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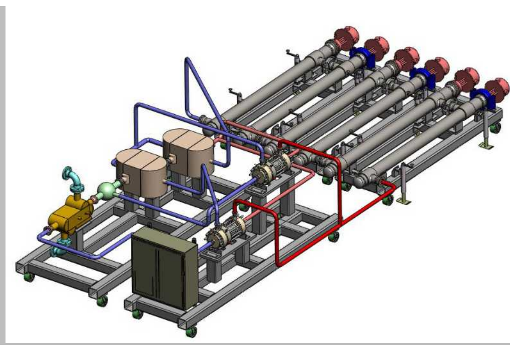

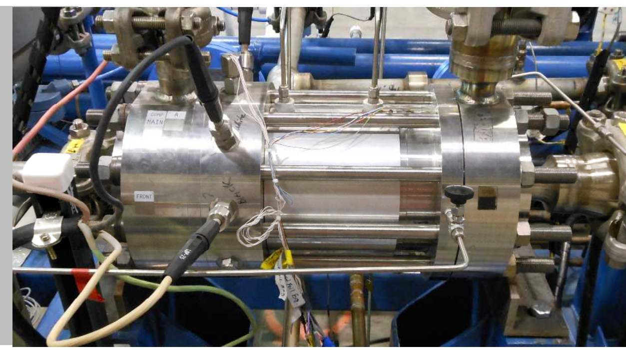

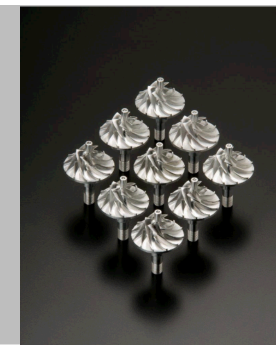

Supercritical Carbon Dioxide Closed Brayton Cycle: Development and Applications

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

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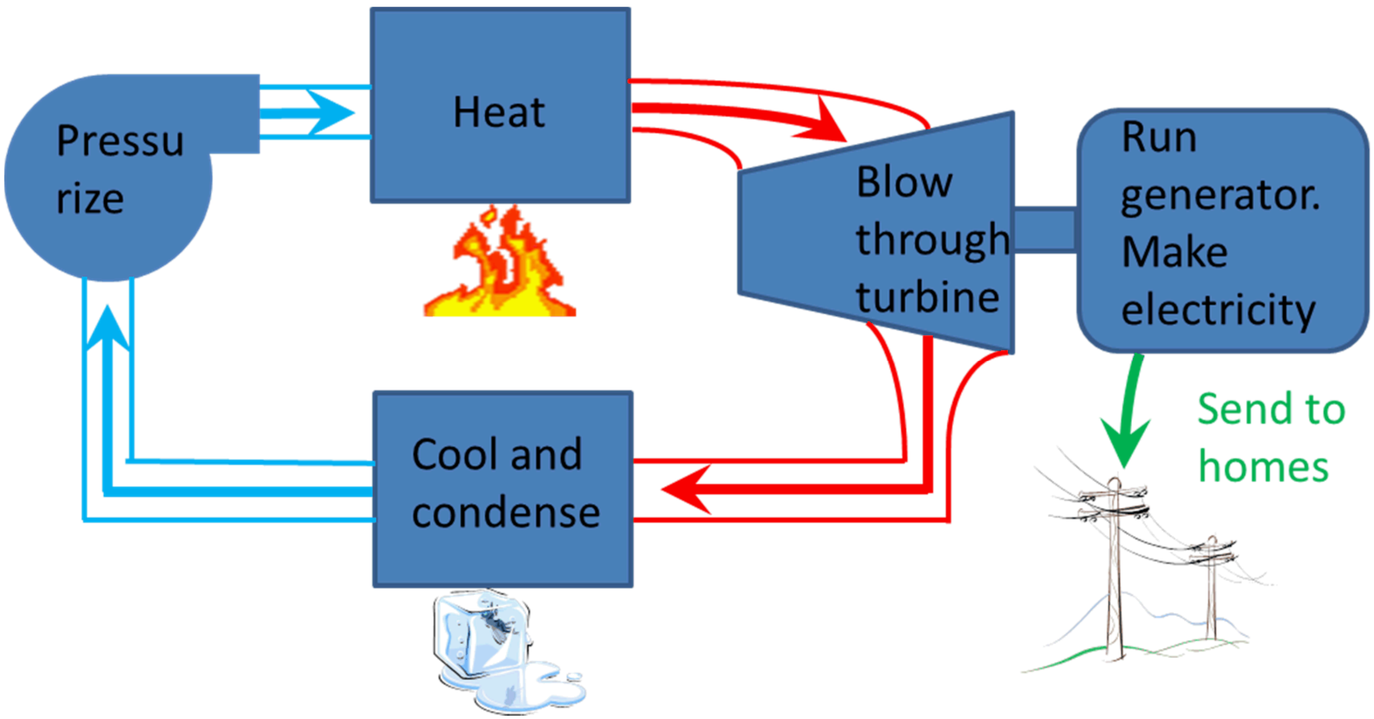
Overview

