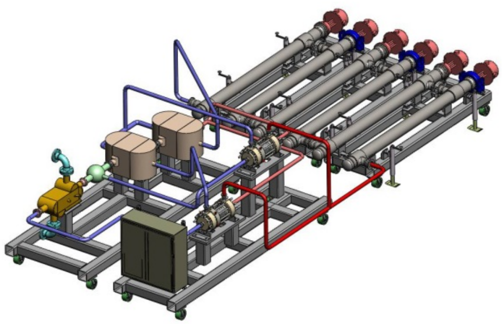
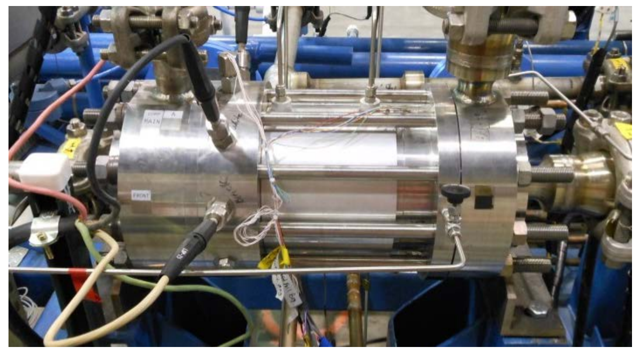
U.S. DEPARTMENT OF ENERGY | Nuclear Energy

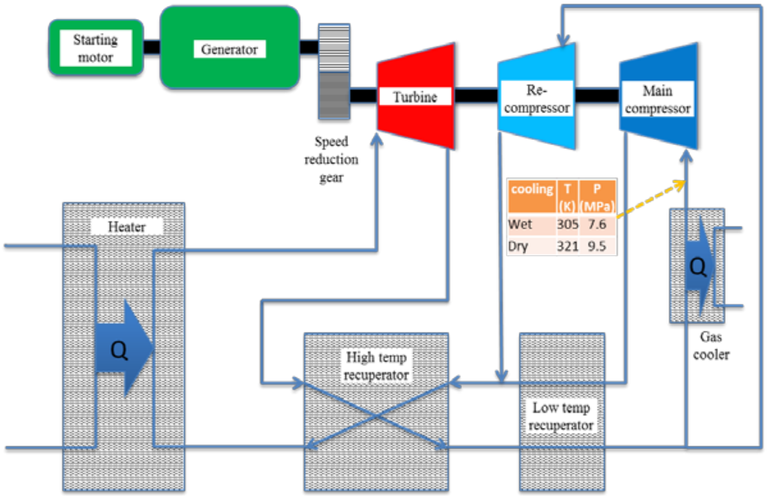



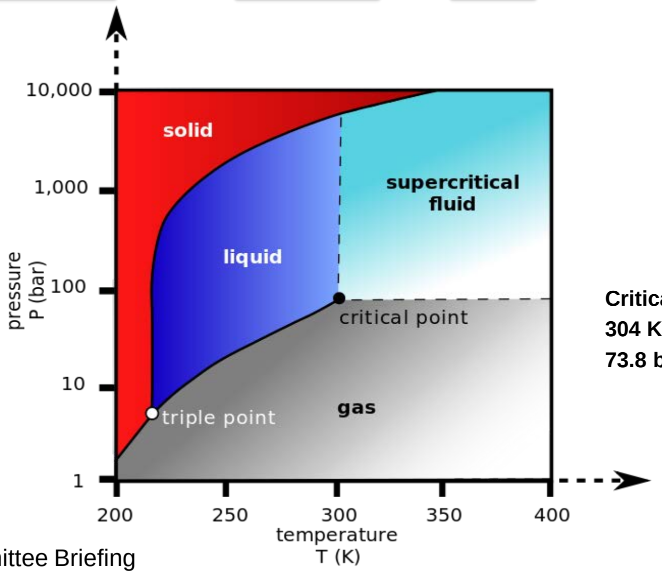

Supercritical CO_2 Brayton Cycle Development

Gary E. Rochau, Technical Area Lead
Advanced SMR Energy Conversion

Supercritical CO_2 (sCO_2) Brayton Cycle

- **sCO_2 Brayton Cycle remains in a single-phase throughout the process and does not require added energy to convert from liquid to gas phases or condense gas to liquid like traditional the Rankine Steam Cycle, leading to greater energy conversion efficiency**
- **At operating temperatures, sCO_2 has high enthalpies (energy/mass) and physical densities greater than steam which minimizes the volume of working fluid and system size required for an equivalent energy conversion reduces capital cost**





