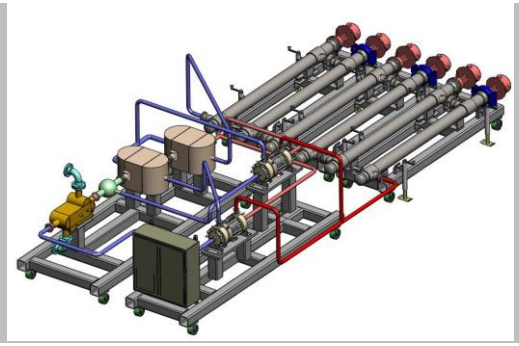
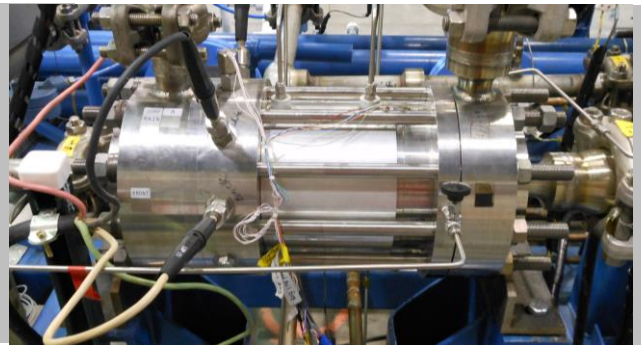
Exceptional service in the national interest

Sandia National Laboratories





Commercializing the sCO_2 Recompression Closed Brayton Cycle

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6221 Advanced Nuclear Concepts
Nuclear Energy Systems Laboratory/Brayton Lab (ne.sandia.gov/nesl)

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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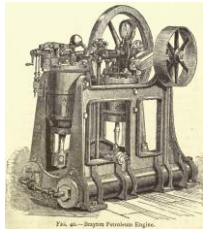
Pathway to "Technology Commercialization"

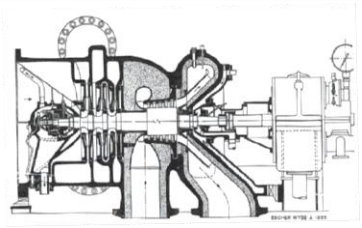
Gov. R&D → Shared Cost → Ind. Development

Scientific Discovery → Brayton Cycle Power Cycle Concept → Gas Brayton Power Cycles → Supercritical Brayton Power Cycles → High Efficiency Brayton Power Generators → **Commercial Brayton Generators**

2nd Law of Thermodynamics (Carnot 1824)

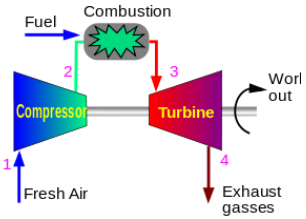


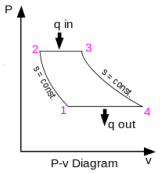
Ready Engine (Brayton 1872)

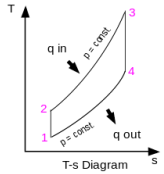


Closed Air Brayton Cycle (Ravensburgh, 1956)

sCO2 Recompression Closed Brayton Cycle (Sandia National Laboratories, 2014)







- R&D Optimized Brayton Cycle Demonstration ~2022
- Simple Brayton Cycle Pilot Demonstration ~2022
- R&D Foundational Demonstration ~2019

Discovery → Laboratory Scale → Prototype/Pilot → Industrialization

General R&D → Specific R&D → Development

Sandia's Energy Conversion Program

- **SNL's high-efficiency thermal-energy-conversion objective is to:**
  - **Lead to science-to-engineering solutions**
  - **High-efficiency heat-to-electricity conversion**
  - **Limit the use of fresh water**
- **Develop supercritical closed Brayton cycle technology by:**
  - **Solving materials-science challenges,**
  - **Applying system engineering,**
  - **Integrating and up-scaling existing technology, and**
  - **addressing operational-control challenges at or near the critical point of fluids**

Recompression Closed Brayton Cycle (RCBC) Test Article (TA) at Sandia National Labs

- **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**
- **Developed Cycle Controls**
- **Progressing toward power generation**
- **Developing maintenance procedures**

TA Description:

