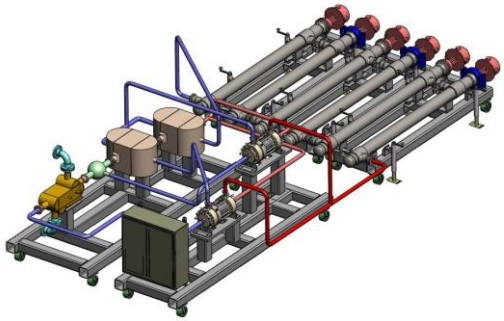
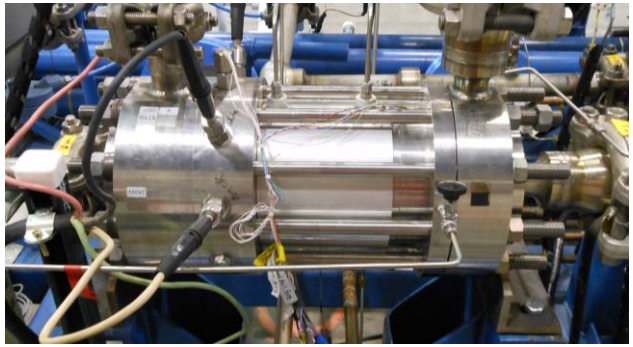
Exceptional service in the national interest

Sandia National Laboratories





S-CO2 Brayton Cycle Development Program

Gary E. Rochau

Advanced Nuclear Concepts

Technical Area Lead for Energy Conversion

DOE Advanced Reactor Technologies

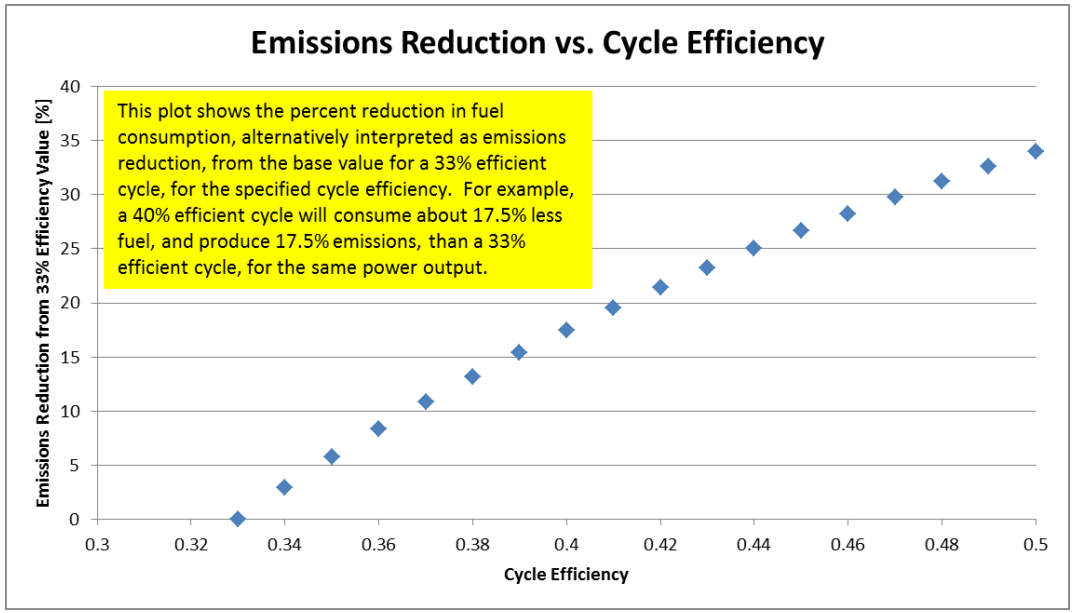
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

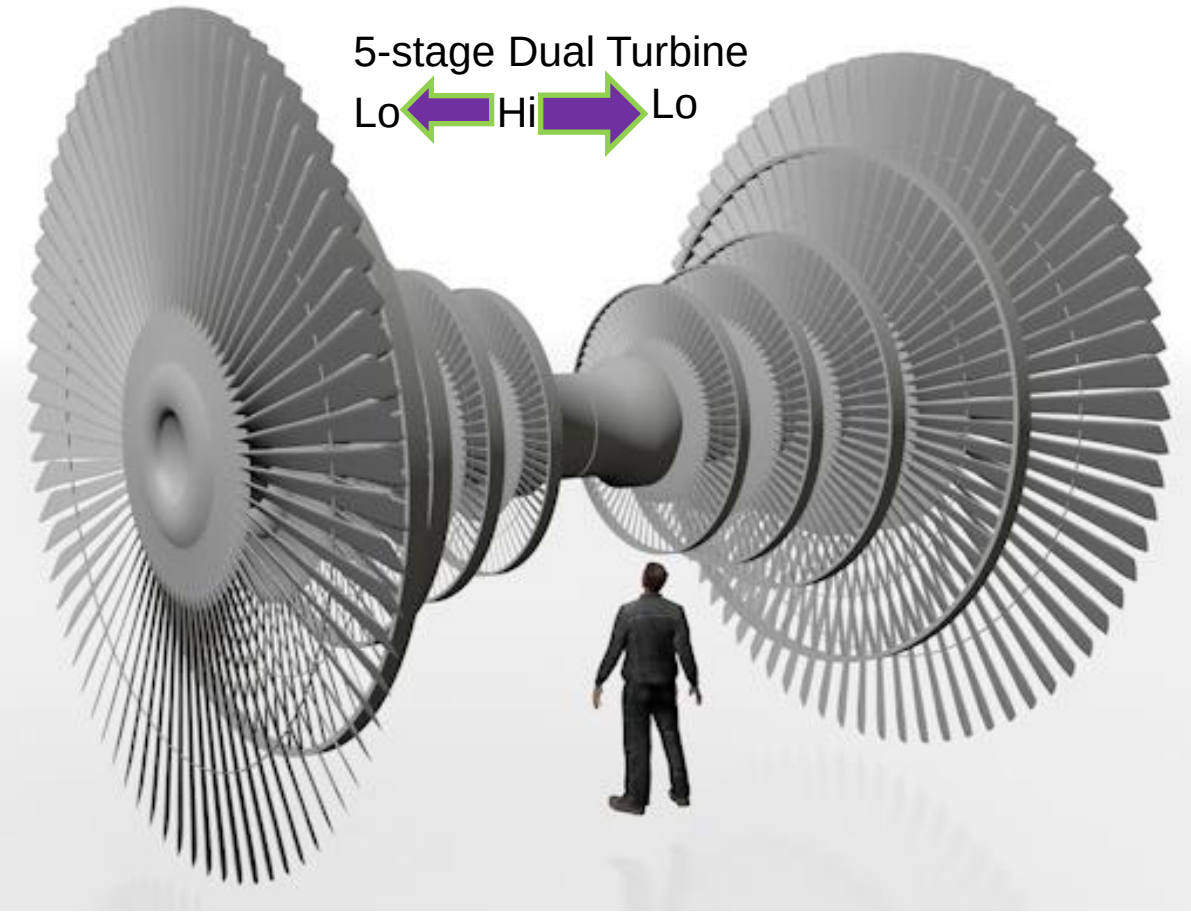
sCO_2 Benefits & Challenges

- **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 ($/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

3-stage Single Turbine
Hi → Lo

1 meter sCO_2 (300 MWe)
(Brayton Cycle)