Critical Point
304 K = 31 C
73.8 bar = 7.38 MPa

sCO_2 Benefits & Challenges

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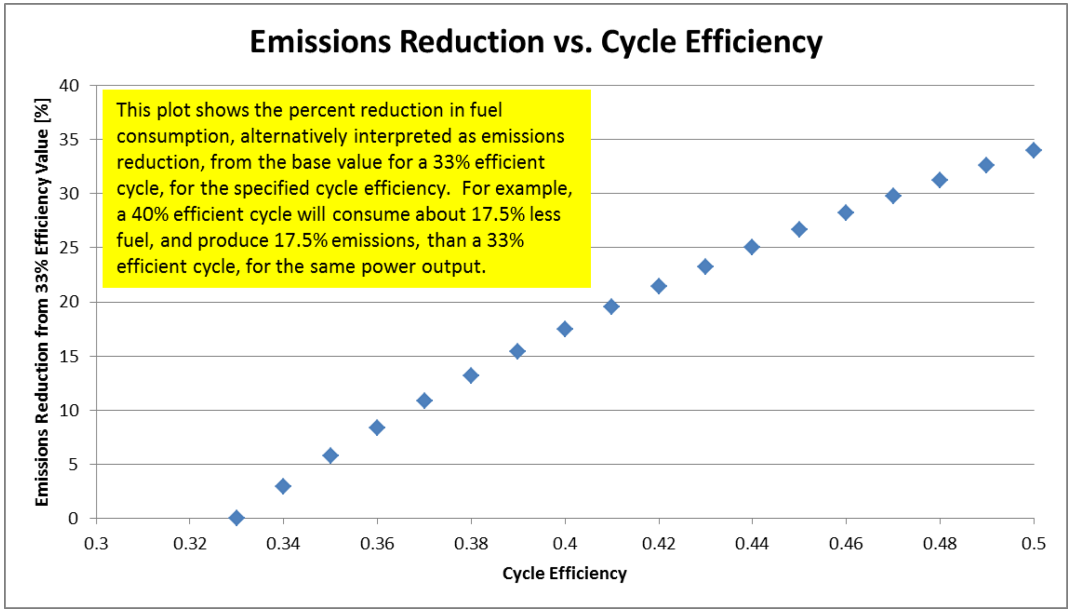
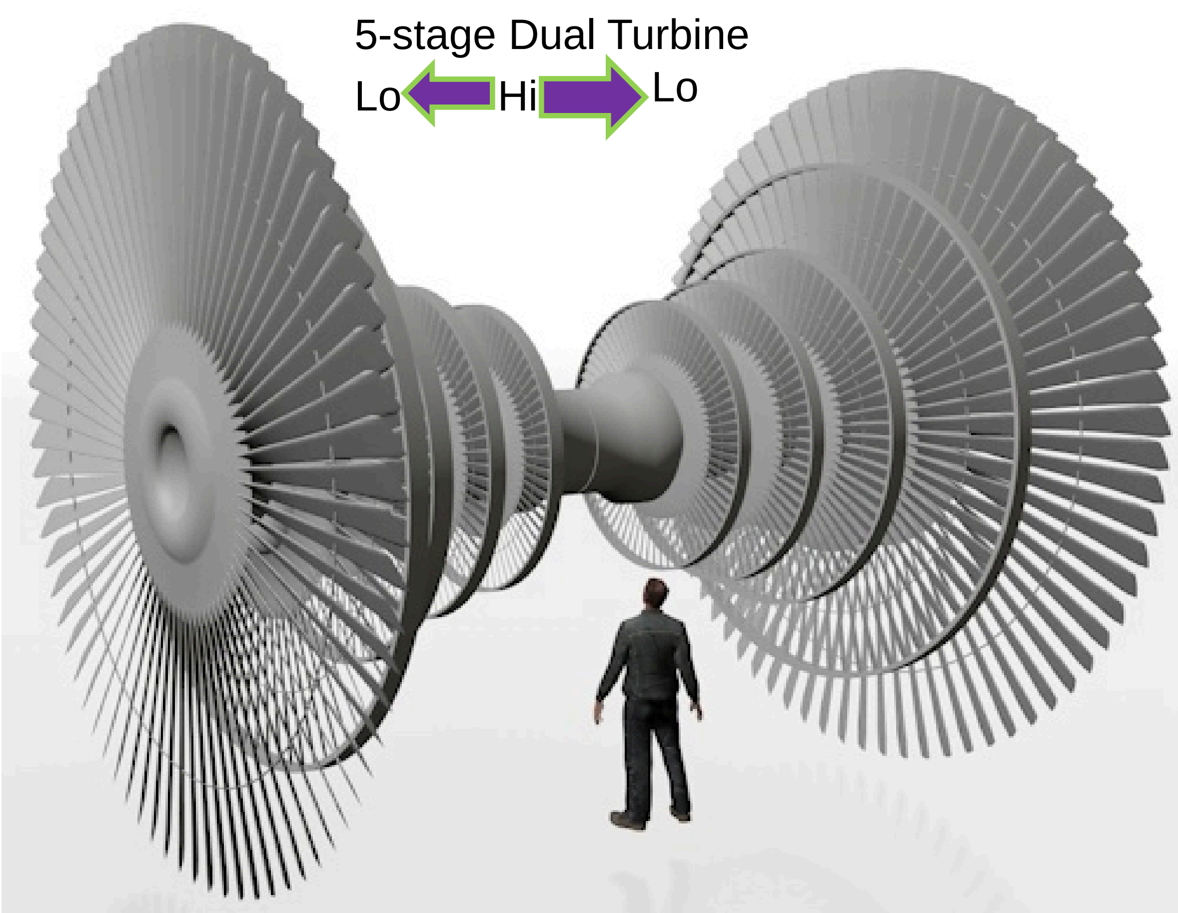
- **Benefits**
  - Economic advantages
    - *Smaller size relative to steam system – reduced capital cost*
    - *Increased efficiency – increased electricity production for same thermal input – lower cost of electricity production ($/KWhr)*
  - Environmental improvement
    - *Greenhouse gas reduction*
    - *Reduced water consumption*
    - *Dry cooling/suitable for arid environments*



- **Challenges**
  - Confirm viability of existing components and suitability of materials
  - Accommodating a wide range of operating parameters and applications
  - Integrating and scaling up existing technologies into a new application
  - Developing robust operating procedures for operating at critical point

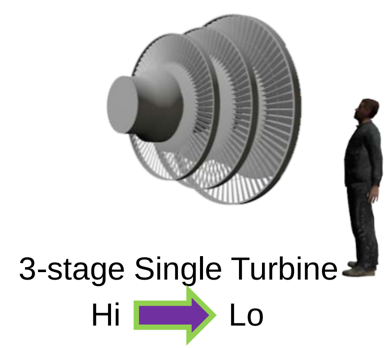
Transformational Energy Systems



20 meter Steam Turbine (300 MWe)
(Rankine Cycle)

Comparison

- Rankine efficiency is 33%
- Supercritical CO_2 (sCO_2) potential to surpass 40% efficiency
- Greatly reduced cost for sCO_2 compared to the cost of conventional steam Rankine cycle
- sCO_2 compact turbo machinery is easily scalable

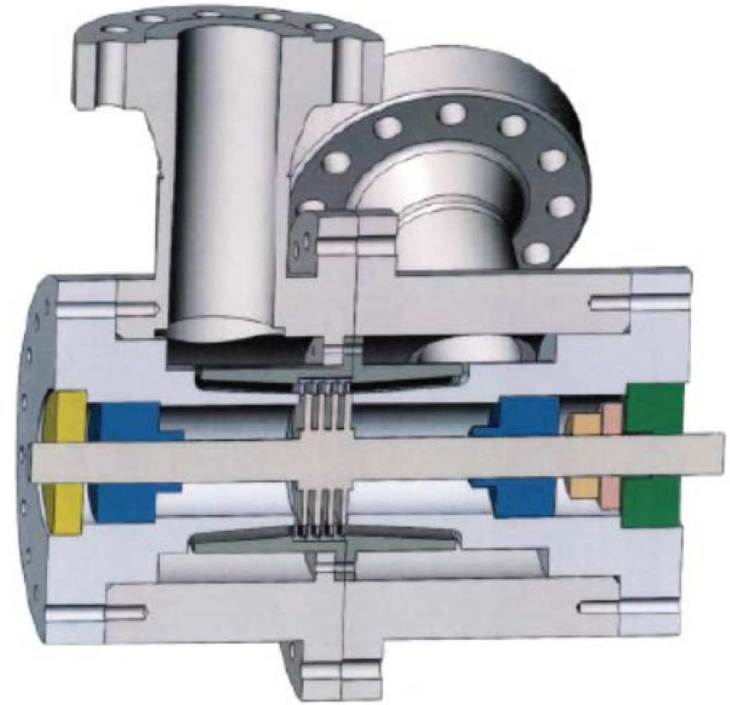


1 meter sCO_2 (300 MWe)
(Brayton Cycle)

Office of Nuclear Energy Roadmap

- **Objective #3 - Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals**

- **Maturing this technology promotes the Administration's "all of the above" clean energy strategy;**
  - Contributes towards meeting national and energy goals
  - Promotes domestic industry growth
  - Facilitates industrial competitiveness

