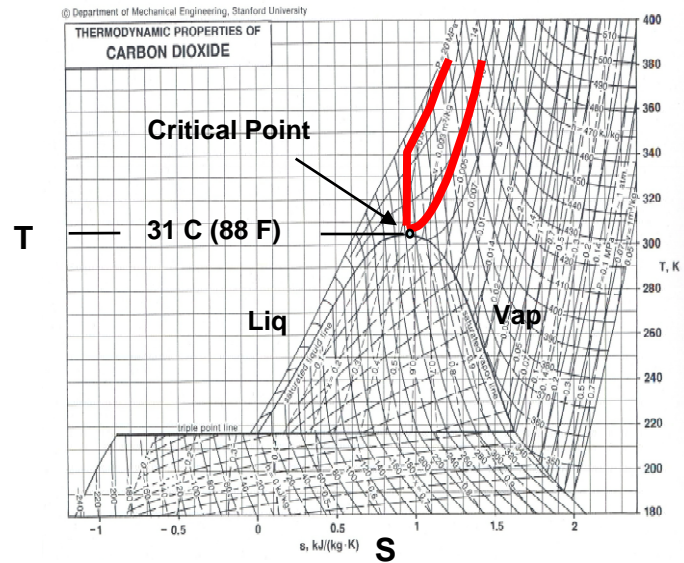
Liquid like Densities with CO₂

Very Small Systems,
High Efficiency due to Low Pumping Power

Cycle Efficiencies vs Source Temperature
for fixed component efficiency

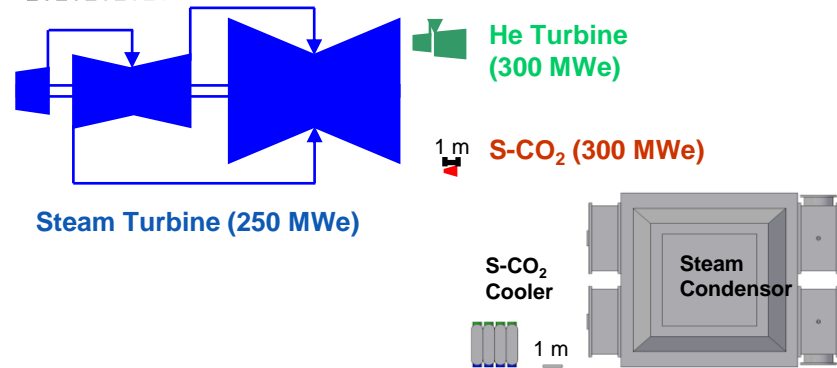


High Efficiency at Lower Temp
(Due to Non-Ideal Gas Props)



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

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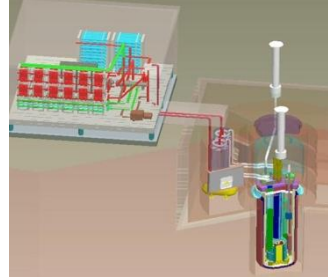
Supercritical CO₂ Cycle Applicable to Most Thermal Heat Sources

Solar



SNL Solar Tower

Military Fix Base & Marine

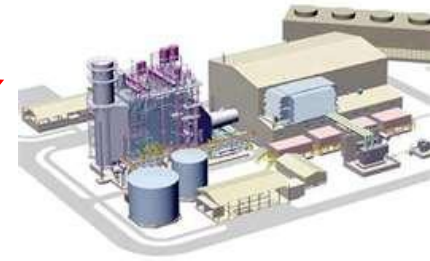
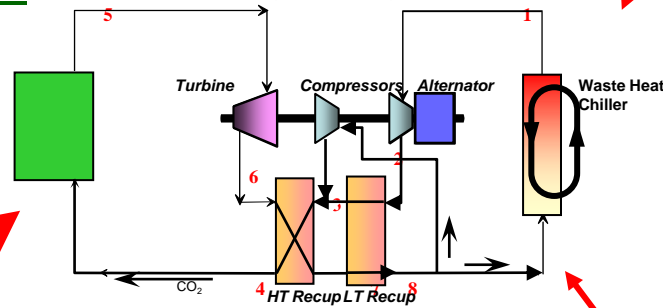


ARRA Geothermal

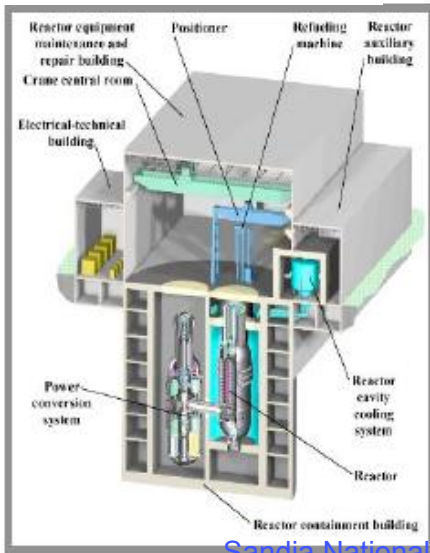


Waste Heat Bottoming Cycle to a Gas Turbine

Supercritical CO₂ Brayton Cycle

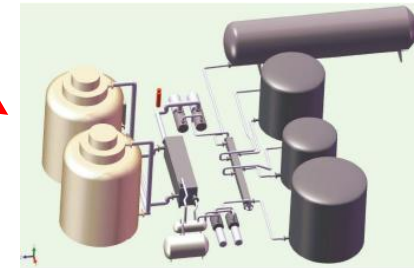


Nuclear (Gas, Sodium, Water)



DOE-NE Gen IV

Carbon Capture & Sequestration
CCS
Fossil



Energy Storage & Heat Transport & CCHE

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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-CO₂