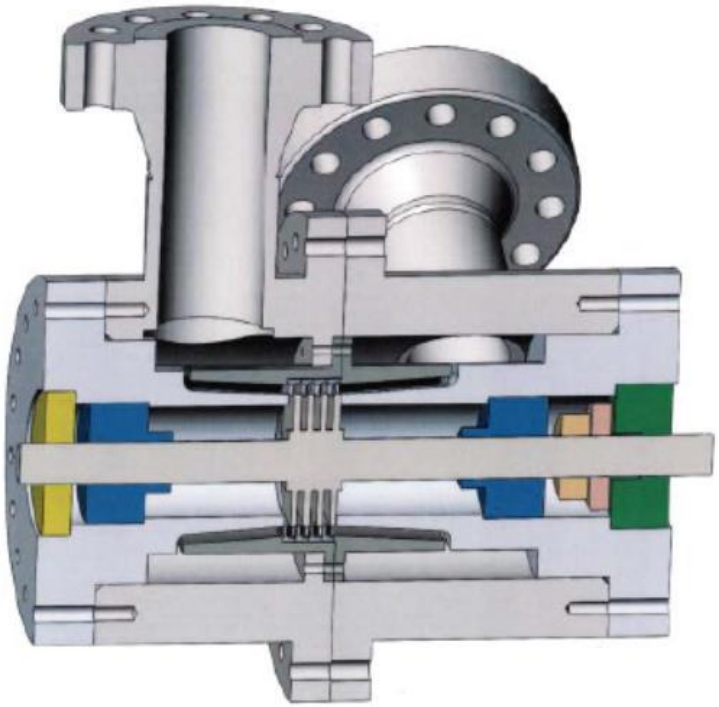
Office of Nuclear Energy Roadmap

- **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



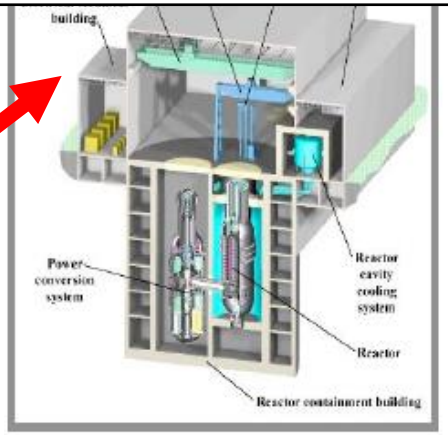
Supercritical CO_2 Cycle Applicable to Most Thermal Sources

Sandia National Laboratories

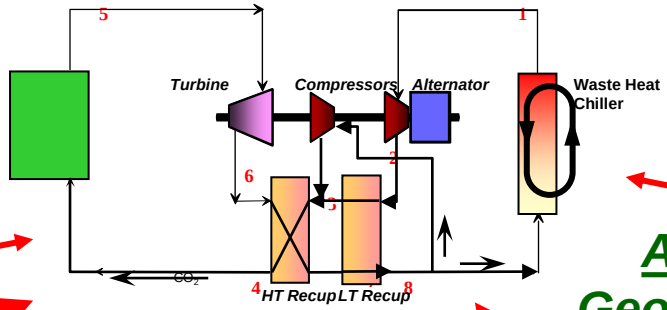
SunShot Power Cycle

DOE-NE Advanced Reactors

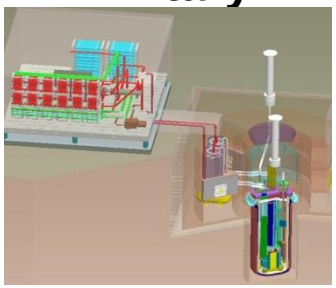
Nuclear (Gas, Sodium, Water)



Supercritical CO_2 Brayton Cycle

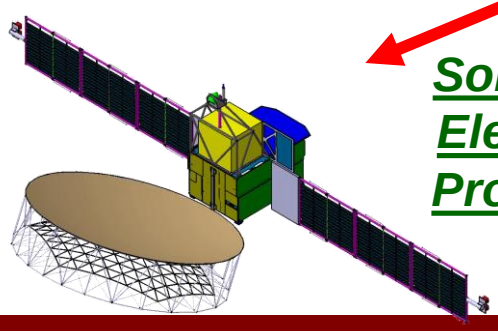


Military



CONUS Marine Mobile?

ARRA Geothermal



Solar Elec. Prop.

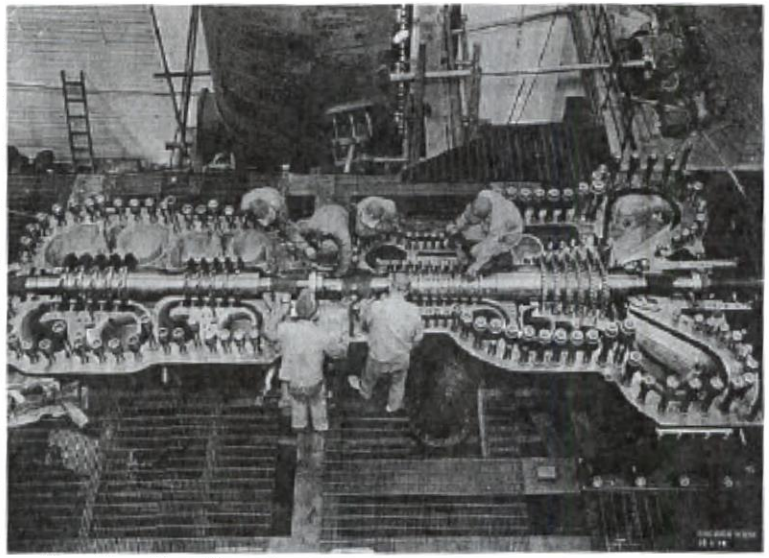
Fossil

Sequestration Ready

The turbomachinery industry has been here before

- **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.**

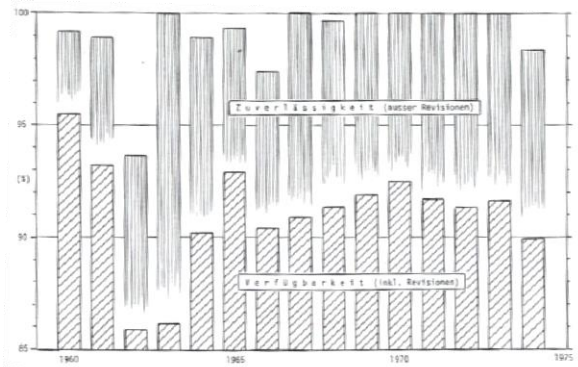
Turbomachinery housing of the **12 MW** Nippon Kokan plant, built by Fuji Electric, based on EW design.