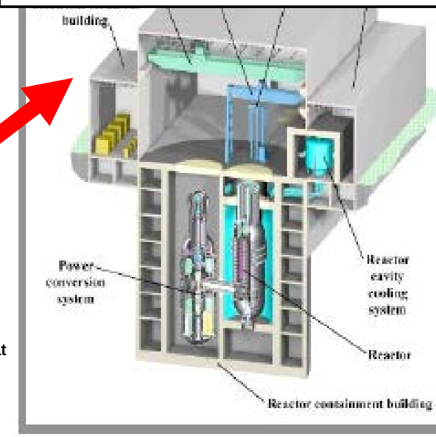


10 MWe Turbine ~ 30 in
Courtesy EchoGen

Supercritical CO_2 Cycle Applicable to Most Thermal Sources

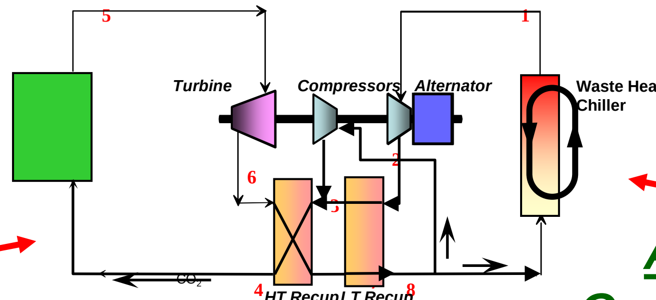
DOE-NE Advanced Reactors

Nuclear (Gas, Sodium, Water)

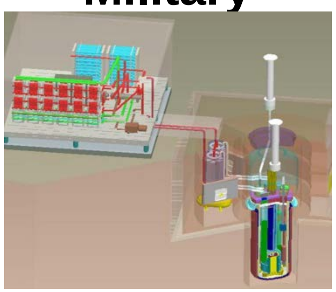


SunShot Power Cycle

Supercritical CO_2 Brayton Cycle



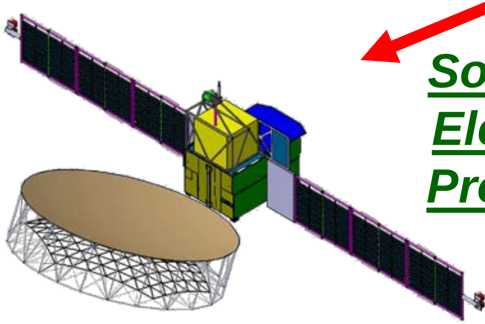
Military



CONUS Marine Mobile?

ARRA Geothermal

Solar Elec. Prop.



Fossil
Sequestration Ready

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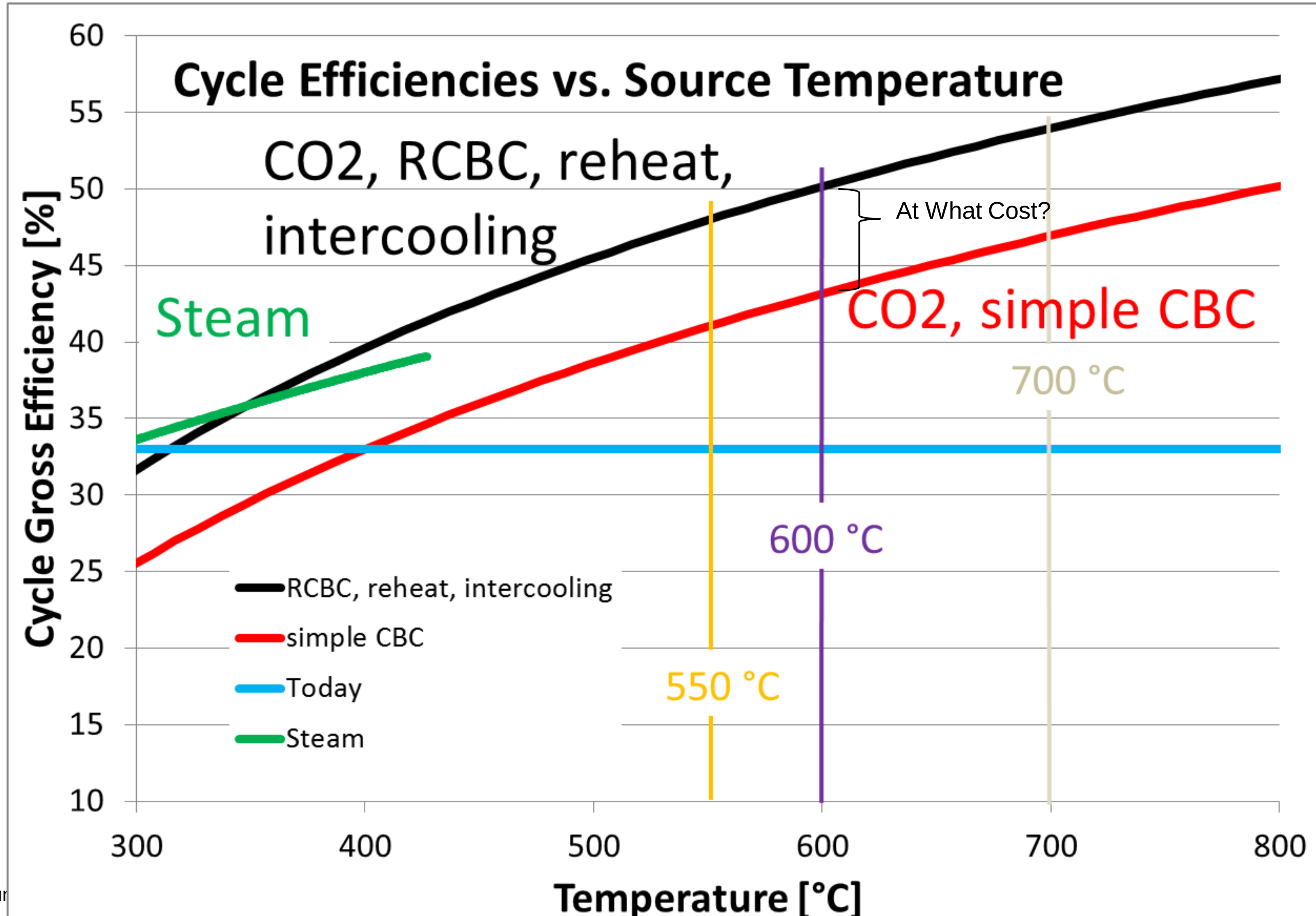
Many applications push the material requirements

Nominal Application-Specific Conditions for sCO_2 Turbo Machinery
(Ref. sCO_2 Power Cycle Technology Roadmapping Workshop, February 2013, SwRI San Antonio, TX)

Application	Organization	Motivation	Size [MWe]	Temp [C]	Pressure [MPa]
Nuclear	DOE-NE	Efficiency, Size, Water Reduction	10 – 300	350 – 700	20 – 35
Fossil Fuel (Indirect heating)	DOE-FE, DOE-NETL	Efficiency, Water Reduction	300 – 600	550 – 900	15 – 35
Fossil Fuel (Direct heating)	DOE-FE, DOE-NETL	Efficiency, Water Reduction, Facilitates CO_2 Capture	300 – 600	1100 – 1500	35
Concentrating Solar Power	DOE-EE, DOE-NREL	Efficiency, Size, Water Reduction	10 – 100	500 – 1000	35
Waste Heat Recovery	DOE-EERE	Efficiency, Size, Simple Cycles	1 – 10	< 230 – 650	15 – 35
Geothermal	DOE-EERE	Efficiency	1 – 50	100 – 300	15