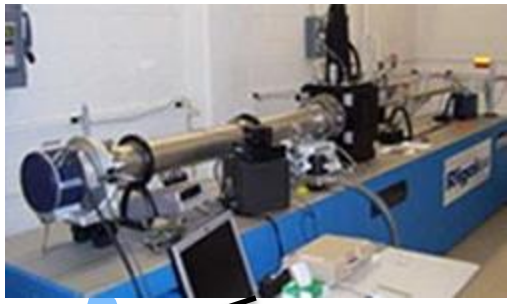
Heater – 750 kW, 550°C
Max Pressure - 14 MPa
TACs – 2 ea, 125 kWe @ 75 kRPM,
2 power turbines, 2 compressors
High Temp Recuperator - 2.3 MW duty
Low Temp Recuperator – 1.7 MW duty
Gas Chiller – 0.6 MW duty
Load Bank – 0.75 MWe
Gas Compressor to scavenge TAC gas
Inventory Control
Turbine Bypass(Remote controlled)
ASME B31.1 Coded Pipe, 6 Kg/s flow rate
Engineered Safety Controlling Hazards
Remotely Operated

DOE Laboratory R&D Partnerships

SNL Solar Test Facility

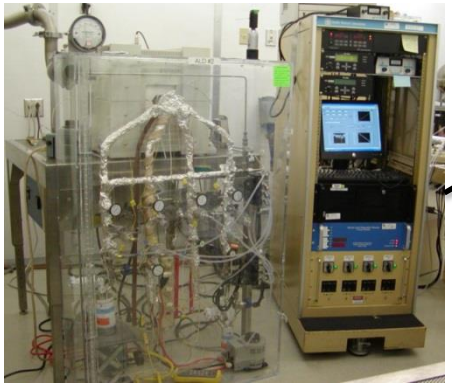
SNL Brayton Laboratory

UW-Madison Stress Corrosion

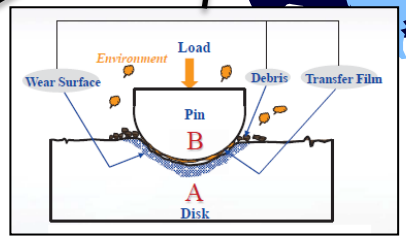


SNL Materials Chemistry

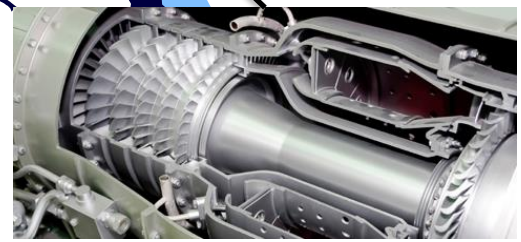
ANL Material Corrosion Lab



SNL Surface Materials & Coatings



SNL Tribology



ORNL Advanced Structural Materials

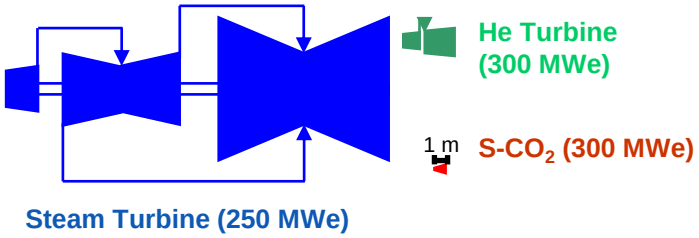
Status of the Commercial Development Effort

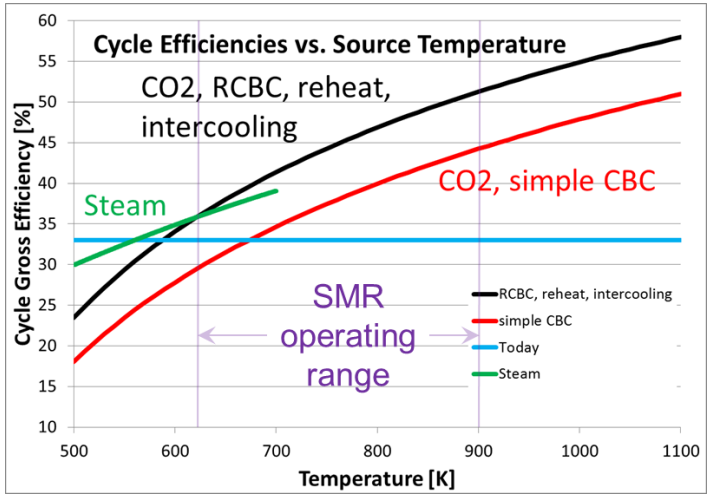
Sandia National Laboratories

- **Proof of Concept S-CO_2 loops**
  - **SNL, Echogen, KAPL-Bettis, Czech Republic, Japan, GE-GRC**
- **Gas Turbine Bottoming Cycle**
  - **3 Corporations; 10 MWe**
- **Solar Towers**
  - **2 Corporations; 1-10 MWe**
- **Carbon Capture & Sequestration**
  - **3 Corporations, 5, 7, 70 Mwe**
- **Waste Heat Recovery**
  - **3 Corporations**