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



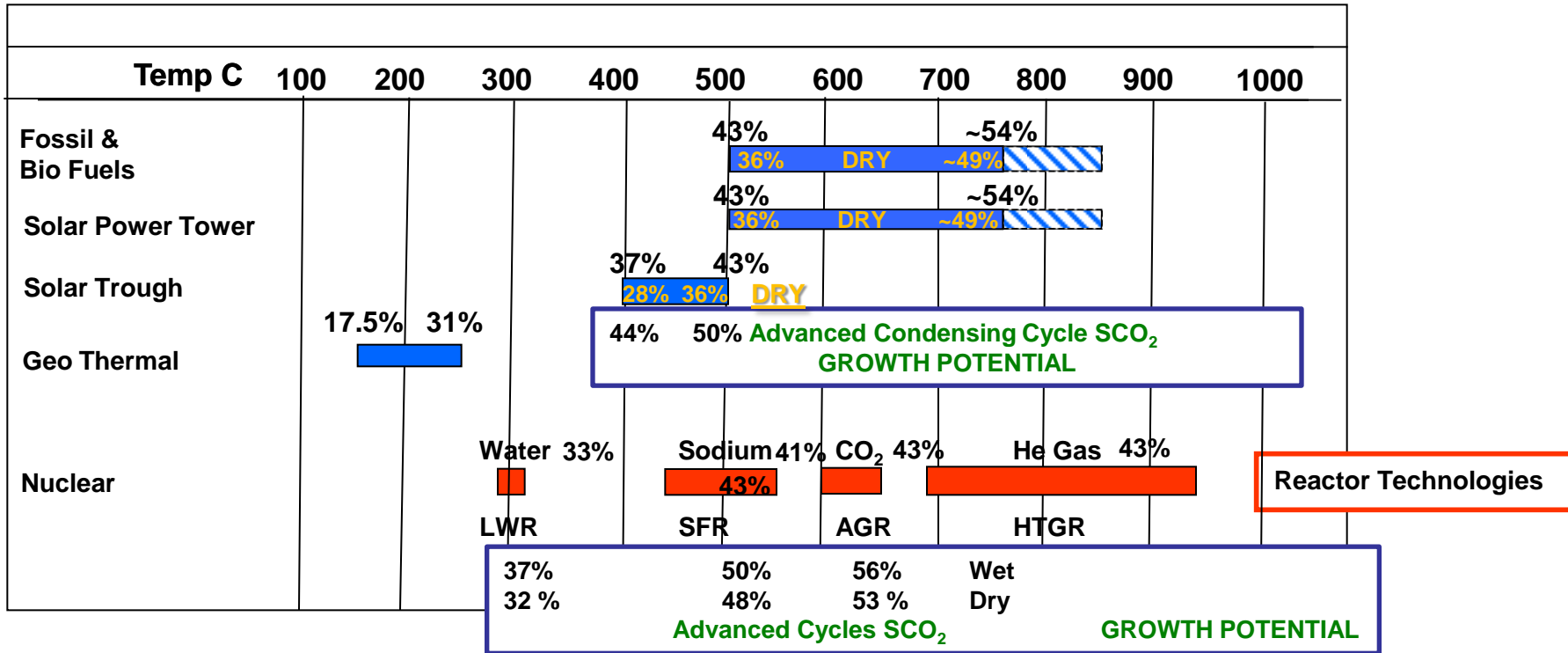
**Modular & Self Contained
Power Conversion Systems
~ 1.5 m x 8 m**

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Advanced
Heat Exchangers
Meggit / Heatric Co.



Heat Source Operating Temperature Range & SCO₂ Power Conversion Efficiency for Various Heat Sources



S-CO₂ 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

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Assumptions (Turbomachinery Eff: 85%, 82%, 90% / SC/CO₂ Cycle Approach: 15% cycle losses, 10% heat losses, 10% in. cooling, 10% out. cooling)

National Nuclear Security Administration under contract DE-AC04-94AL85000.





S-CO₂ Power Cycle Economic and Environmental Benefits

- DOE has invested 5 years and ~ \$10-11 M on **Proof-of-Principle S-CO₂ Power Systems**
- **The Potential Economic and Environmental Benefits of S-CO₂ 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)**

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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/SCO₂ 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)

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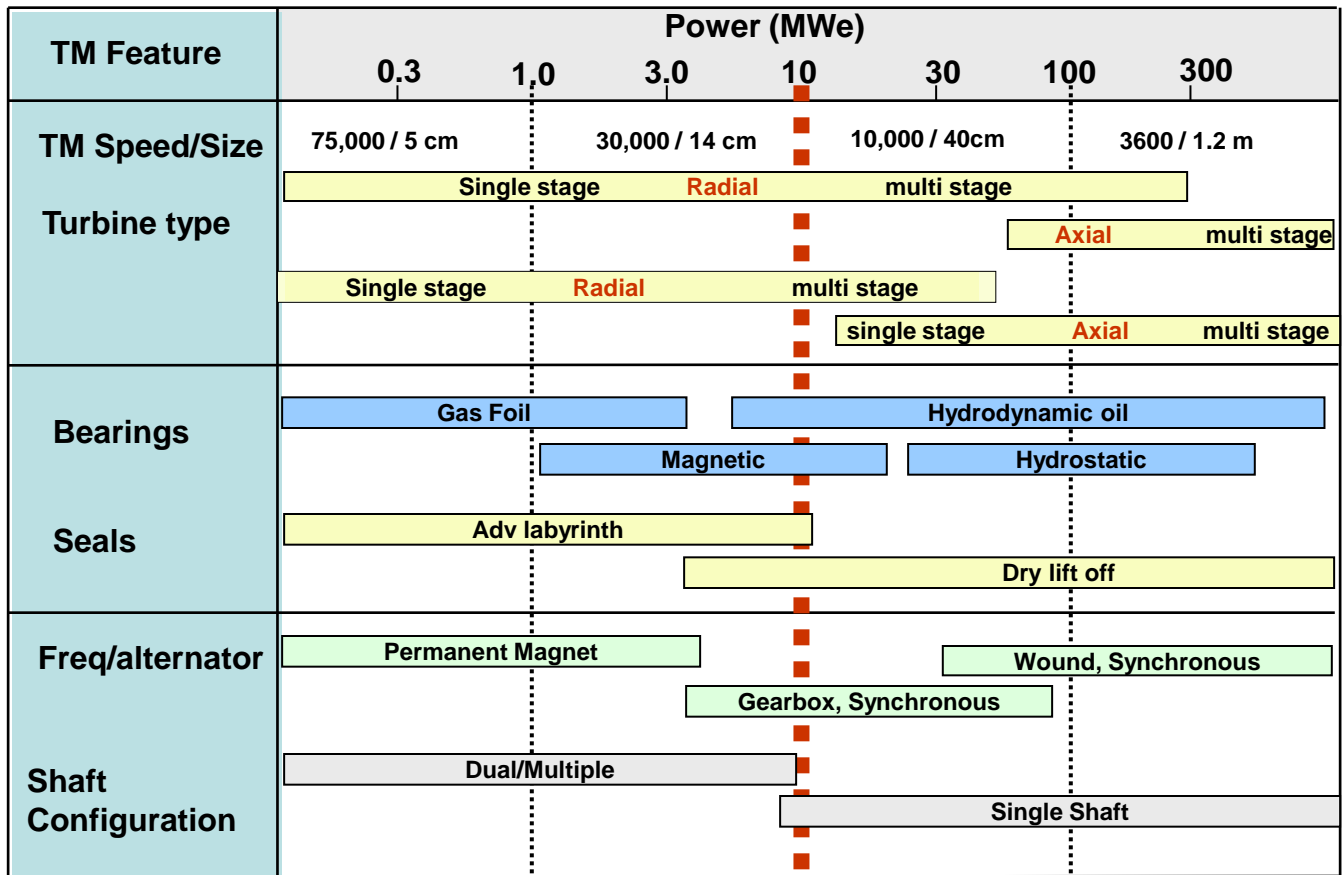