Pathway to High Conversion Efficiency



Recompression Closed Brayton Cycle (RCBC)Test Article (TA)

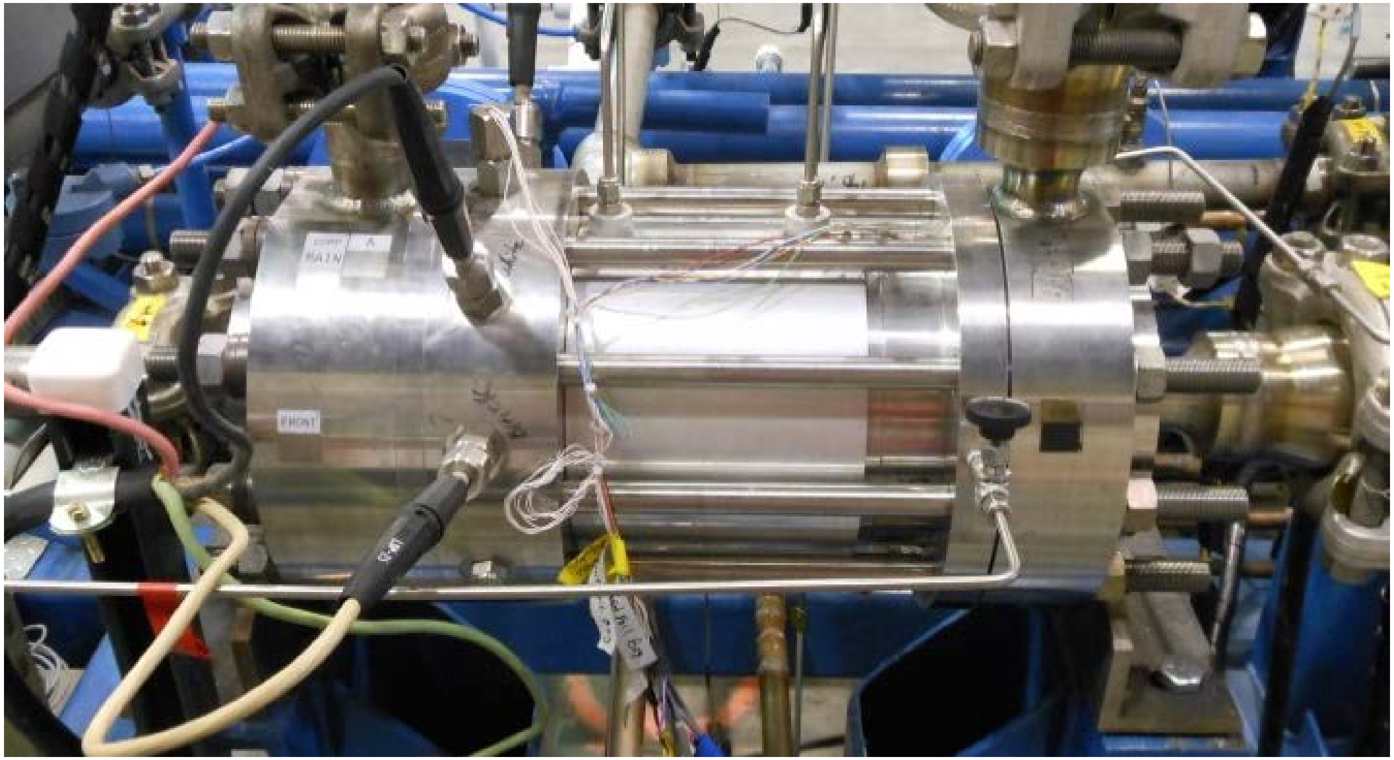
- **TA under test since 4/2010**
- **Over 100 kW-hrs of power generated**
- **Operated in 3 configurations**
  - **Simple Brayton**
  - **GE Waste Heat Cycle**
  - **Recompression**
- **Verified cycle performance vs theory**
- **Developing Cycle Controls**
- **Developing maintenance procedures**

<u>TA Description:</u>

Heater – 750 kW, 550°C
Max Pressure - 14 MPa
TACs – 2 ea, 125 kWe @ 75 kRPM,
  2 power turbines, 2 compressors
High Temp Recuperator - 2.3 MW duty
Low Temp Recuperator – 1.7 MW duty
Gas Chiller – 0.6 MW duty

Load Bank – 0.75 MWe
Gas Compressor to scavenge TAC gas
Inventory Control
Turbine Bypass(Remote controlled)
ASME B31.1 Coded Pipe, 6 Kg/s flow rate
Engineered Safety Controlling Hazards
Remotely Operated

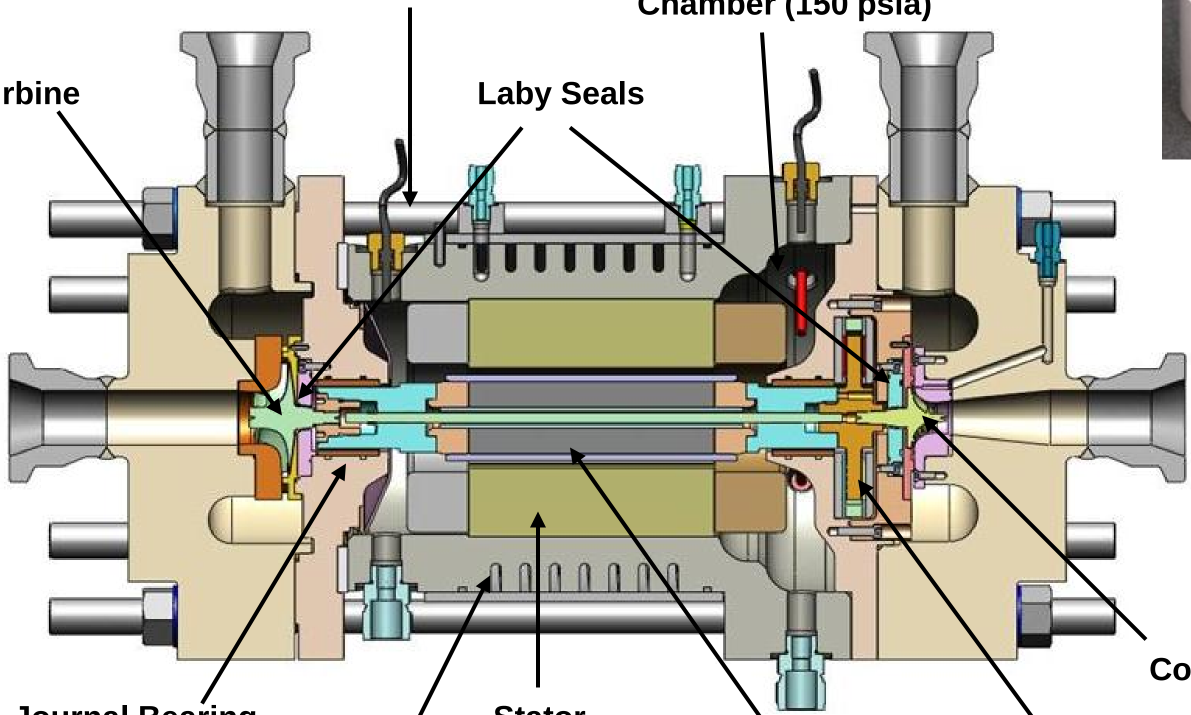
The Turbine-Alternator-Compressor (TAC)