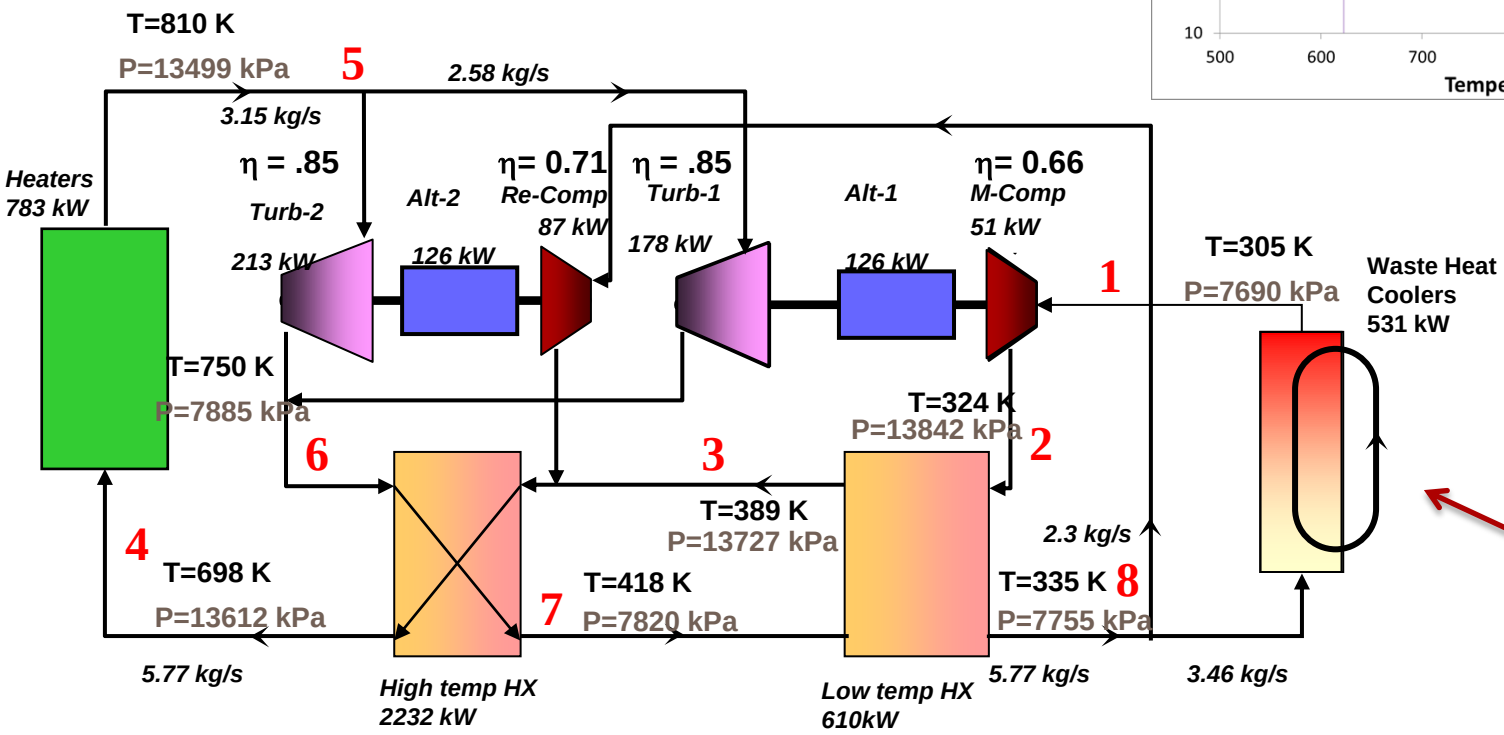
SNL/DOE Design Target for Proof-of-Principle Split-Flow Re-compression S-CO_2 Brayton Cycle