Scaling Study



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



High Technology
High \$/kWe



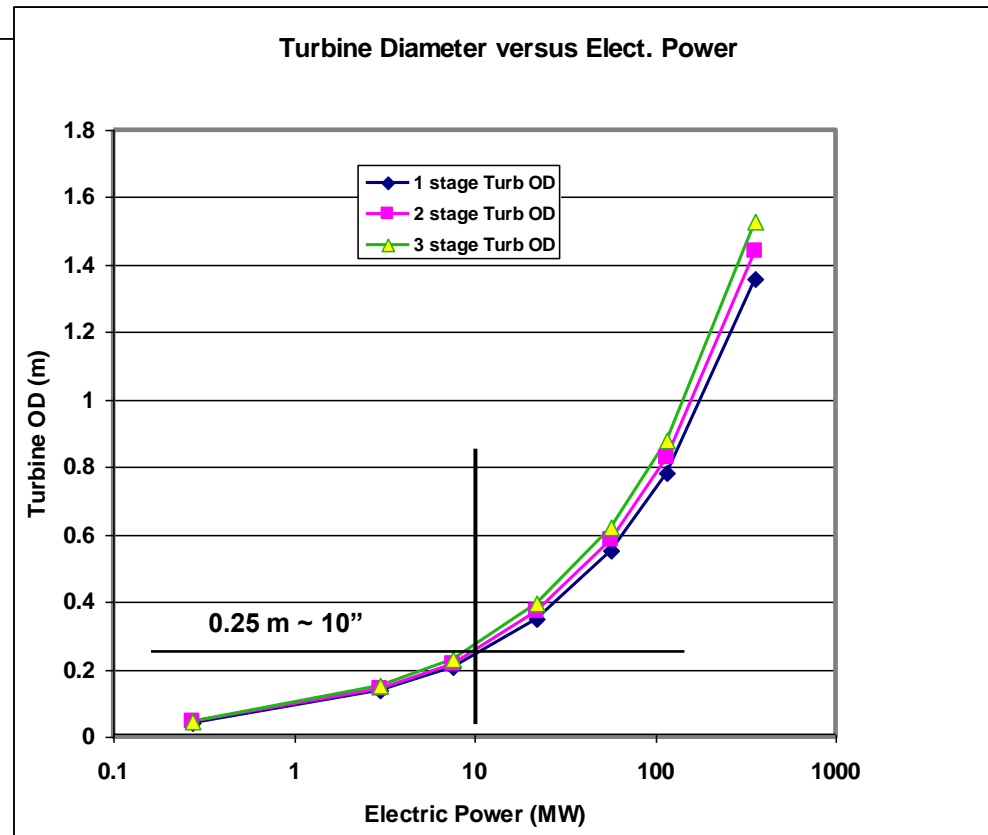
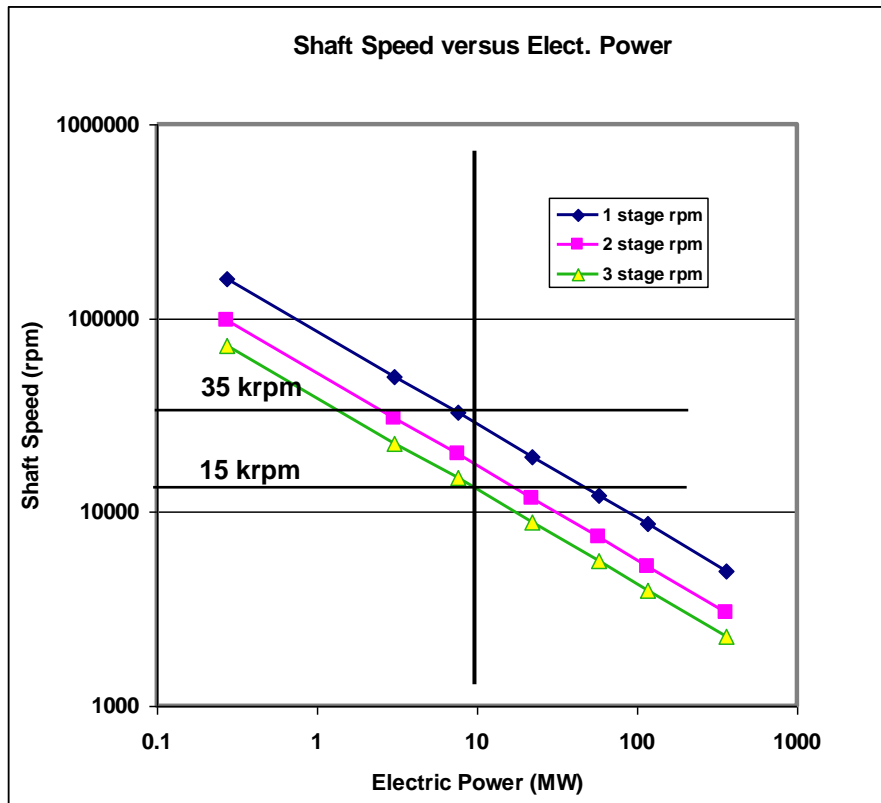
Commercial Technology
Lower \$/kWe

• 10 MWe allows use of Commercial Technologies

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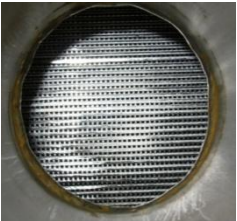
Approximate Shaft Speed and Turbine Wheel Diameter



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

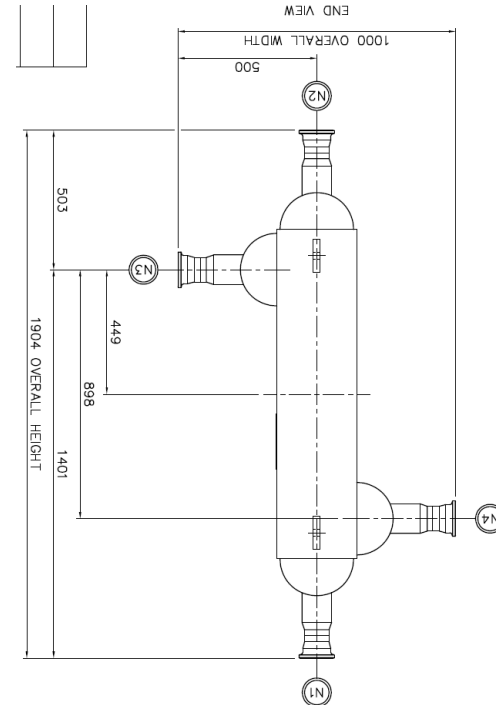
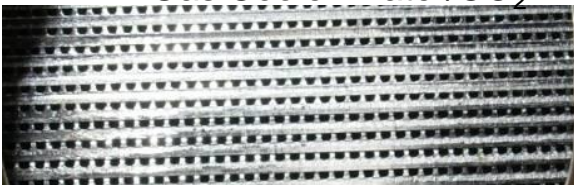
= \$ 600/kW_e