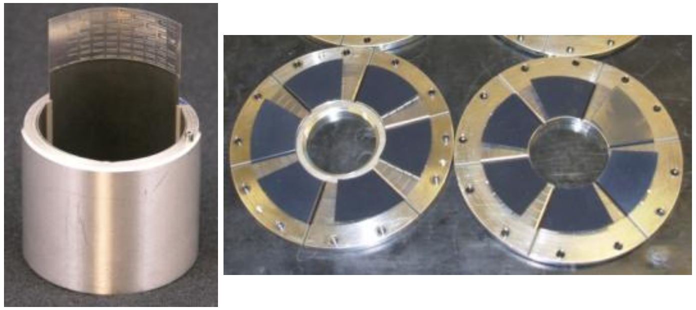


~24" Long by 12" diameter

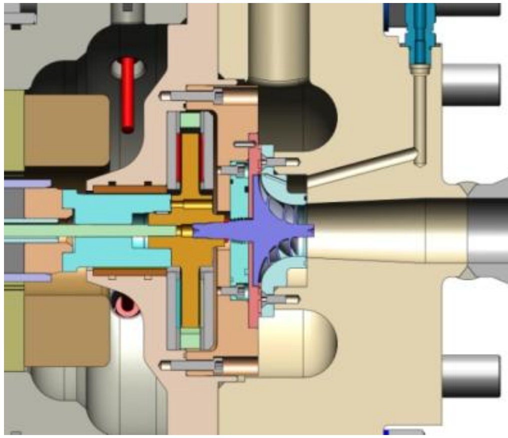
Key Technology Turbo- Alternator-Compressor Design