Sandia National Laboratories





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



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

The Sandia test assembly

Supercritical CO_2 Cycle Applicable to Most Thermal Sources

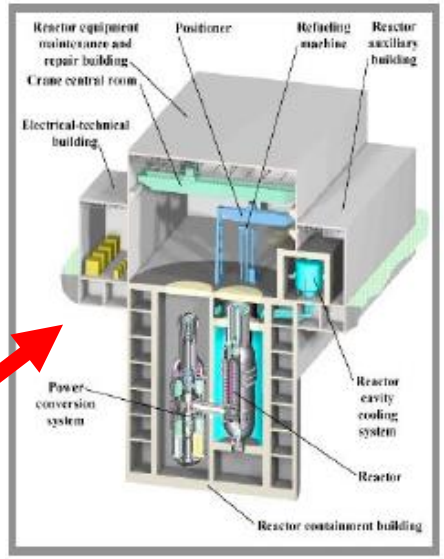
Sandia National Laboratories

Solar

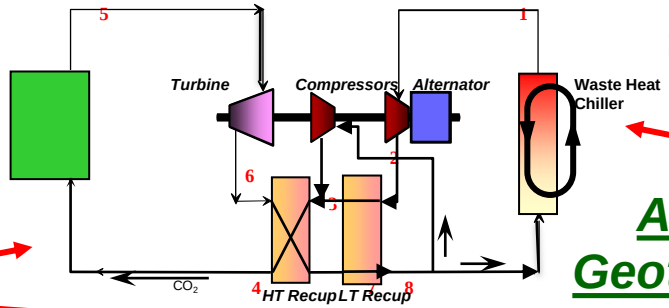
SunShot Power Cycle

Nuclear
(Gas, Sodium, Water)

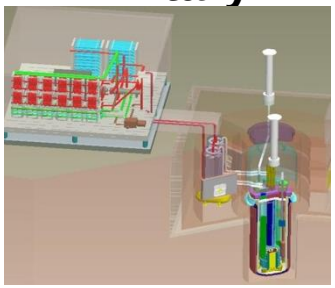
DOE-NE Advanced Reactors



Supercritical CO_2 Brayton Cycle

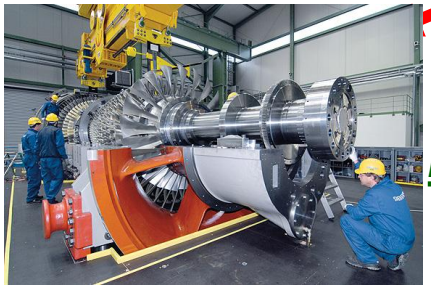


Military



CONUS Marine Mobile?