Gas Cooler Water/CO₂



LT Recup



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

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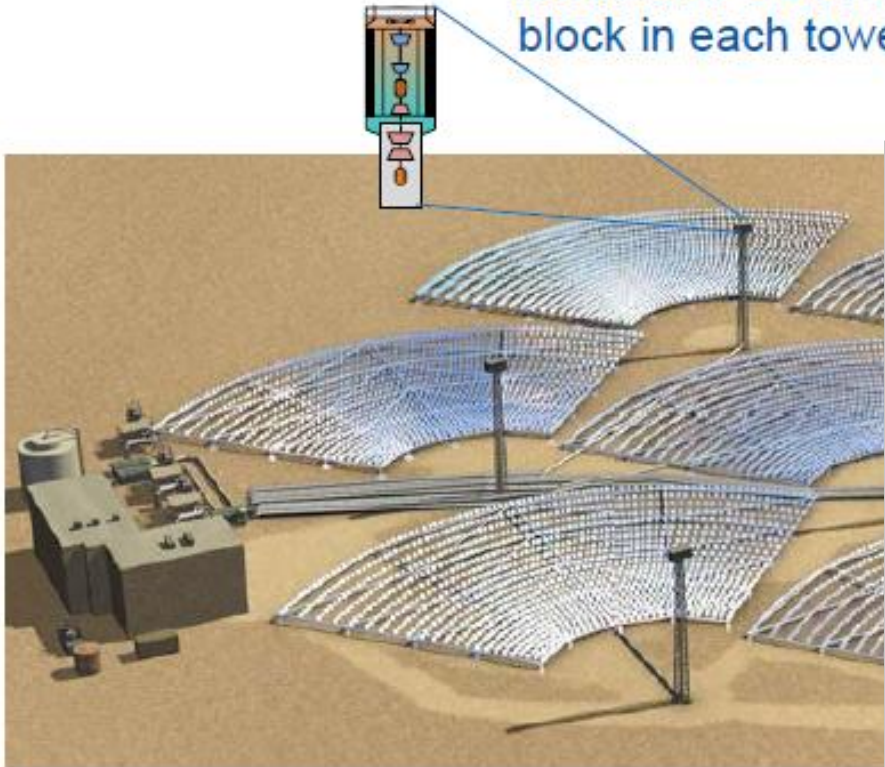


Concentrated Solar Applications

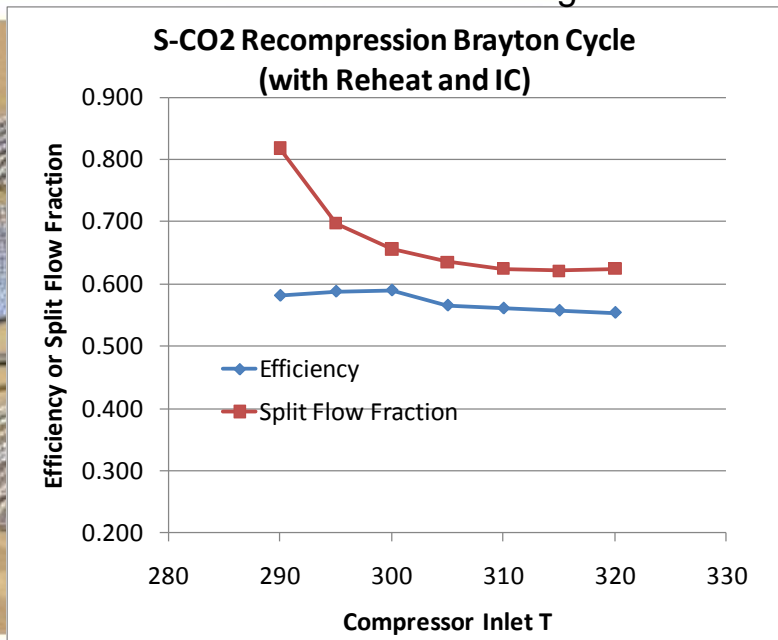
Small or Big ?

1-10 MWe or 100 MWe

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



Advanced S-CO₂ Power System
Reheat and Inter-Cooling TIT=700C



or centralized s-CO₂ power block with salt receivers?






DOE Supercritical CO₂ Program Description

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- 
- **DOE Gen-IV S-CO₂ 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-CO₂ Brayton Loop to Reproduce Other Cycles
 - **Summary and Conclusions**
 - **10 MW_e Development and Demonstration Program Plans and Cost**
 - **Potential for Improved Economics**





Key Technology

Turbo- Alternator Compressor Design

Permanent Magnet Generator with Gas Foil Bearings

~24" Long by 12" diameter

Tie Bolts (Pre-stressed)

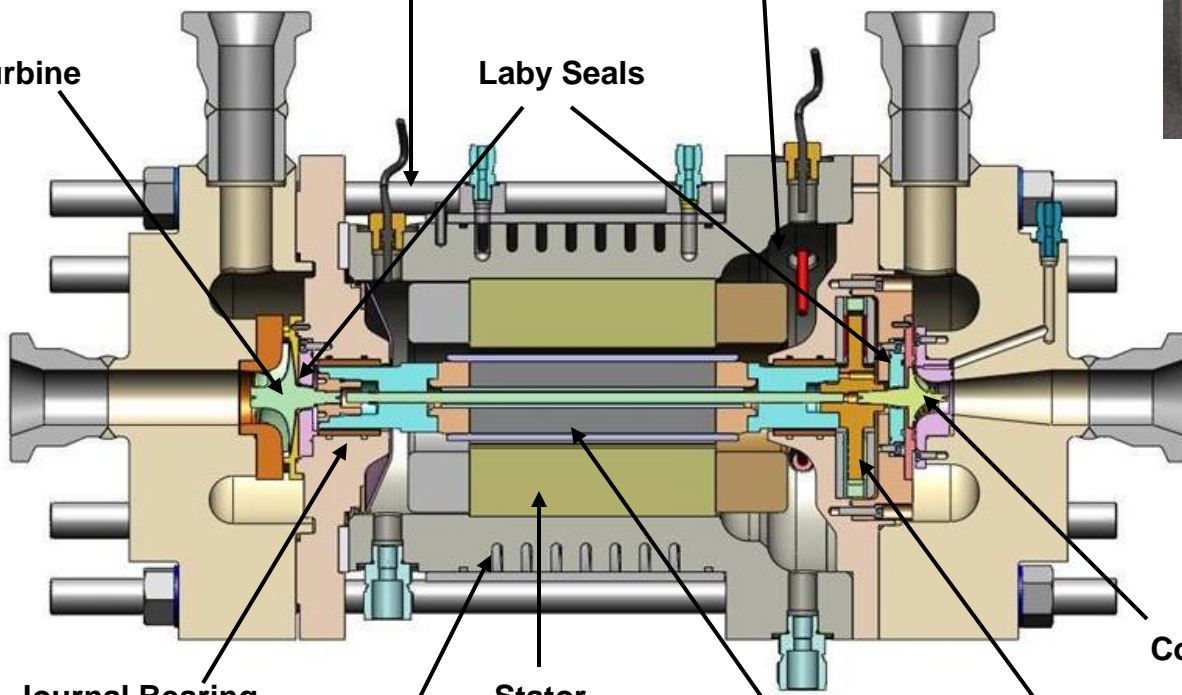
Low Pressure Rotor Cavity Chamber (150 psia)