Permanent Magnet Generator with Gas Foil Bearings



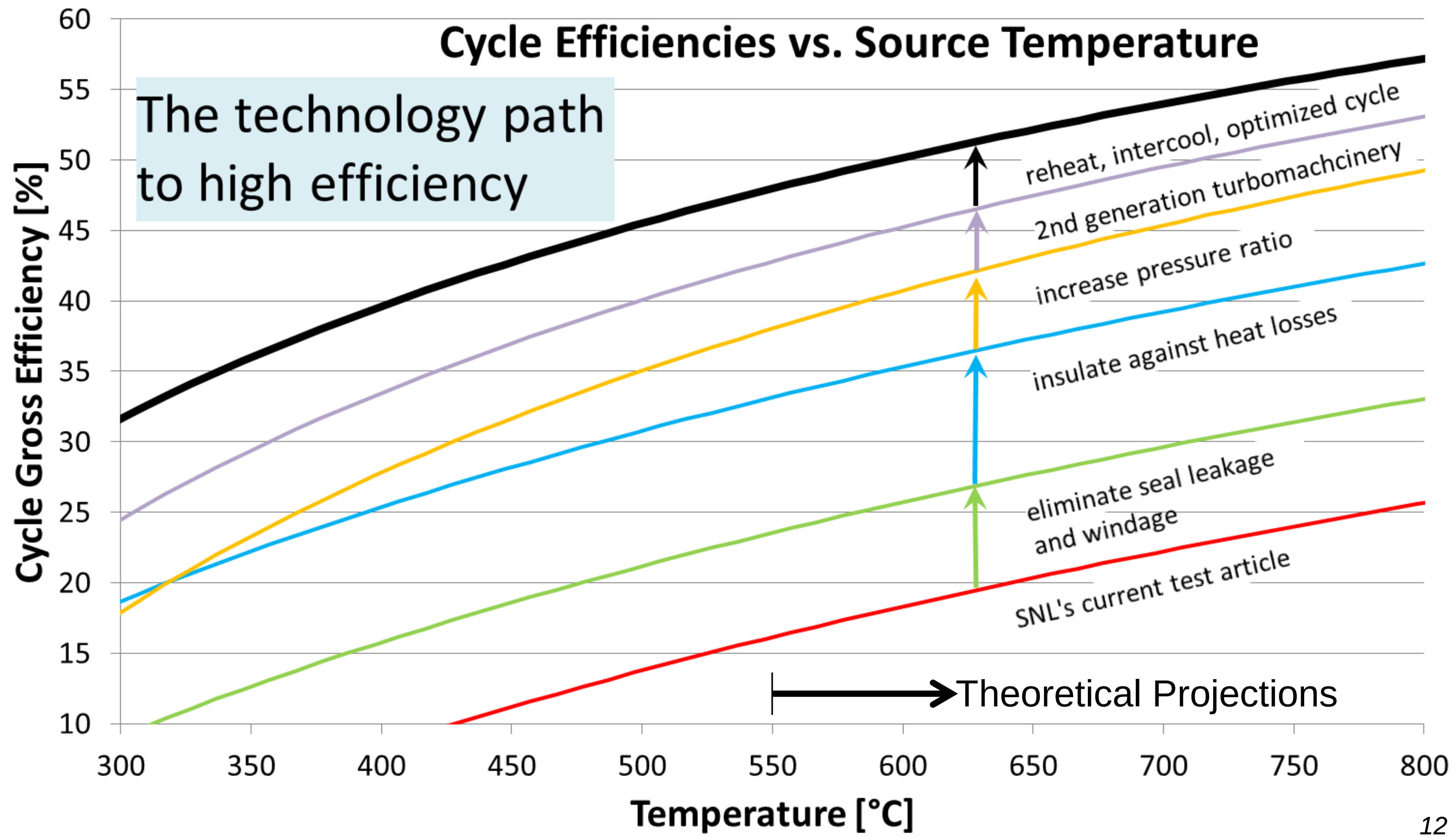


Gas-Foil Bearings

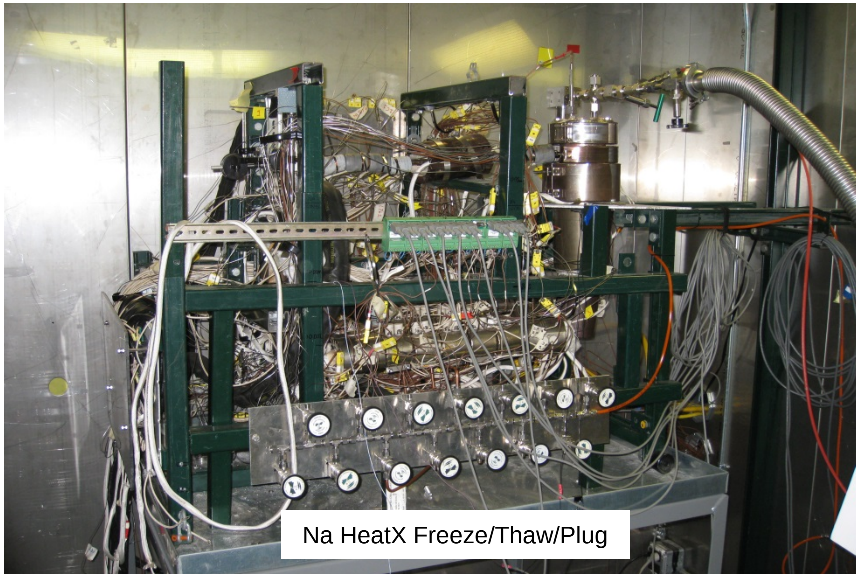


125 kWe (max) at 75,000 rpm

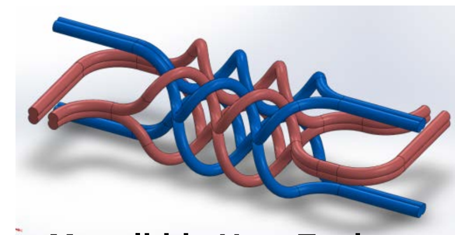
Pathway to High Conversion Efficiency

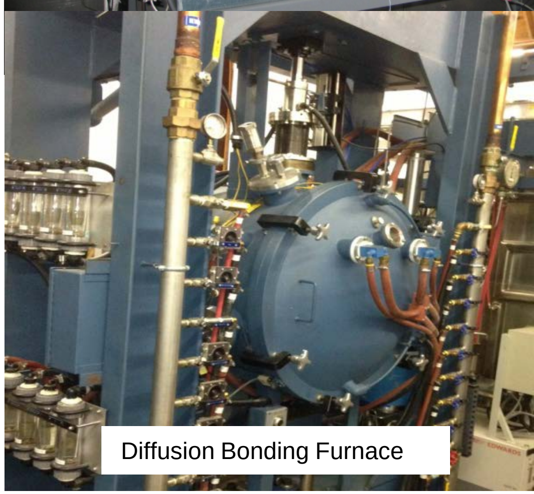


Advanced SMR Energy Conversion Heat Exchanger Development


Na HeatX Freeze/Thaw/Plug


Na/CO2 Interaction


Monolithic Heat Exchanger Provisional U.S. Patent


Diffusion Bonding Furnace


U.S. mfg Bonded Fuel Diff.


Prototype Na/CO2 PCHE

The turbomachinery industry has been here before

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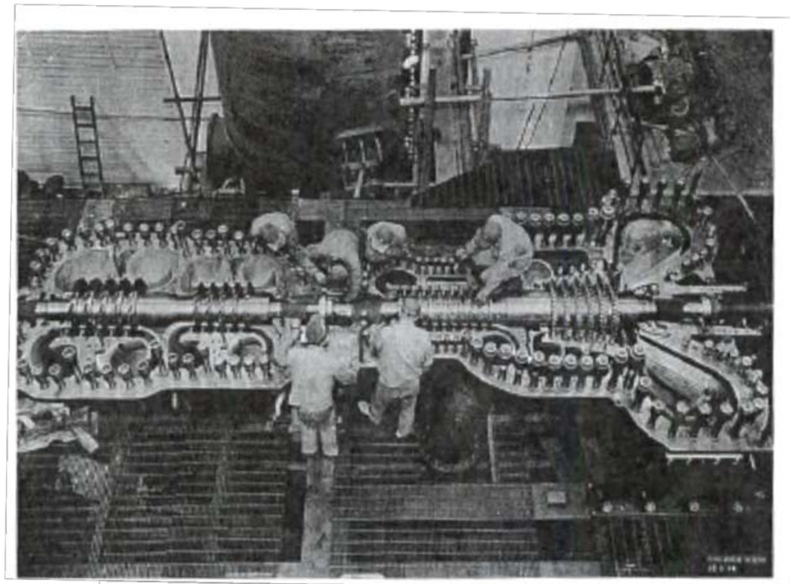
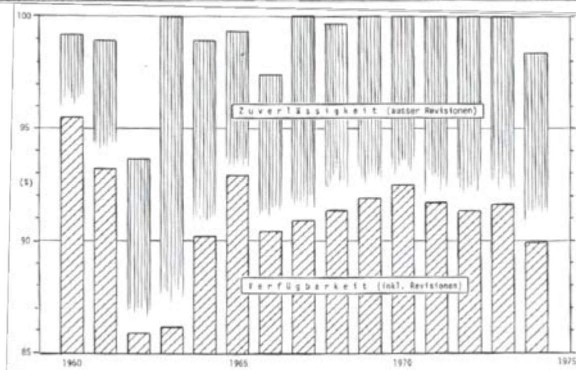
- **Escher Wyss (EW) was the first company known to develop the turbomachinery for CBC systems starting in 1939**
- **24 systems built, with EW designing the power conversion cycles and building the turbomachinery for all but 3.**
- **Plants installed in Germany, Switzerland, Vienna, Paris, England, Russia, Japan, Los Angeles, and Phoenix.**

Turbomachinery housing of the **12 MW** Nippon Kokan plant, built by Fuji Electric, based on EW design.