ARRA Geothermal



Gas Turbine Bottoming

Fossil

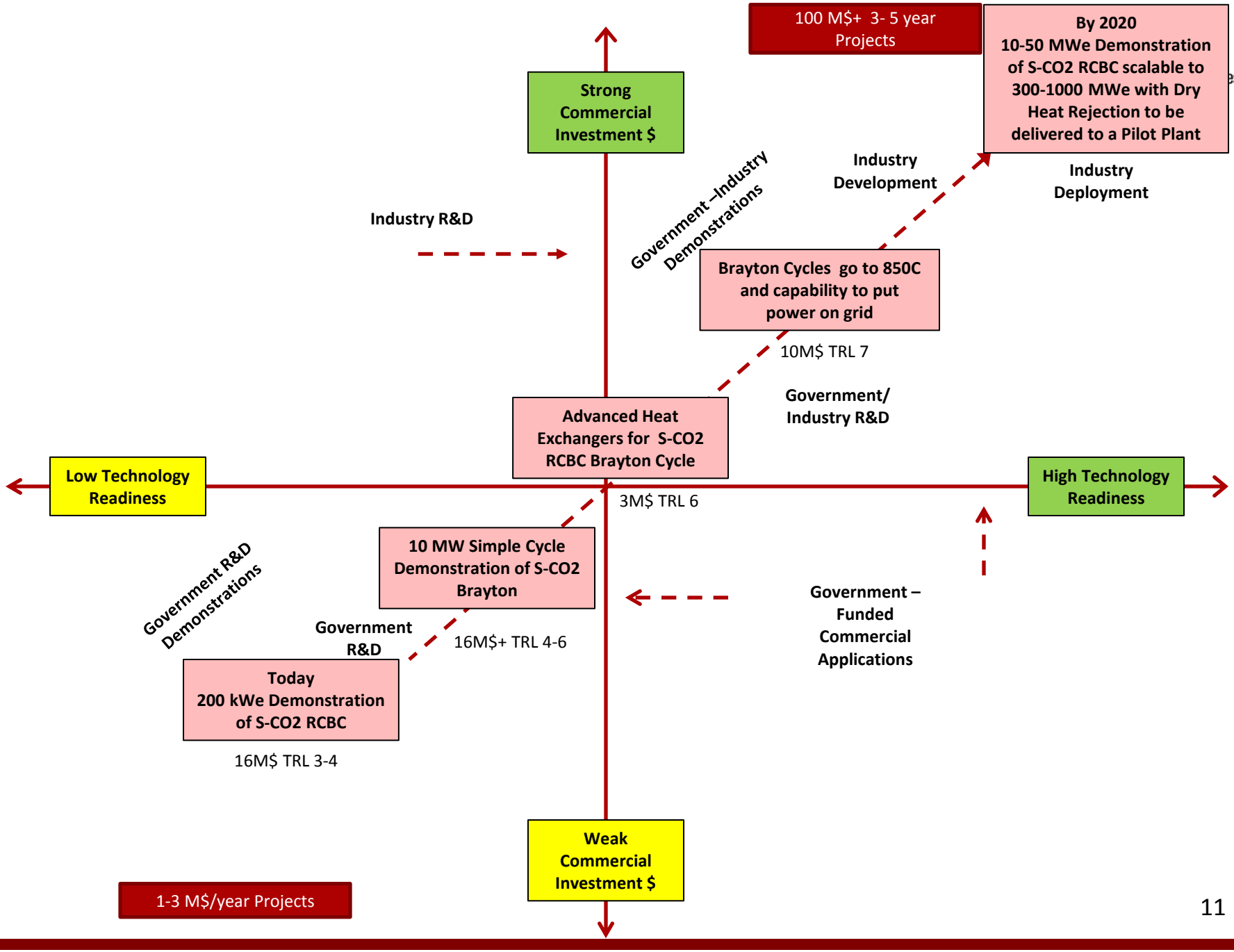
Sequestration Ready

Sandia's Mission Focus

- **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."**
- **System Attributes**
  - **Re-configurable** to allow the testing of commercially attractive configurations and system components that can be transferred to industry
  - **Formally applied systems engineering** in the identification and retirement of technical risks in a phased approach
    - Phase 1: to first proceed from the existing 150KWe system to the 10 MWe-550˚C system
    - Phase 2: to higher power levels and temperatures after 2019
  - **Demonstrate SNL's capability** to systematically:
    - Apply graded approach using applicable scientific and engineering rigor
    - Address development and maturation risks of commercially viable technologies for putting power on the grid, reducing the use of water, reducing carbon emissions, and/or reducing capital costs based on "industry pull."

Commercialization Approach

- Broaden Industrial Engagement in R&D
  - Identify industrial stakeholders through Federal Business Opportunities to seek “funds-in” CRADAs for technology development
  - Offer IP portfolio for licensing
  - Use NE program funds/facilities to address technical risks expressed by industry
  - Recognizing R&D capabilities of SNL and utilizing facilities
- Demonstrate Foundational Technology
  - At the highest possible temperature with code qualified materials
  - At the highest practical power level that leads to a pilot demonstration and “market pull”
- Initial engagements will build a foundation to a “R&D consortium” for advancing the TRL level for larger scale and higher temperature demonstrations
  - Primary Funding from Industry – Industry design role
  - Seed money from DOE – System Integration, demonstration, and evaluation
  - Government use licensing
- DOE support “might” end at Pilot Scale Demonstration


100 M$+ 3- 5 year Projects
By 2020
10-50 MWe Demonstration of S-CO2 RCBC scalable to 300-1000 MWe with Dry Heat Rejection to be delivered to a Pilot Plant
Strong Commercial Investment $
Industry Development
Industry Deployment
Industry R&D
Government –Industry Demonstrations
Brayton Cycles go to 850C and capability to put power on grid
10M$ TRL 7
Government/ Industry R&D
Advanced Heat Exchangers for S-CO2 RCBC Brayton Cycle
Low Technology Readiness
High Technology Readiness
3M$ TRL 6
10 MW Simple Cycle Demonstration of S-CO2 Brayton
Government R&D Demonstrations
Government R&D
16M$+ TRL 4-6
Government – Funded Commercial Applications
Today
200 kWe Demonstration of S-CO2 RCBC
16M$ TRL 3-4
Weak Commercial Investment $
1-3 M$/year Projects