Gas-Foil Bearings

Turbine

Laby Seals



Compressor

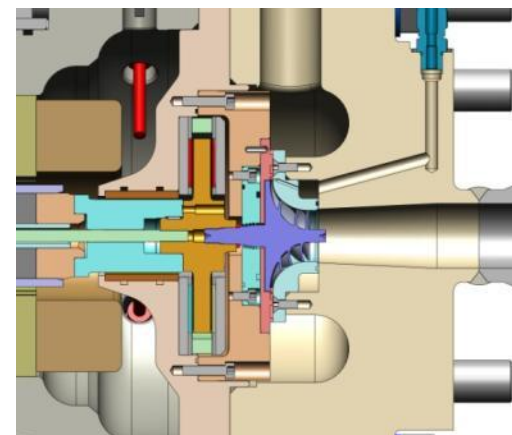
Journal Bearing

Water Cooling

Stator

PM Motor Generator

Thrust Bearing



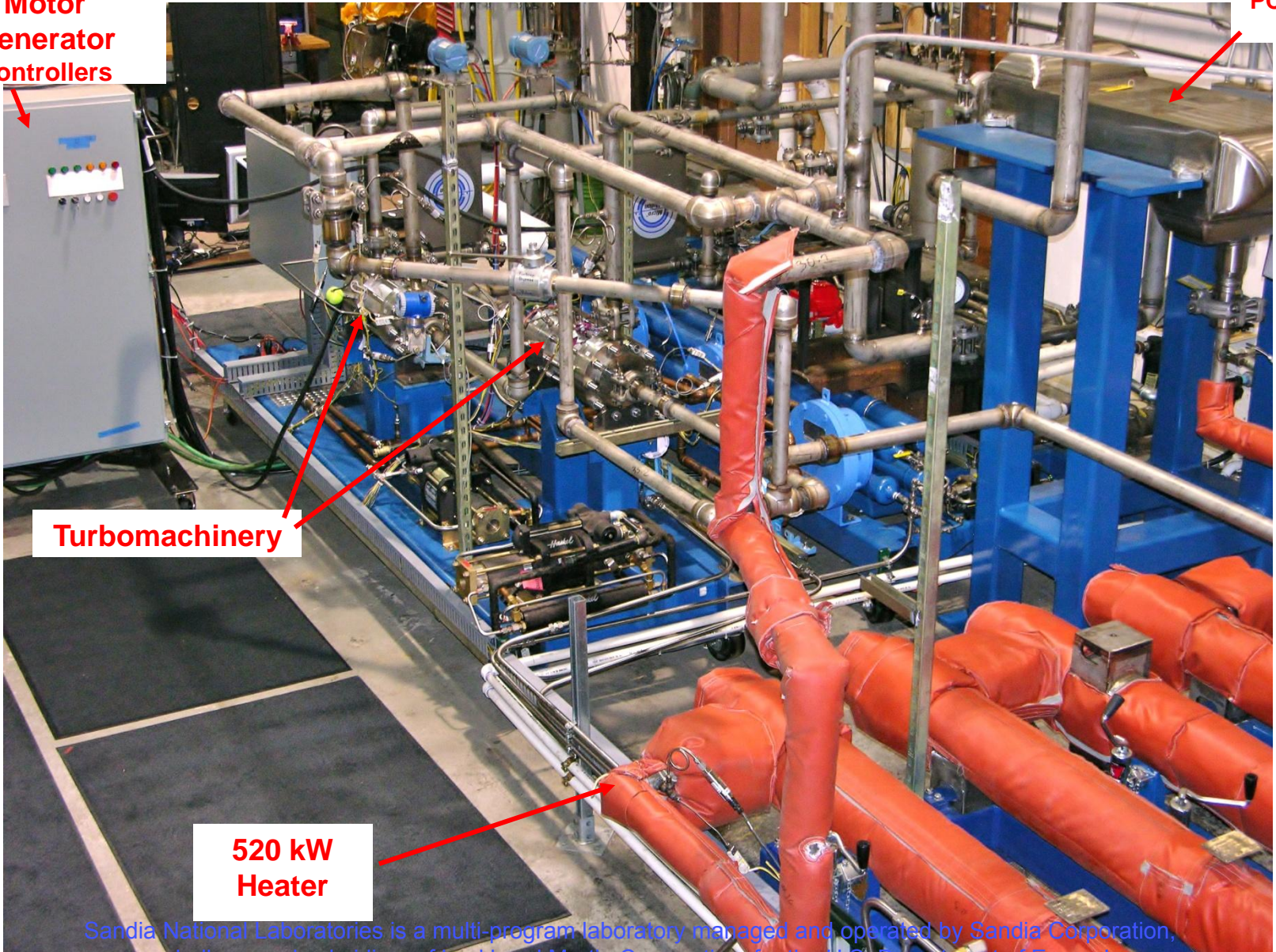
125 kWe at 75,000 rpm
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GenIV-Supercritical CO₂ Brayton Cycle Loop

Motor
Generator
Controllers

PCHE Recup
2.3 MW



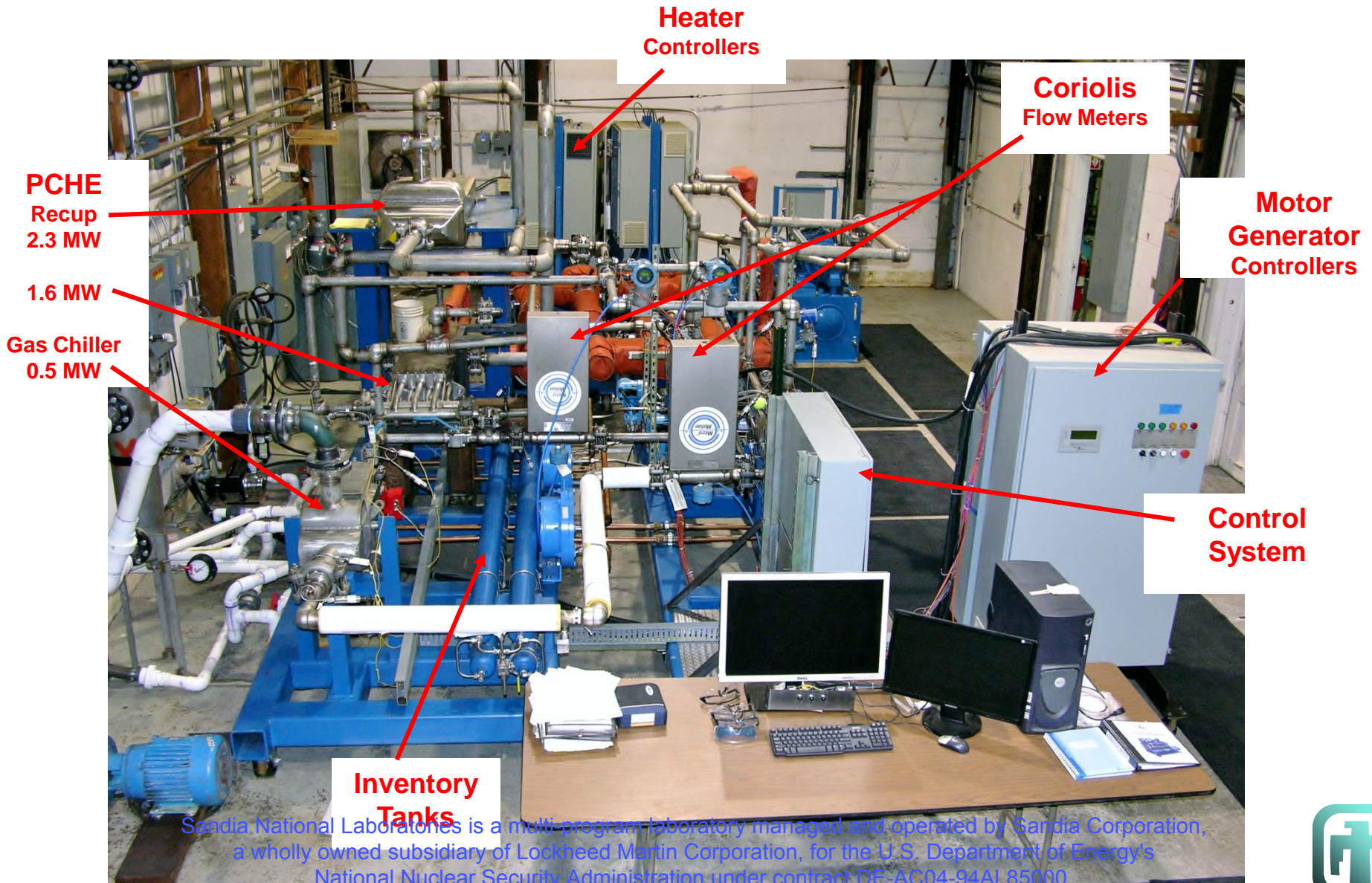
Turbomachinery

520 kW
Heater

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Supercritical S-CO₂ Brayton Cycle DOE-Gen IV