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

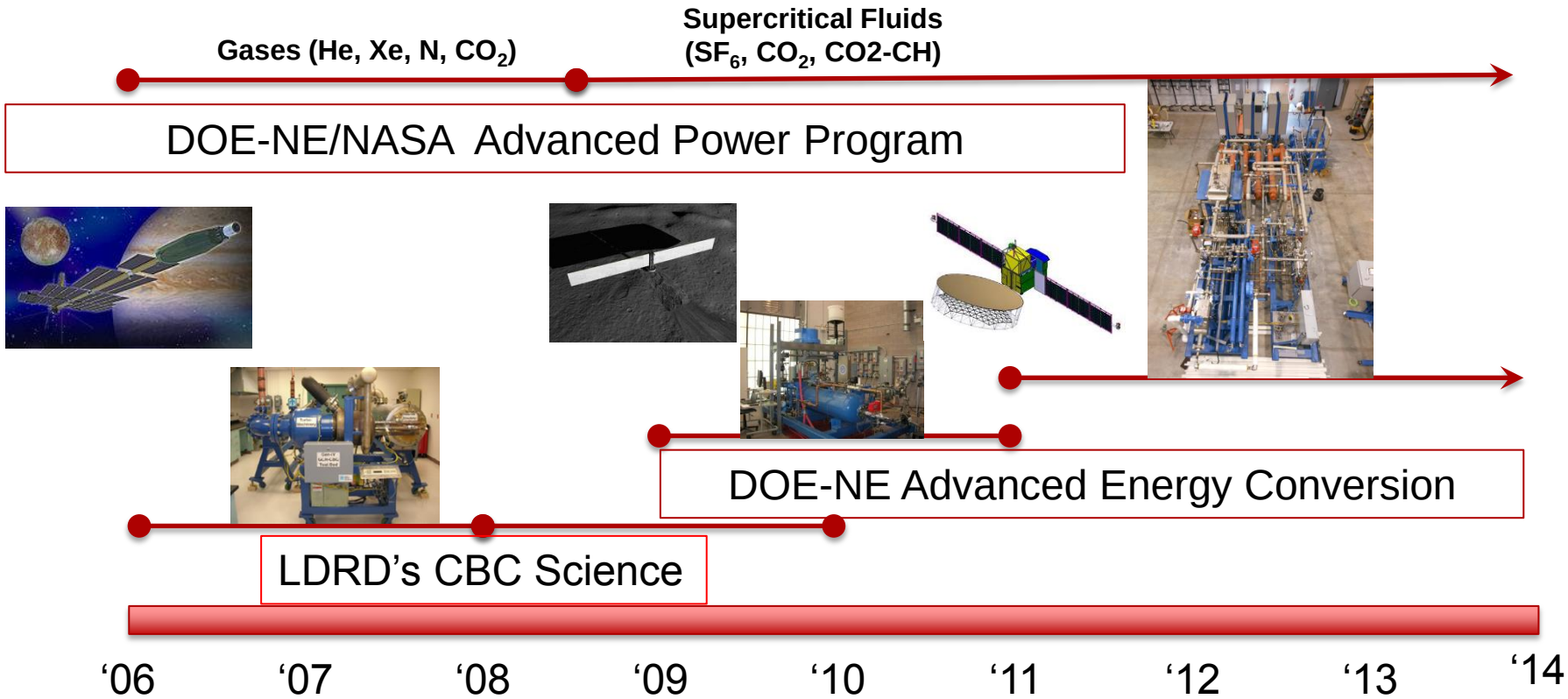
Reliability factor >95%

Availability factor > 90%



History of SCO_2 BC Program @ SNL

- **Late 1960's, innovative designs and working fluids were analyzed, showing very favorable potential, specifically with SCO_2 working in a recompression cycle.**
- **This theory largely lay dormant until Sandia LDRD-funded research yielded promising results in 2006-07.**
- **Sandia research into space based reactors and auxiliary power to support the Jupiter Icy Moon Orbiter (JIMO) program promulgated these LDRD projects.**

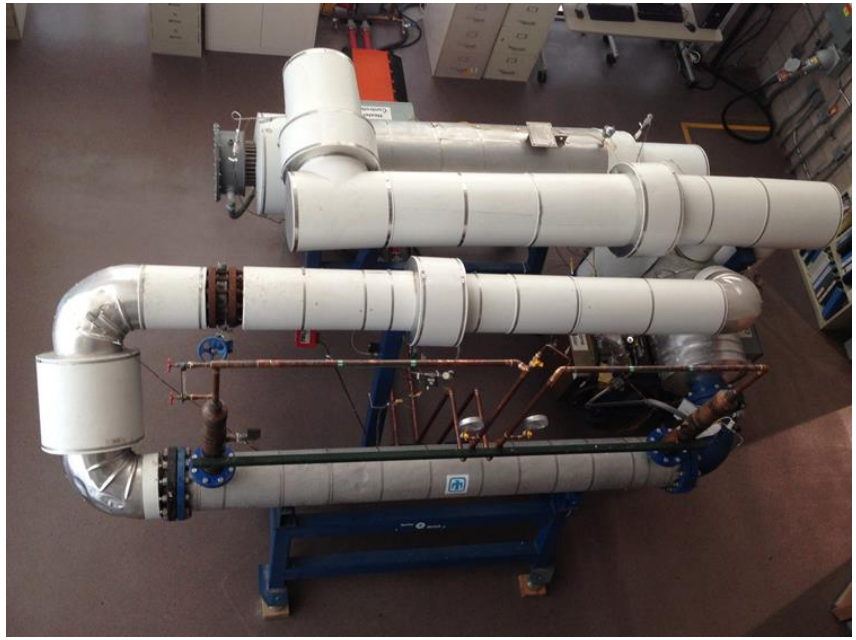


Established Sandia Brayton Facilities

$1.5M LDRD starting in 2006. This demonstrated the viability of the science.

Sandia Research Supercritical fluid Compressor Loop

Sandia Research 10 kW Gas Brayton Loop



Newly added: Valve Calibration Loop
Newly added: Natural Convection, Dry Heat Rejection Loop
Under construction: Heat Exchanger Test Loop, Phase 1 - water
In design: Heat Exchanger Test Loop, Phase 2 – sCO_2

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

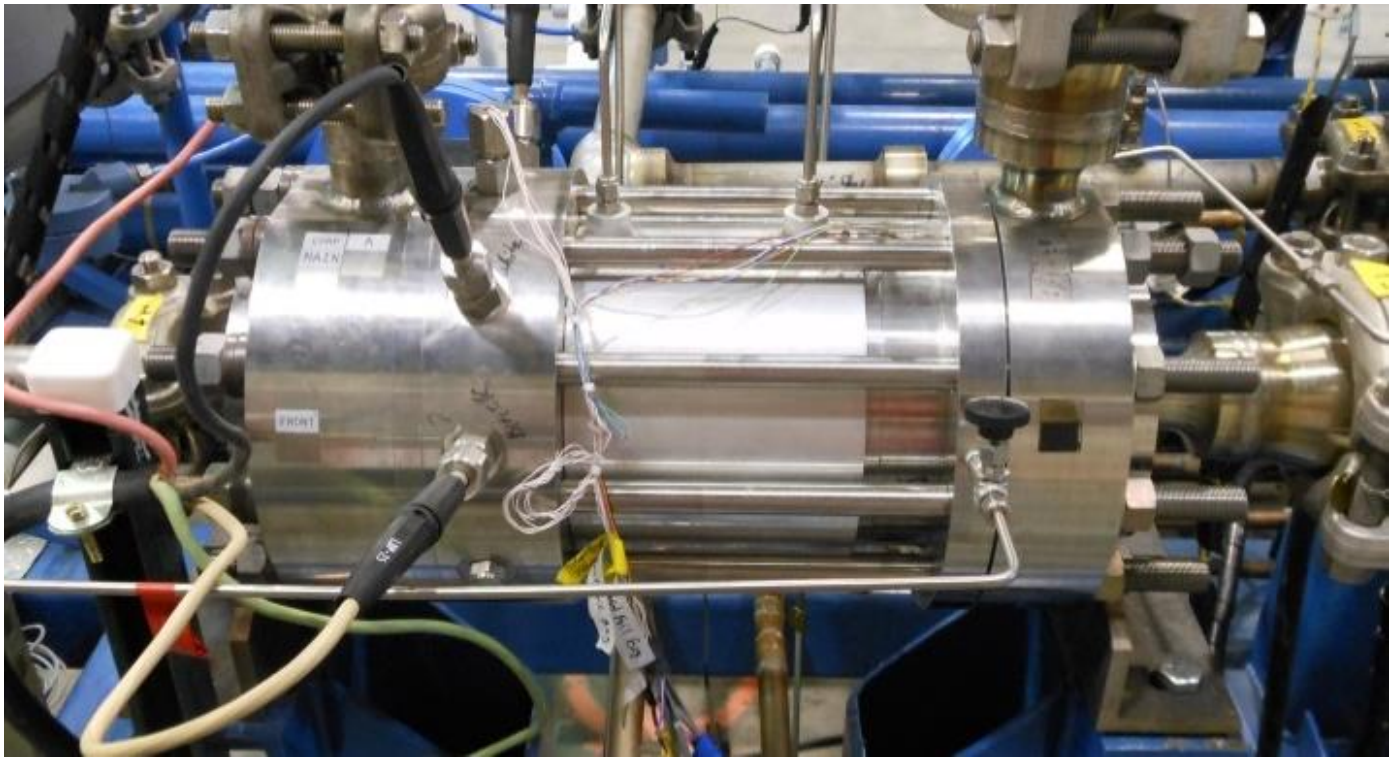
- TA under test since 4/2010
- Over 100 kW-hrs of power generated
- Operated in 3 configurations
  - Simple Brayton
  - GE Waste Heat Cycle
  - Recompression
- Testing of each component
- Verified cycle performance
- Developed Cycle Controls
- Developing maintenance procedures