Fluid: Air @ 28 kg/s
Tur. Inlet Temp 600-660°C
Intercooling
Net Eff. =23-25%

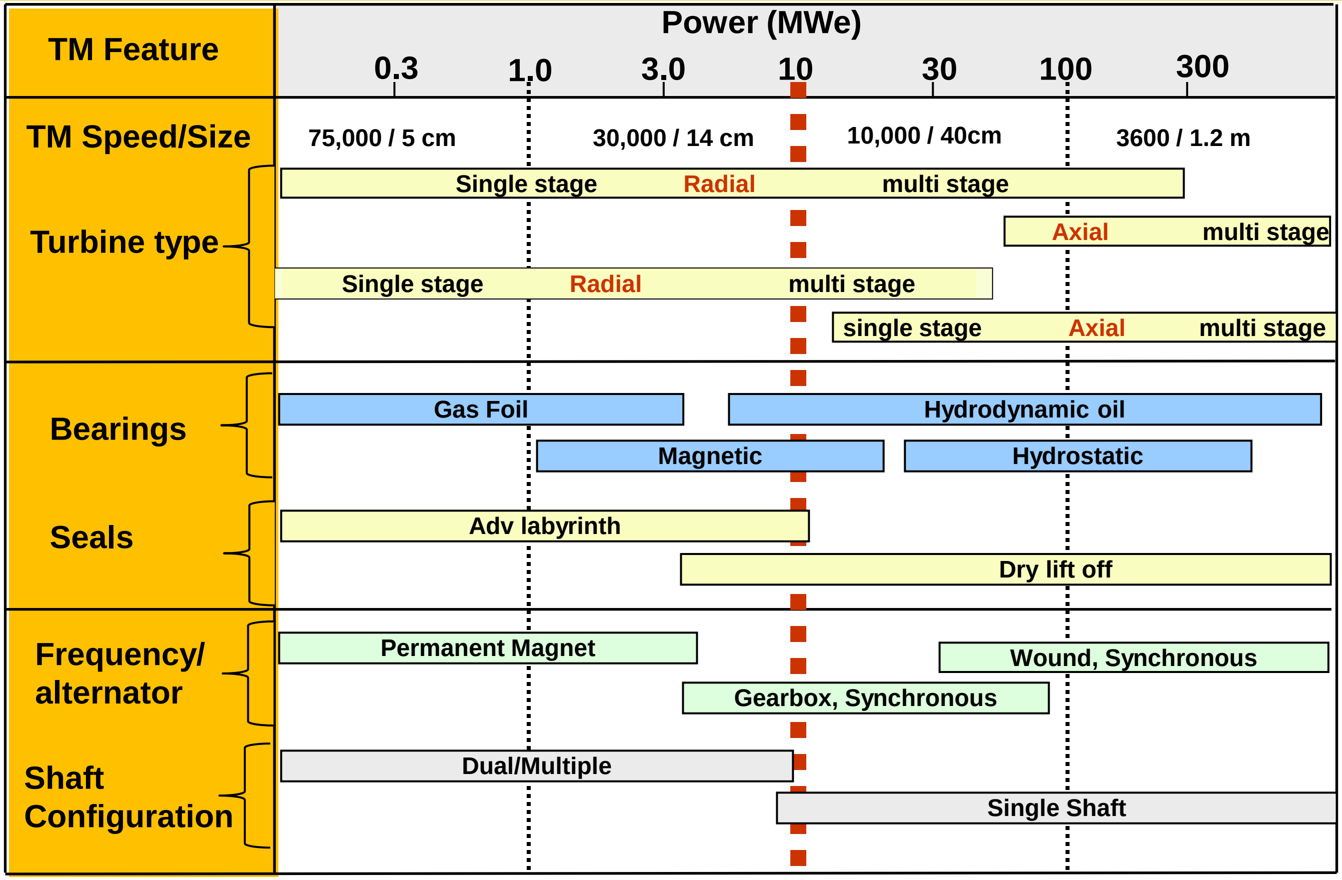
Reliability factor >95%

Availability factor > 90%

What's Next?

- **Commercialize a system <u>scalable</u> to 1000 MWe.**
- **Stronger emphasis on industry collaboration through CRADAs to provide equipment infrastructure resources.**
- **Improve the technology readiness and move toward "power on the grid" demonstration.**
  - Move from TRL 3 to TRL 7 with the help of DOE and Turbomachinery Industry
  - Follow a systems engineering approach (ex. DOE 413)
  - A demonstration system must be built and extensively tested.
  - Must be directly "**scalable"** to power plant levels and put power on the grid
  - Performance must be well understood, modeled and benchmarked.
    - *Availability and Reliability*
    - *Start-up and Shut-down*
    - *Heat source transients*
- **Commercialization objective achieved when industry begins to mature sCO_2 Closed Brayton Cycles with "order books" indicating commercial production of systems.**

Scaling Rules and Ranges of Application for Components



High Technology
High $/kWe

→

Commercial Technology
Lower $/kWe

10 MWe allows use of primarily commercial technologies

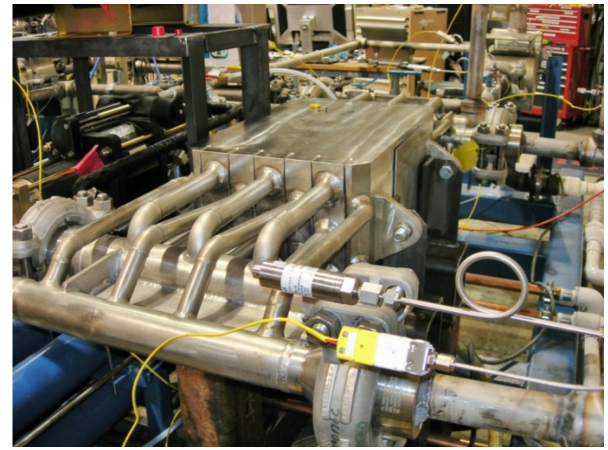
High Temperature Materials Needs

125 kWe sCO_2 turbine rotor
550°C, INCONEL 718
(proposed for 700°C service – not in code)

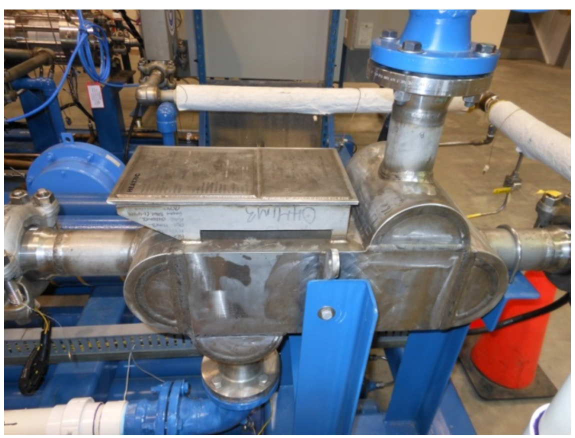
- **High temperature-high pressure boundaries for Primary Heat Exchangers and Piping**
- **The goal is high nickel sCO2 corrosion resistant alloy in large diameter pipe that can handle 850°C at 30 Mpa**
- **Current temperature limit is 650°C**
- **Slabs of such materials exist, but no manufacturer produces affordable material in less than years of lead time**