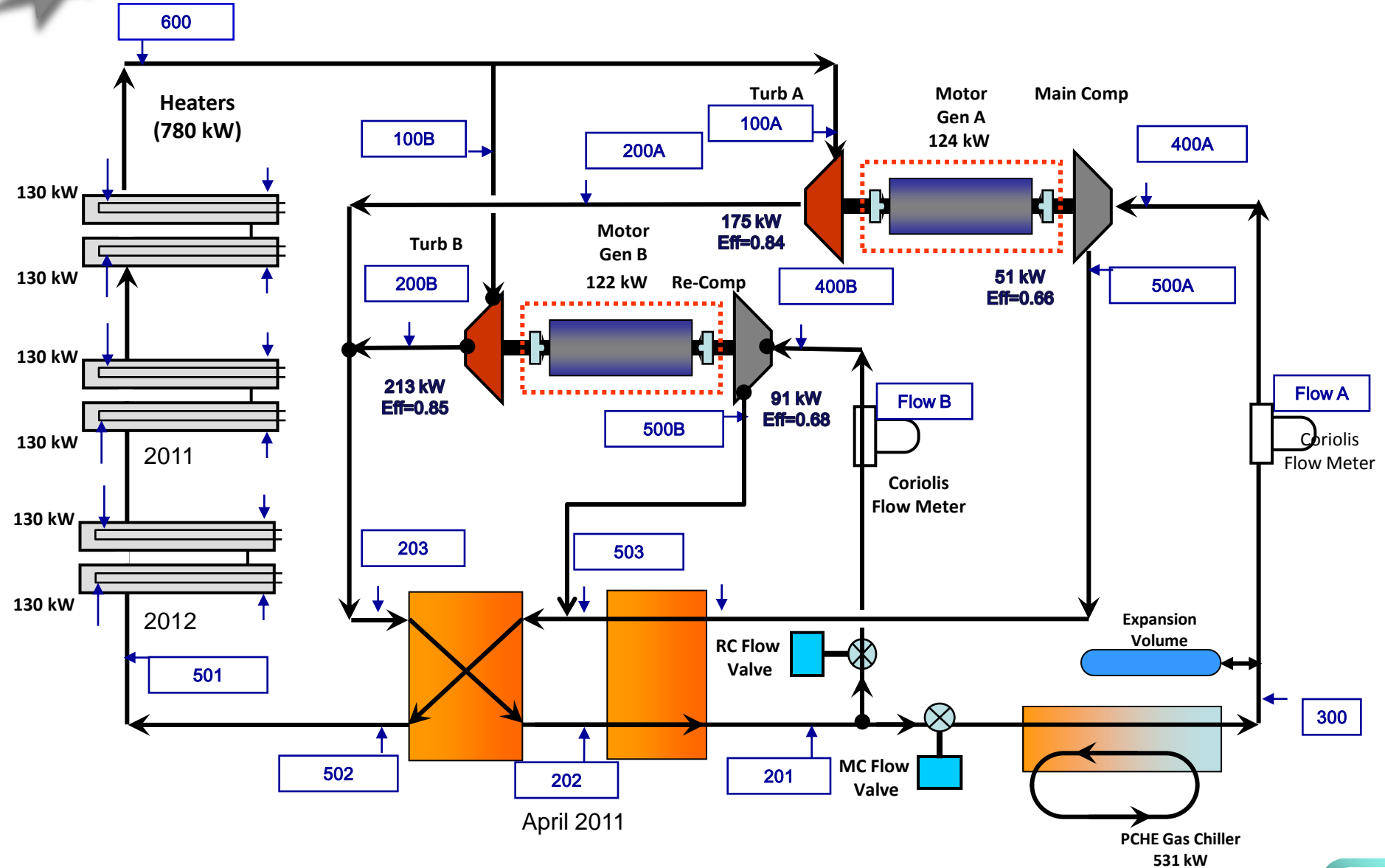


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Supercritical CO₂ Brayton Loop

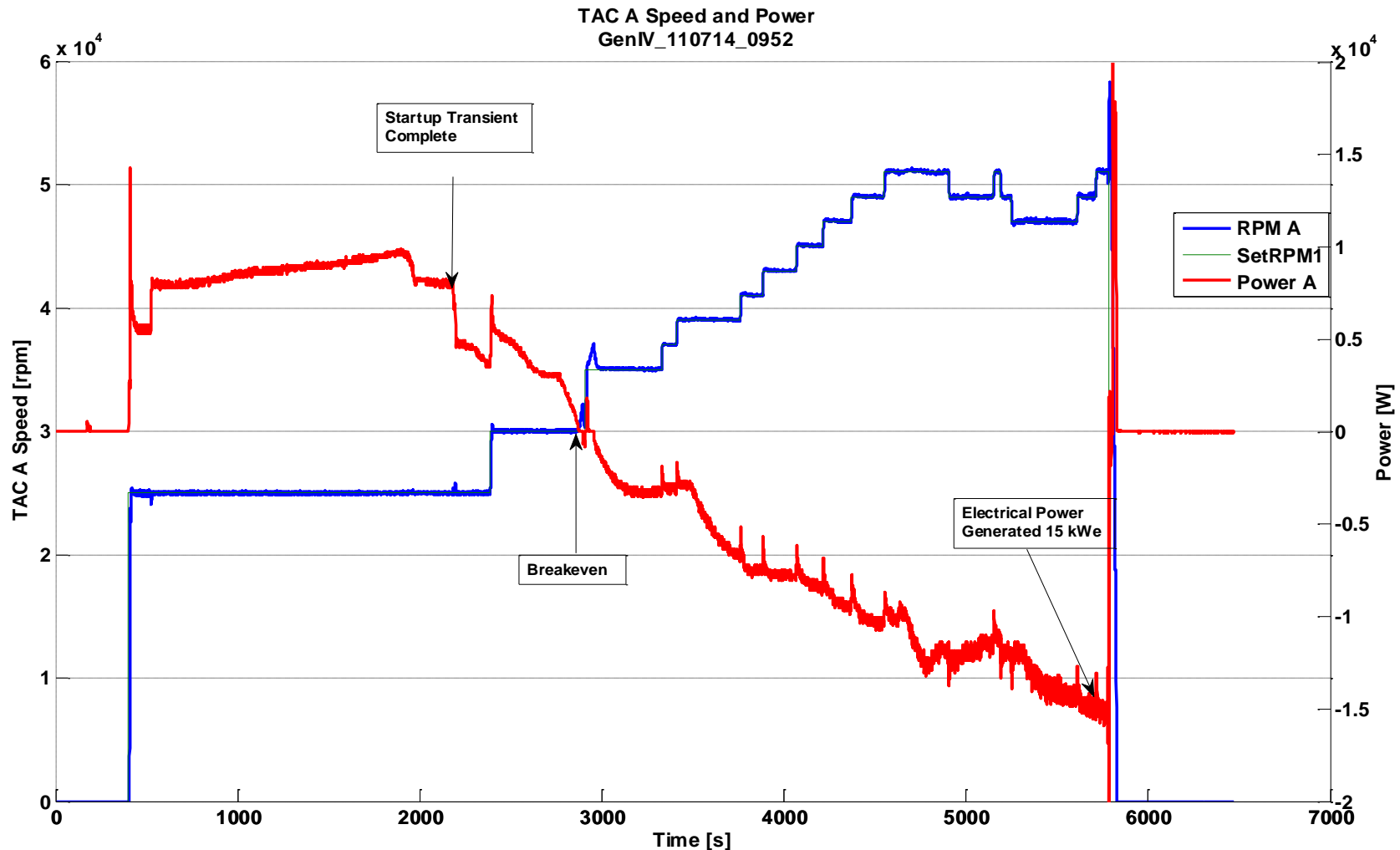
Final Design, Currently Existing, and Alternative Layouts