TA Description:

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

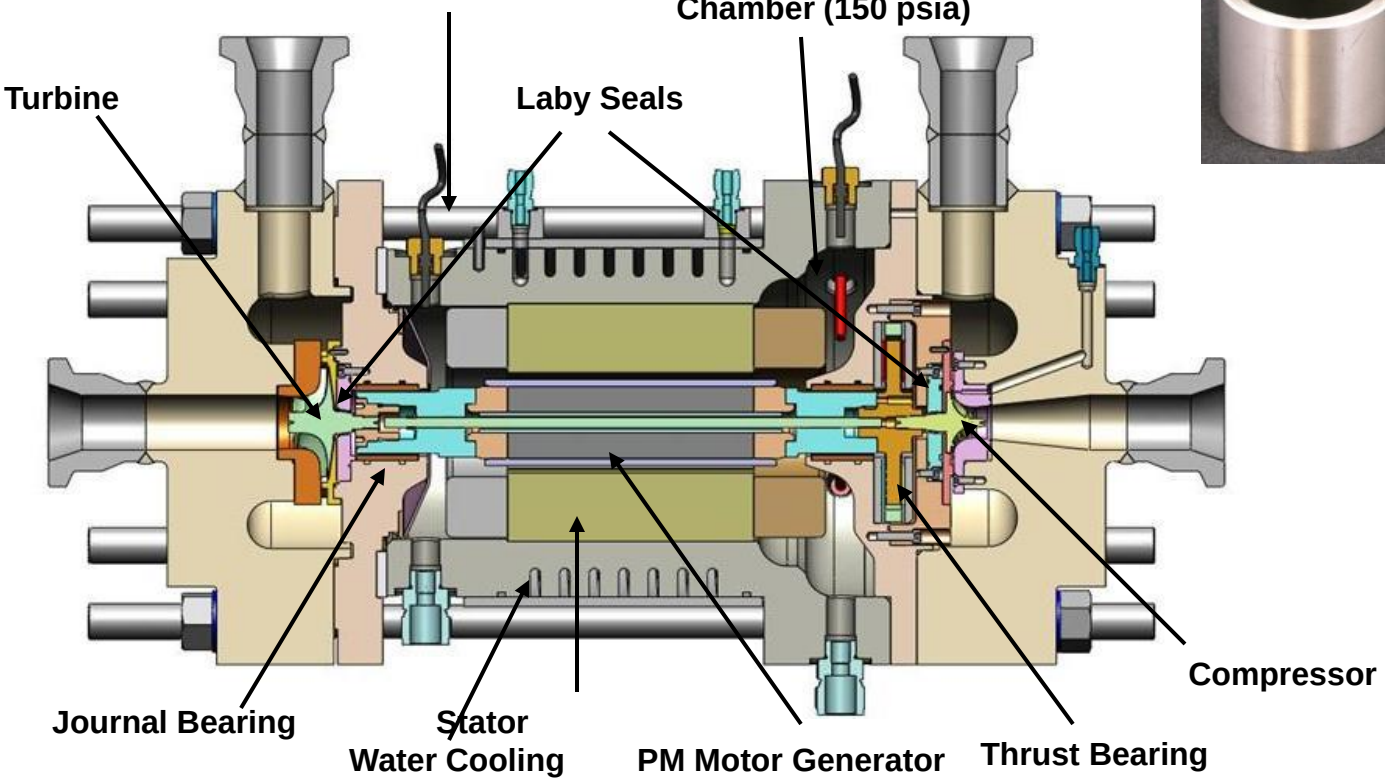
The Turbine-Alternator-Compressor (TAC)

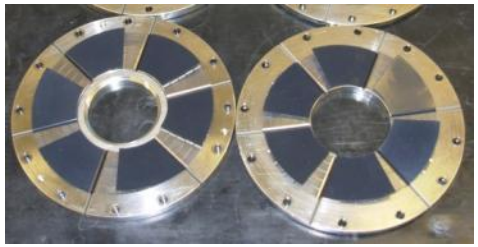


~24” Long by 12” diameter

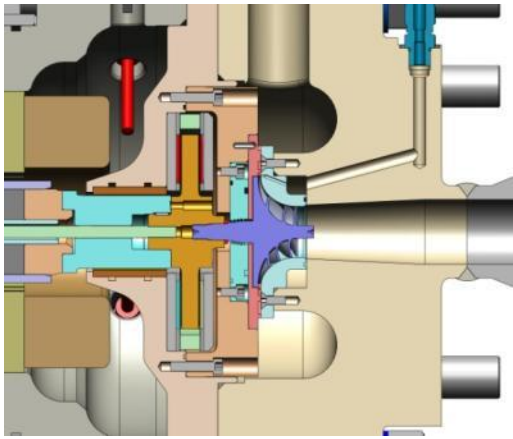
Key Technology
Turbo- Alternator-Compressor Design