Advanced Heat Exchangers For High Efficiency And Small Volume

High Temperature Recuperator



Low Temperature Recuperator



Gas Water Chiller

Prototype Sodium/CO2 PCHE

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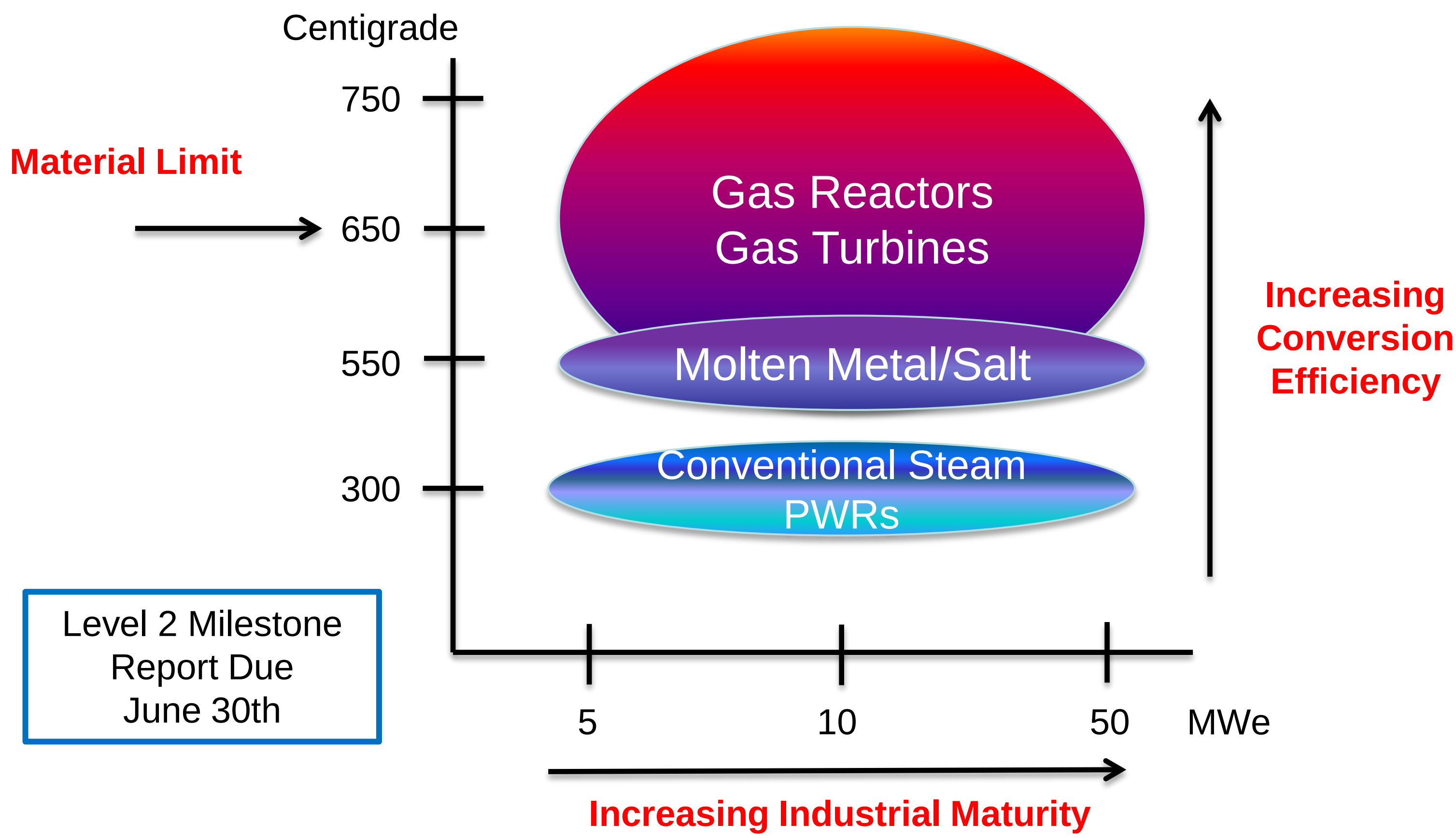
Demonstration Subsystem Options Survey

- **Scanning the Turbine, Compressor, Power Generation industry to identify readiness of subsystem components for various CBC applications.**



Level 2 Milestone
Report Due
June 30th

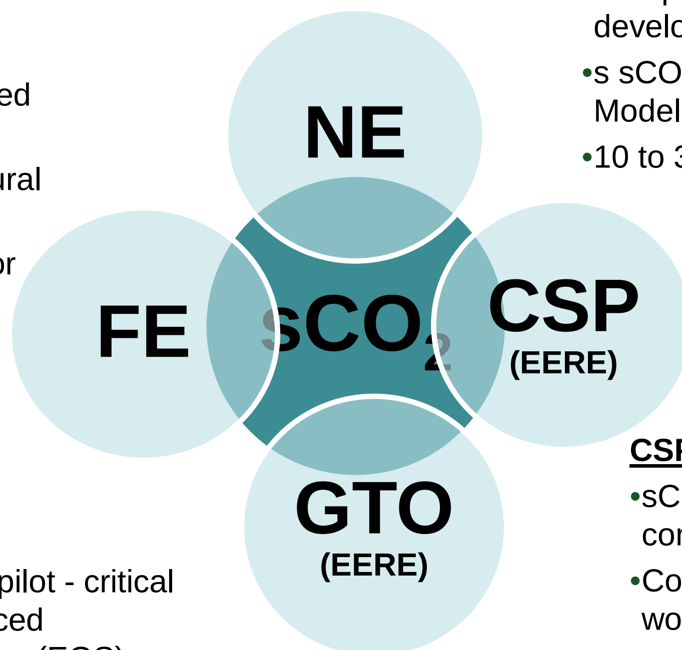
sCO_2 Programmatic Research Areas continuing under STEP

FE:

- CO2 viscosity and thermal conductivity correlation.
- Thermo & techno-economic studies
- Oxy-Pressurized fluidized bed combustion (PFBC) pilot plant - detailed design & cost estimates.
- Update creep-rupture and microstructural data - high alloy materials
- Advanced internally-cooled compressor design - testing and evaluation
- Indirect
  - 300 to 600 Mwe
- Direct
  - 300 to 600 Mwe

NE:

- Sodium – sCO_2 interaction studies
- Compact sCO_2 heat exchanger development
- s sCO_2 Systems Codes Dynamic Modeling V&V
- 10 to 300 Mwe



CSP:

- sCO_2 solar receivers, materials compatibility
- Cost-effective heat transfer fluid/cycle working fluid heat exchangers
- Transient operation / solar flux environments - control systems
- Modeling and analysis of sCO_2 integration with CSP systems using dry cooling
- 10 to 100 MWe

GTO:

- Power generation pilot - critical phase CO2 Enhanced Geothermal Systems (EGS) field pilot
- Numerical simulations
- Geothermal-specific component R&D
- 1 to 50 MWe

sCO_2 FY14 Activities

- **Continue Program activities**
  - Nuclear Energy (NE)
    - *Brayton Cycle R&D, HTXR, Na-CO2, Modeling, Plugging loop*
  - Fossil Energy (FE)
    - *High temperature operations focusing on higher efficiencies, material development, C-sequestration*
  - EERE – Concentrated Solar Program (CSP)
    - *Continue to support Sunshot; SWRI*
  - EERE – GeoThermal Office (GTO)
    - *Continue to support the affect of sCO_2 on materials*
- **sCO_2 Technology Team *(aka Tech Team)***
  - sCO_2 Charter - Complete
  - Request for Information (RFI) for sCO_2 program support – Issued
  - Hold a sCO_2 Workshop - June 23rd

Anticipated sCO_2 FY15 Activities

- Continue Program Technology Assessment activities
  - EERE (CSP & GTO) - continues to develop sCO_2 solar receivers and study degradation mechanisms of sCO_2 containment materials
  - NE – work on primary heat exchangers and liquid sodium / sCO_2 interaction continues
  - FE - continues to investigate s sCO_2 cycle modeling, analysis, determining the physical properties of sCO_2, and corrosion mechanisms for materials of sCO_2
  - Supercritical Transformational Energy Power Generation (STEP)
  - Cost-shared Demonstration (size & location tbd)
  - Schedule
    - Issue FOA (1st /2nd Qtr FY'15)
    - Receive Applications (3rd Qtr FY'15)
    - Award/Post Award Process (4th QTR FY'15)

Summary

- **STEP initiative is a multi-office collaborative DOE program to scale up emerging technology and accelerate commercialization of Supercritical Carbon Dioxide (sCO_2) Brayton cycle energy conversion system**
- **DOE proposes to conduct a cost-shared demonstration program that all Offices would benefit from:**
  - Demonstration facility(s) size (TBD) (System Demonstration or Component Testing)
  - Requires recompression for optimal efficiencies over recuperated systems
- **Ultimate temperatures, scalability, and materials to be explored**
- **Secures U.S. competitive advantage in a transformational clean energy technology**
  - Assumes demonstration facility is operating by 2019 to facilitate technology transfer
  - Industry is marketing high efficiency commercial energy conversion systems using sCO_2