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



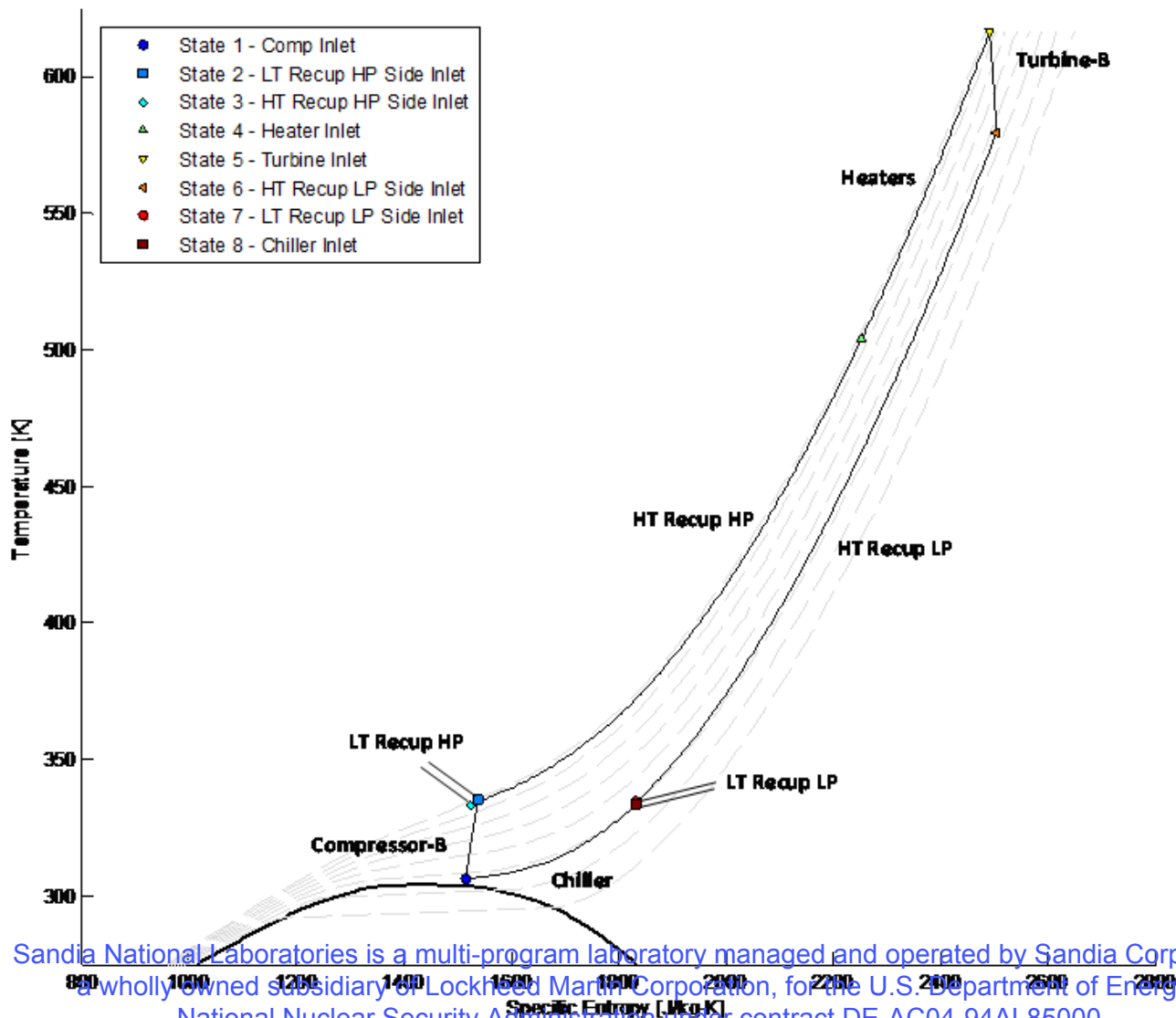
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Measured T-S Diagram