Permanent Magnet Generator with Gas Foil Bearings





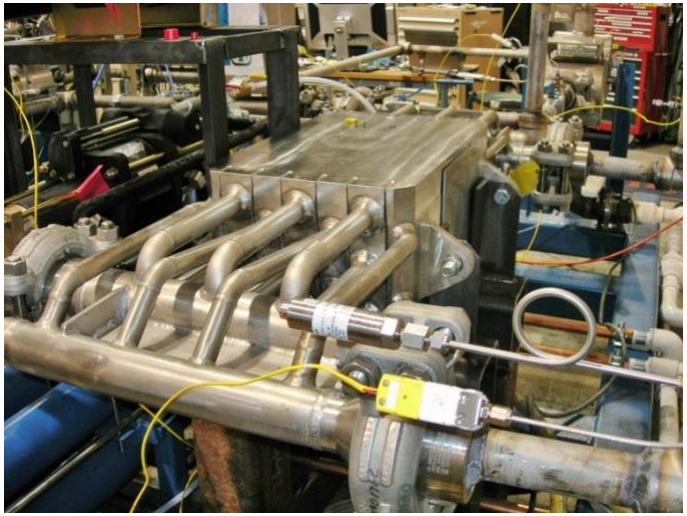
Gas-Foil Bearings



125 kWe (max) at 75,000 rpm

Advanced Heat Exchangers for Low Cost, High Efficiency and Small Volume

High Temperature Recuperator

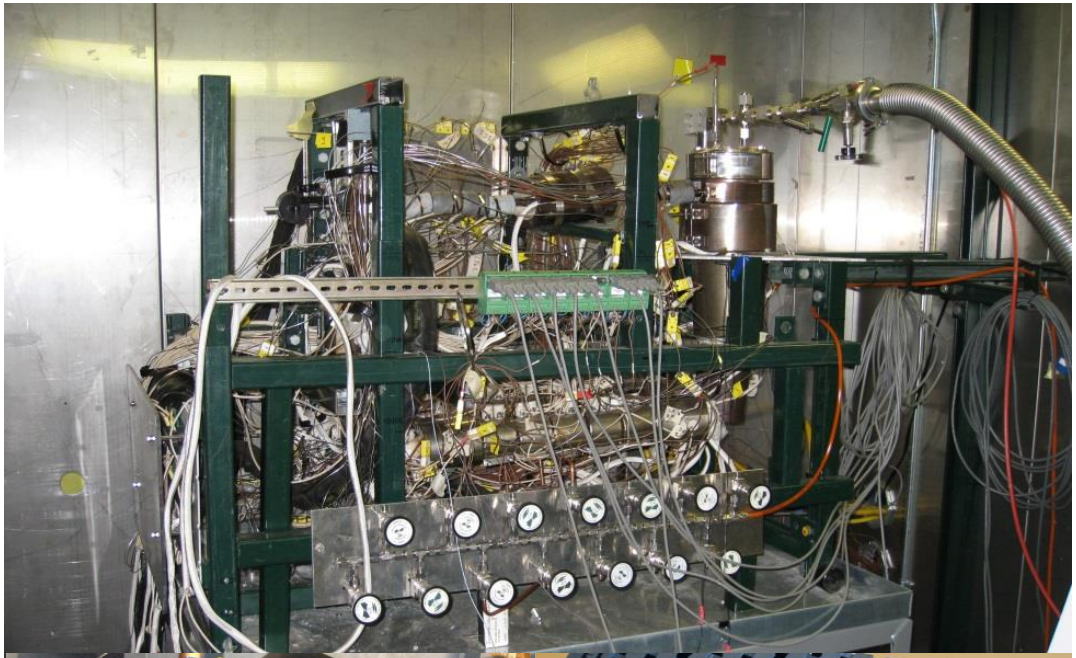


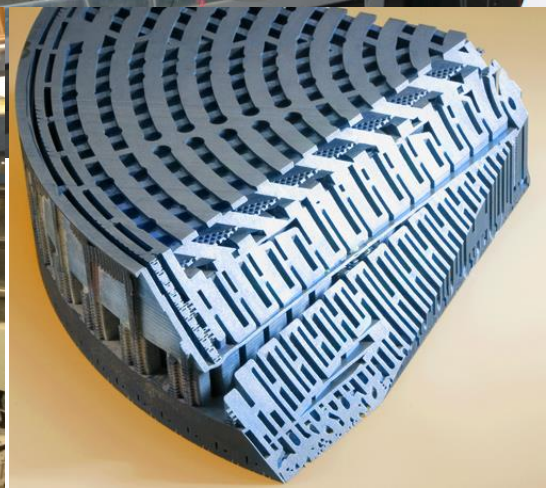
Low Temperature Recuperator

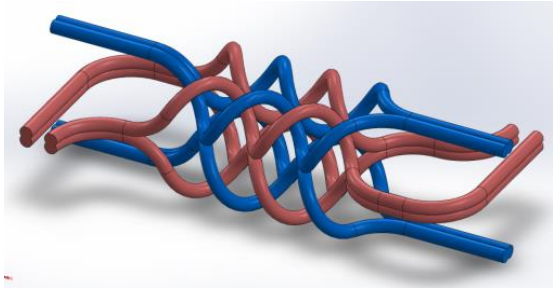
Gas Water Chiller

Prototype Sodium/CO2 PCHE

AdvSMR Energy Conversion Heat Exchanger Development





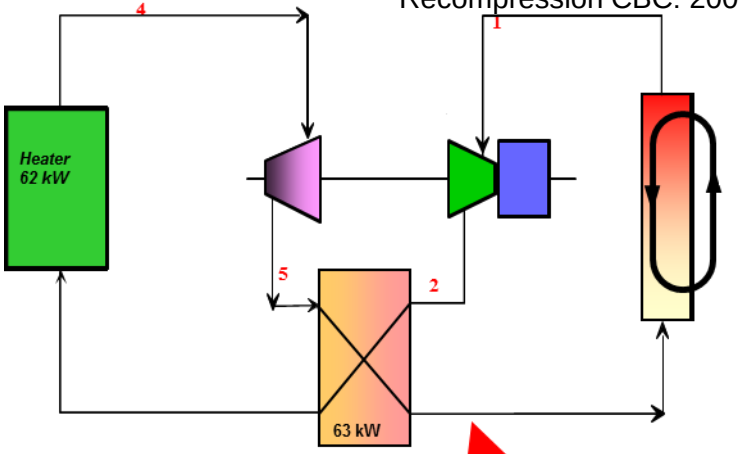


Monolithic Heat Exchanger
Patent Pending

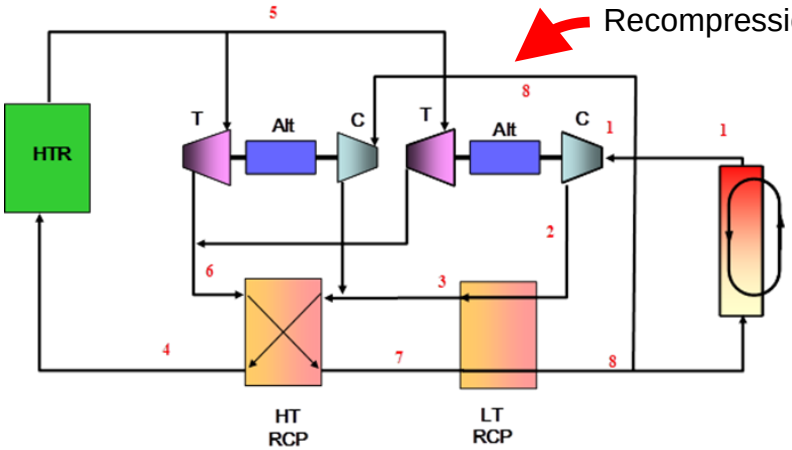
Test Summary and Operational Experience Closed Brayton Cycle (CBC) TA

- Commissioning tests to verified component and system operations.
- First tests simple CBC configuration in April, 2010.
- 37 tests in the simple CBC configuration
- 21 tests in the designed RCBC configuration
- 22 tests in the modified RCBC configuration
- 6 tests in the GE waste heat recovery configuration
- For each test, operational procedures established, performance data analyzed and results logged.
- Each test increases base of operation experience

Cycle Scales:
Air CBC : 10 kW
Simple CBC: 100 kW
Recompression CBC: 200 kW

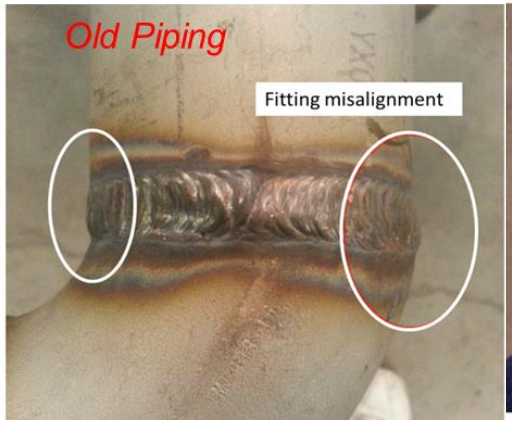


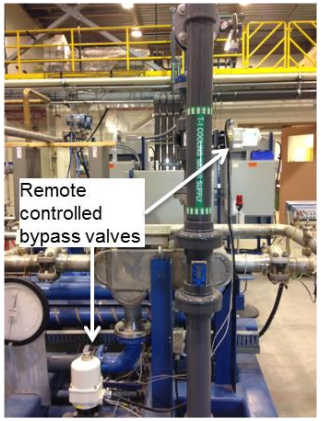
Simple
Recompression

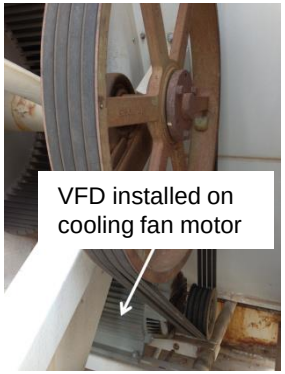


Program Advancement

- **Completed strategic activities**
  - **Efficiency→ highly automated processes implemented**
  - **Capabilities → extensive review of component performance**
  - **Quality of operations → best practices from Space Shuttle program**
  - **Safety → electrical, temperature, pressure, human operations**
  - **Best data review practices from Space Shuttle Main Engine program**
  - **Competitive positioning → mitigating risks and achieving goals**
  - **Achieving design point → eliminate or mitigate losses**
  - **Inventory Control → manage mass loading of the loop**
- **Current Identified Limitation**
  - **Motor/Generator Control →Loss of control at 30-40 kWe**
  - **Bearing Temperatures and Windage**





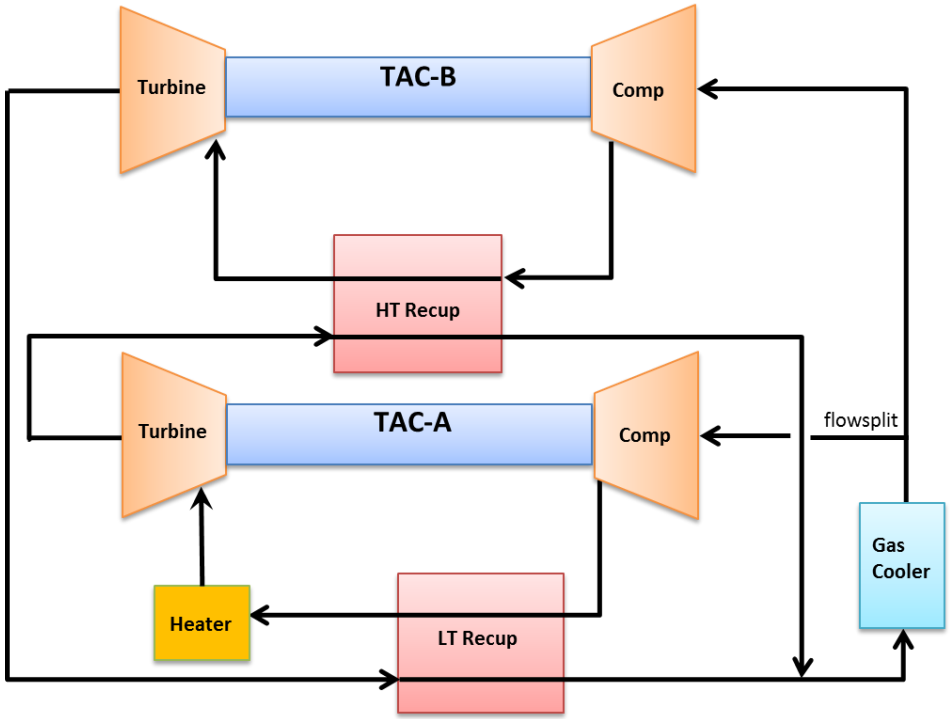


EPRI CRADA

- **EPRI initiated a CRADA in summer, 2013**
  - **Compare RCBC performance with selected cycles**
  - **Perform a literature search of various relevant topics**
- **Primary Brayton cycle comparisons were compared with Advanced Ultra Supercritical Steam cycles.**
  - **The basic RCBC efficiency equaled or exceeded the most complex steam cycles being considered.**
  - **Addition of one stage of reheat plus compressor intercooling adds several percentage points of efficiency to the RCBC.**
- **Important results of this CRADA:**
  - **Application of Sandia Brayton Cycle Models**
  - **Formation of a strong working relationship**
  - **Recognition of our common objective to fully understand sCO_2 benefits**
  - **Continued exchange of information between industry and R&D organizations**

General Electric WFO

- GE Global contracted with Sandia to test GE waste heat recovery concept.
- The Sandia TA re-plumbed to simulate the cycle – lesson learned
- Cycle and piping analyses and construction were accomplished in-house to determine feasibility and safety
- February 12, 2014 was the final test, with objectives defined by customer engineering team achieved except the hot restart



What's Next?

- **Commercialize a RCBC system <u>scalable</u> to 1000 MWe by 2020.**
- **Stronger emphasis on industry collaboration through CRADAs to provide equipment infrastructure resources.**
- **Improve the technology readiness of the technology 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).**
  - **Must be directly "scalable" to market levels and put power on the grid**
  - **Operated at temperatures and conditions of interest.**
  - **Requires a pilot plant at a field site for life and reliability performance.**
  - **Performance must be well understood, modeled and benchmarked.**
    - **start-up and shut-down**
    - **Heat source transients**

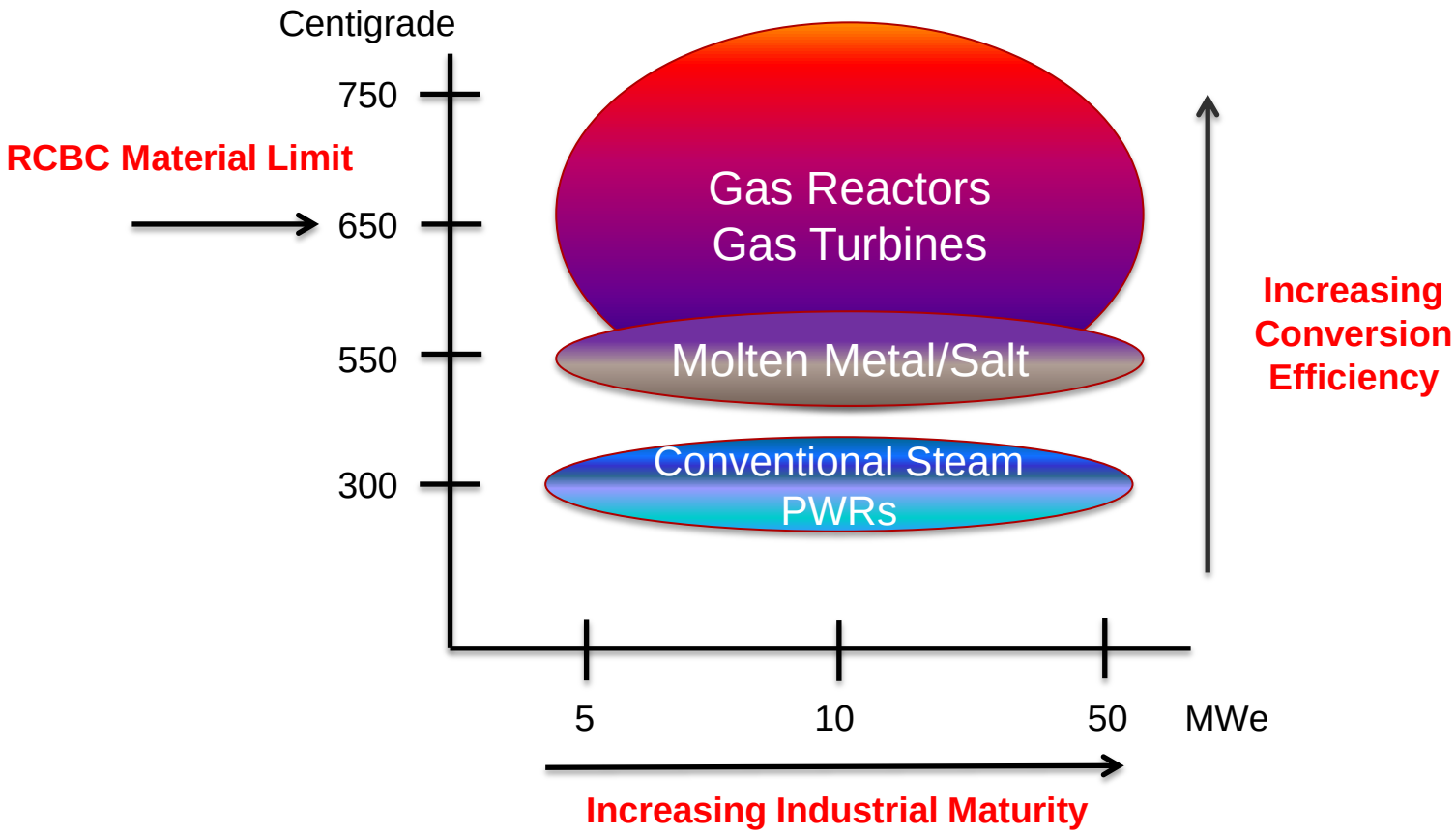
Many requirements push the limits of current technology