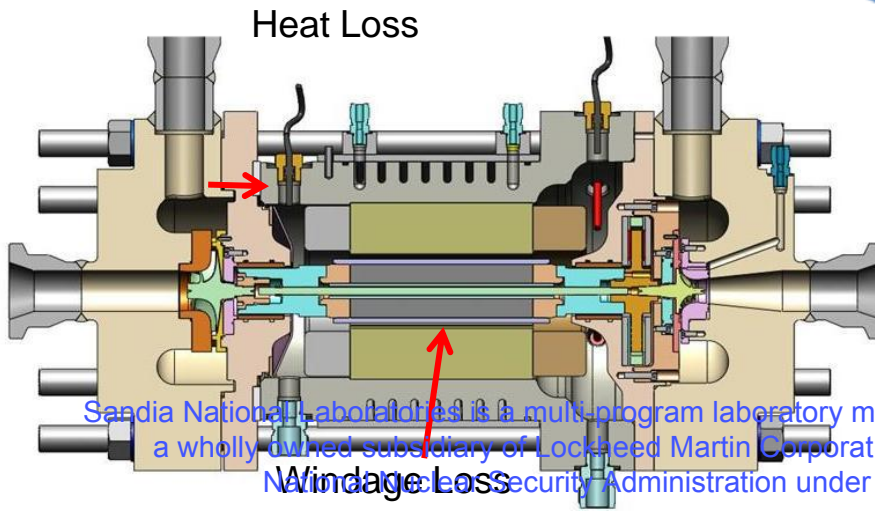
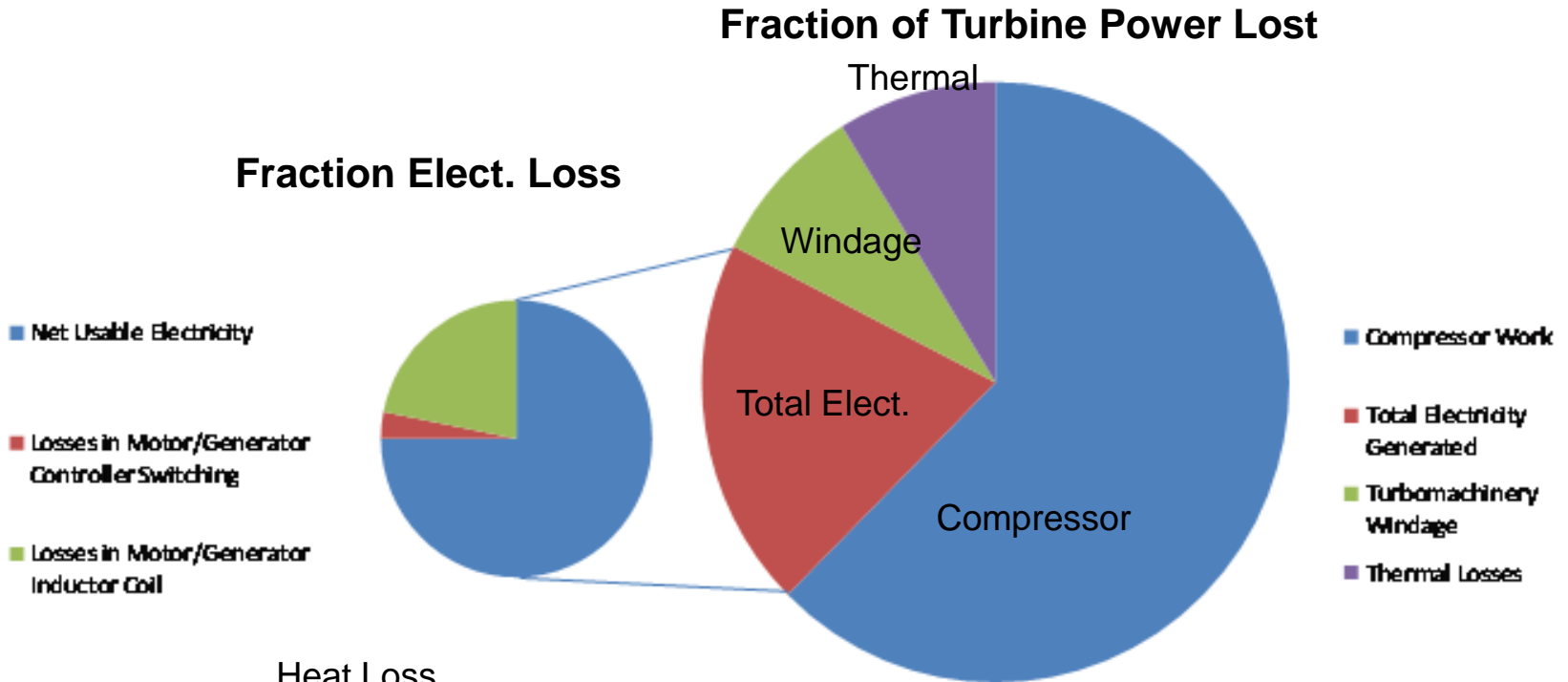
GenIV_110714_0952

T-s Diagram
DOE SHL Test "GenIV_110714_0952"
At 5770 [g] into the test
Generated Power = 15716 [W]



Loss Measurements

C-2 Compressor T-2 Turbine



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S-CO₂: Summary and Conclusions

Potential for S-CO₂ Power Conversion Systems to Improve Nuclear Power Economics





Sandia Research Program Summary

- Sandia/DOE have two operating S-CO₂ 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 CO₂, CO₂-Neon, CO₂ SF₆, CO₂-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-CO₂ 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-CO₂ System for any heat source at the 10 MWe 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 Gov. Funded 10 MWe S-CO₂ power system development to support FE, EERE, NE, NR**
 - **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**

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Backup





Roadmap or Rough Schedule and Cost For a 10 MWe Demo Power Plant

- | | <i>Prelim. Draft</i> |
|---|----------------------|
| • Phase 1: Year 1 + <ul style="list-style-type: none">– Design (Conceptual, Preliminary and Final) | • \$3M - \$7M |
| • Phase 2: Year 2 + <ul style="list-style-type: none">– Purchase, Manufacture, Assemble<ul style="list-style-type: none">• Delivery Schedule may be limiting | • \$22M - \$32M |
| • Phase 3: Year 3+ <ul style="list-style-type: none">– Assemble, Commission Power Unit, Upgrades and Improvements– Make Electricity | • \$7M - \$15M |
| • Phase 4: Year 4+ <ul style="list-style-type: none">– Operations and Testing and Upgrades– Electricity Sales to Grid– Product Development (Fossil, Solar, Geothermal, Nuclear, Military)– Redesign for Modularization | |
| • Deliverables <ul style="list-style-type: none">– Operating S-CO₂ power system Year 3– Product Line Year 4 | |

Preliminary Estimate

\$30M - \$50M

Multiple Corporations are Investing in S-CO₂ Power Systems

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Status of the Commercial & Government Development Efforts

- Proof of Concept S-CO₂ loops
 - SNL, Echogen, DOE (2), Czech Republic, Japan, GE-GRC
- Gas Turbine Bottoming Cycle
 - 3 Corporations; 10 MWe
- Solar Towers
 - 2 Corp; 1-10 MWe
- CCS (click)
 - 3 Corporations, 5, 7, 70 Mwe
- Heat Transport
 - 3 Corporations





S-CO₂ Power Conversion Systems have Major Economic and Environmental Implications

- **More efficient and cost effective natural gas plants**
 - S-CO₂ bottoming cycle plants could improve natural gas plants efficiency /cost
 - Single system S-CO₂ replace steam plants with lower cost higher efficiency
 - Systems can operate with dry cooling
 - Dynamic Load Following is possible (Thermal cycling issues needs investigating)
 - Multiple Corporations are investing in this technology
 - Multiple Bottoming Cycles Proposed (Cascaded, + Proprietary)
- **Current and next generation Coal plants**
 - Pressurized Oxy-Combustion, with S-CO₂ Power Plants Efficiency Improvements to 37-38%
 - Advanced Oxy-Combustion Research Needed
 - Pre-combustion facilitates CO₂ capture
 - high pressure, high density, smaller sized hardware
- **Advanced Nuclear plants**
 - S-CO₂ provide 45 to 50% conversion efficiency for advanced metal cooled (SMR)
 - Cascaded S-CO₂ provide up to 55% efficiency for advanced HTGR
 - Condensing cycle version could increase current LWR plant efficiency to 40%
 - LWR plants could operate at 30-33% efficiency Dry
 - Industrial Design Development and Nuclear Certification are Needed
- **Solar thermal Power Conversion**
 - Designs for solar thermal trough or towers provide 40 to 50 % efficiency conversion, dry cooling, and small modular systems (<10 MWe) that fit on one tower
- **Marine Applications**
 - The compact nature of S-CO₂ Systems are ideal for marine applications and small modular reactors
- **Novel Heat Transport Applications**
 - Combinations of Heating, Cooling, Electrical Power Production, Energy Storage

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