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

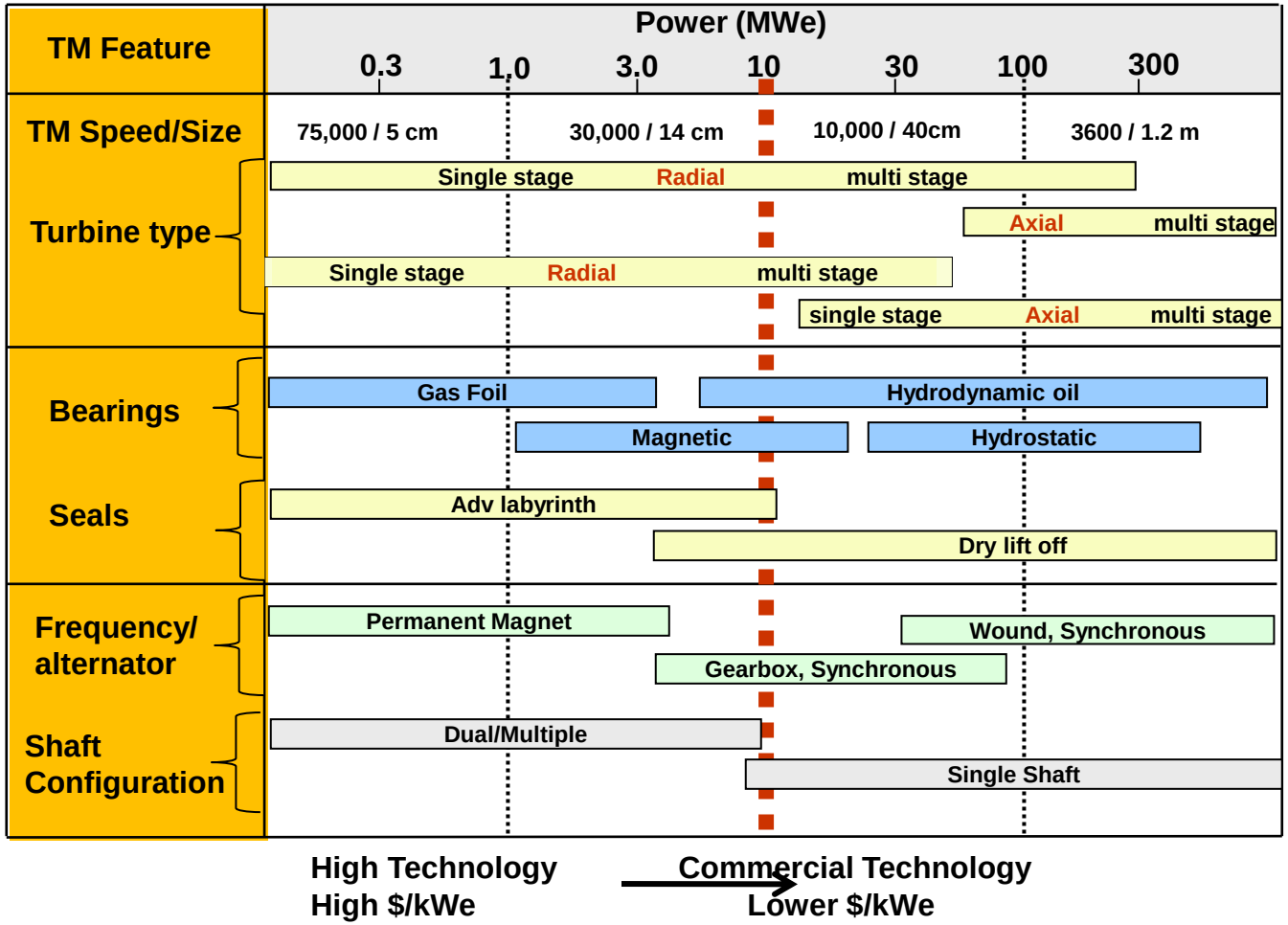
Application	Organization	Motivation	Size [MWe]	Temp [C]	Pressure [MPa]
Nuclear	DOE-NE	Efficiency, Size, Water Reduction	10 – 300	350 – 700	20 – 35
Fossil Fuel (Indirect heating)	DOE-FE, DOE-NETL	Efficiency, Water Reduction	300 – 600	550 – 900	15 – 35
Fossil Fuel (Direct heating)	DOE-FE, DOE-NETL	Efficiency, 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
Shipboard Propulsion	DOE-NNSA	Efficiency, Size	10 – 100	500 – 1000	35
Shipboard House Power	ONR	Efficiency, Size	< 1 – 10	230 – 650	15 – 35
Waste Heat Recovery	DOE-EERE, ONR	Efficiency, Size, Simple Cycles	1 – 10	< 230 – 650	15 – 35
Geothermal	DOE-EERE	Efficiency	1 – 50	100 – 300	15

Demonstration Subsystem Options Survey

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



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



High Technology
High $/kWe

→

Commercial Technology
Lower $/kWe

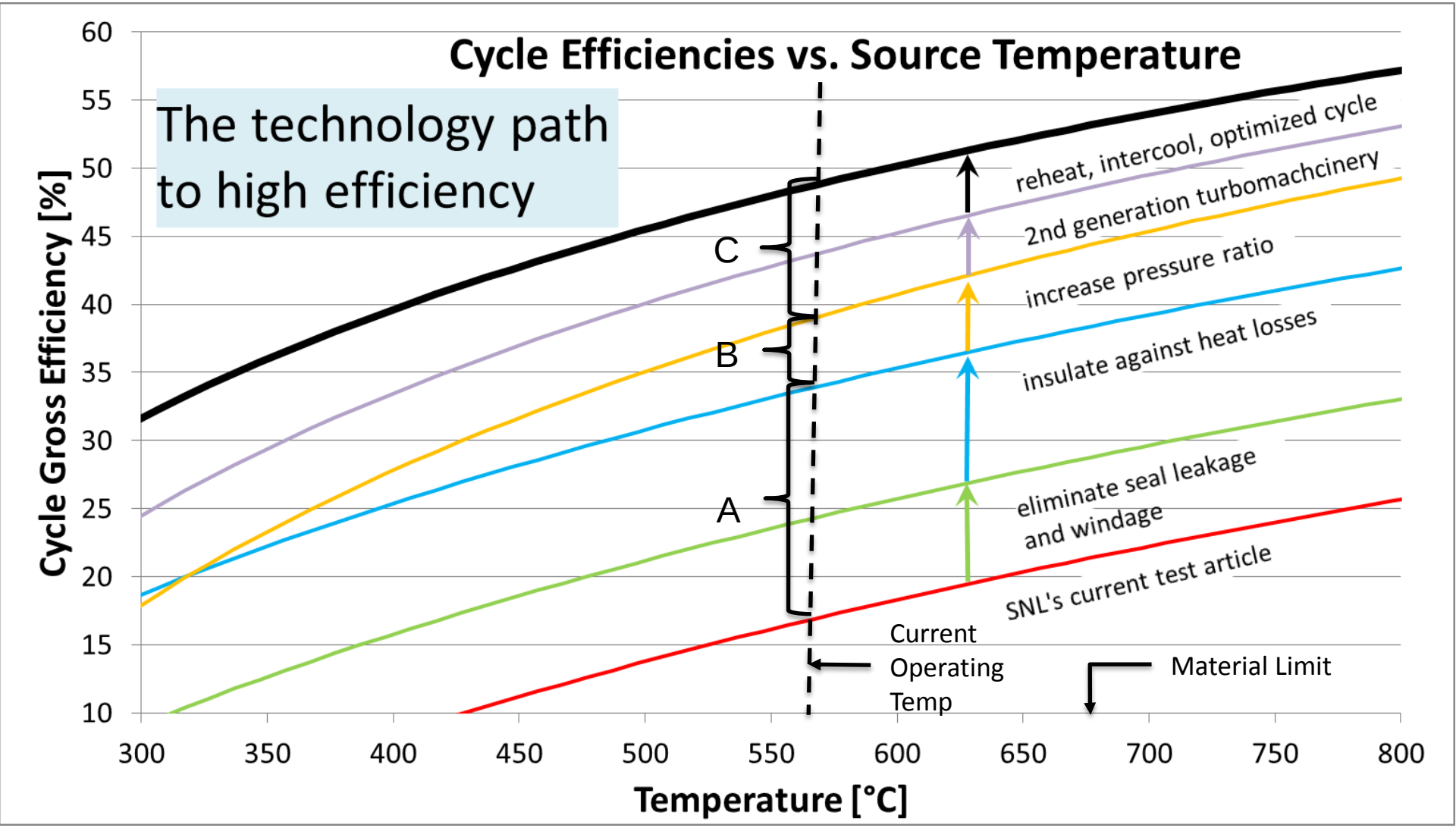
10 MWe allows use of primarily commercial technologies

High Temperature/Pressure Materials needed

125 kWe S-CO2 turbine rotor
550°C, INCONEL 718
(proposed for 700°C service – not in code)

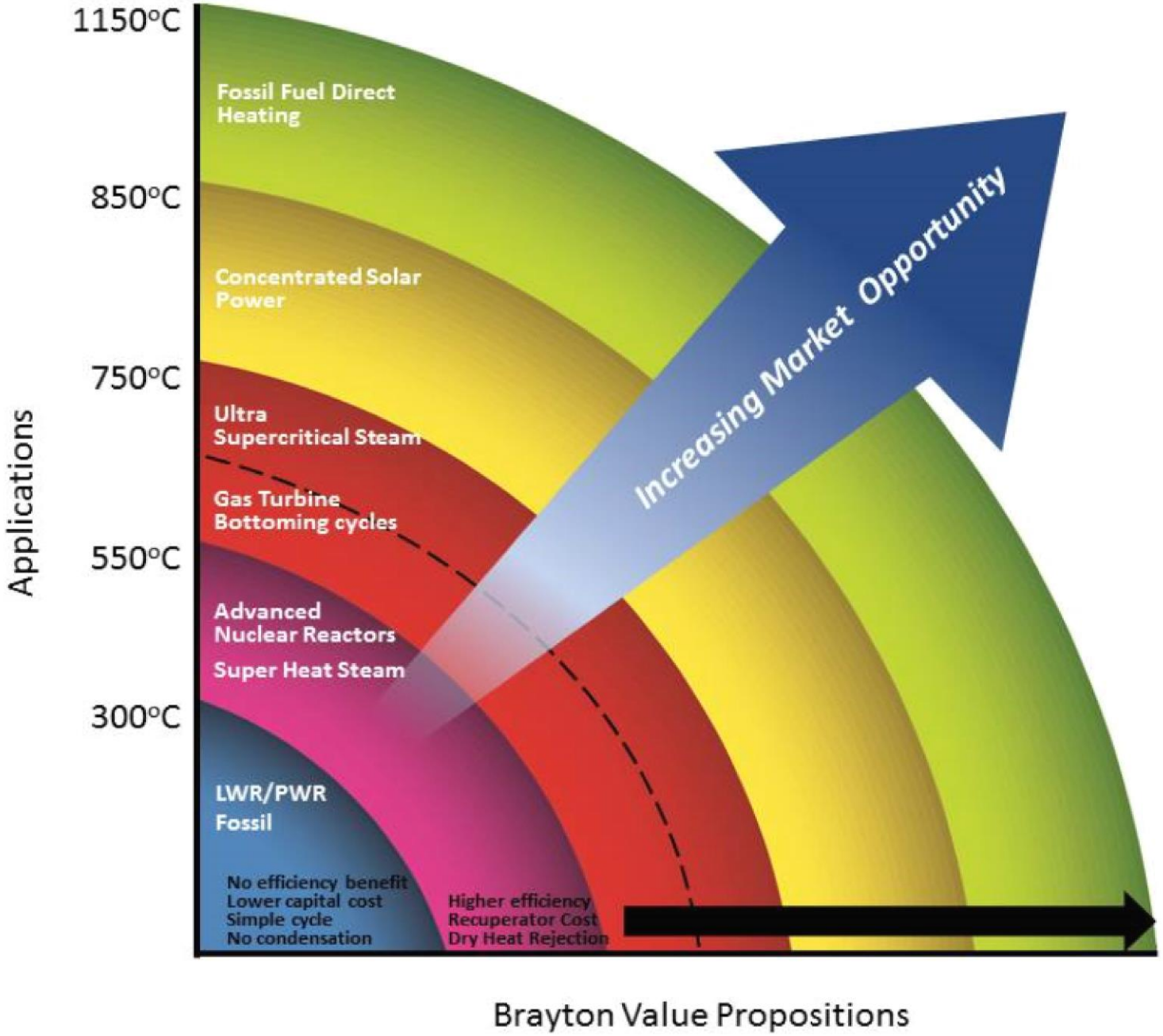
- **Material Issues**:
  - High temperature-high pressure boundaries
  - Primary Heat Exchangers and Piping
  - The goal is high nickel sCO_2 corrosion resistant alloy
  - Large diameter pipe that can handle 850°C at 30 MPa
- **Temperature limit is 650°C**
- **Materials exist:**
  - Manufactures are limited
  - No affordable material
  - Years of lead time

Pathway to High Conversion Efficiency



Near Term Programmatic & Technical Activities

- Programmatic
  - Development of a Comprehensive Technology Roadmap
    - Identify markets leading to RCBC systems
    - Development of “Mission” for the demonstration
- Technical
  - Continued development of the CBC Test Article
    - Continued component testing
    - Continued user support
    - Explore different configurations
    - Establish scaling requirements and specification for large systems
  - Promote operational experience with supercritical fluids
    - Supports larger scale systems
  - Development of components
    - Dedicated systems to establish safety margins
    - Develop maintenance and inspection criteria
    - Corrosion specifications and purity controls


1150°C
850°C
750°C
550°C
300°C
Applications
Fossil Fuel Direct Heating
Concentrated Solar Power
Ultra Supercritical Steam
Gas Turbine Bottoming cycles
Advanced Nuclear Reactors
Super Heat Steam
LWR/PWR
Fossil
No efficiency benefit
Lower capital cost
Simple cycle
No condensation
Higher efficiency
Recuperator Cost
Dry Heat Rejection
Increasing Market Opportunity
Brayton Value Propositions

Exceptional service in the national interest

Sandia National Laboratories

Sandia Mission

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SANDIA's Brayton Mission

"By the end of FY 2019, Sandia National Laboratories shall develop, with industry, a fully operational 550˚C-10 MWe R&D Demonstration SCO_2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology."

Mission System Attributes

- Re-configurable
  - alternative configurations
  - system components
- Formal systems engineering
  - identification and retirement of technical risks
    - Phase 1: establish a foundational technology
    - Phase 2: higher power levels and temperatures
- Demonstrate SNL's capability:
  - Graded approach using applicable scientific and engineering rigor
  - Address development and maturation risks
    - Power on the grid
    - Reduce water
    - Reduce carbon emissions
    - Reduce capital costs based on "industry pull."