- The closed Brayton cycle; what is it
- History of the closed Brayton power conversion cycle
- The cycle renaissance
- Sandia's role
- Long term objectives
- Summary
- Q&A

What is it?

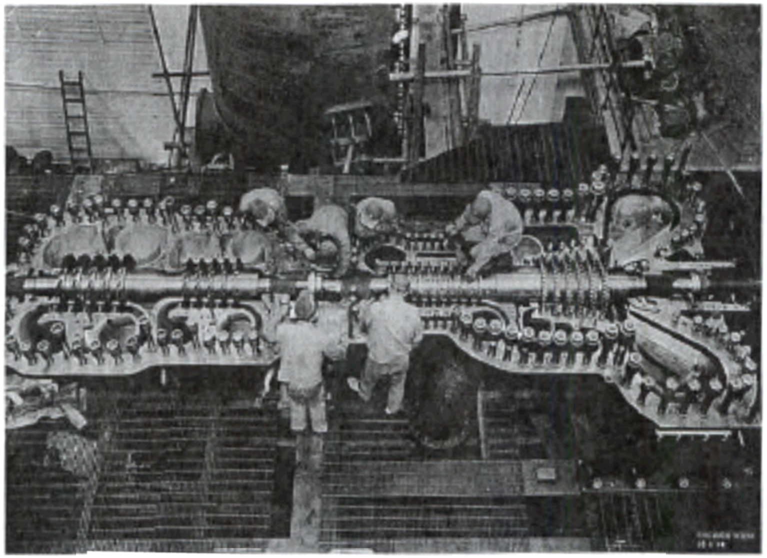
- A jet engine is an open Brayton cycle
- In a closed Brayton cycle, the exhaust from the turbine is sent back to the compressor.
  - Fuel injection and burn → heat source and heat exchanger
  - Heat rejection becomes necessary

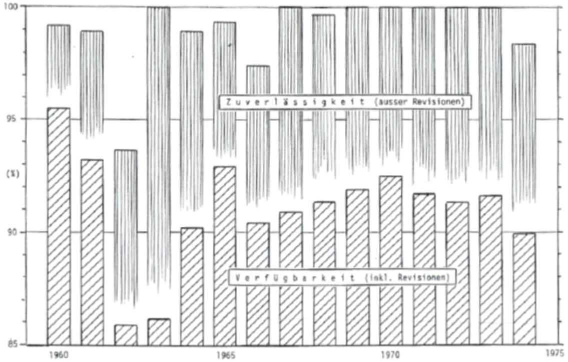


The turbomachinery industry has been here before using air

- **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.





Reliability factor > 95%

Availability factor > 90%

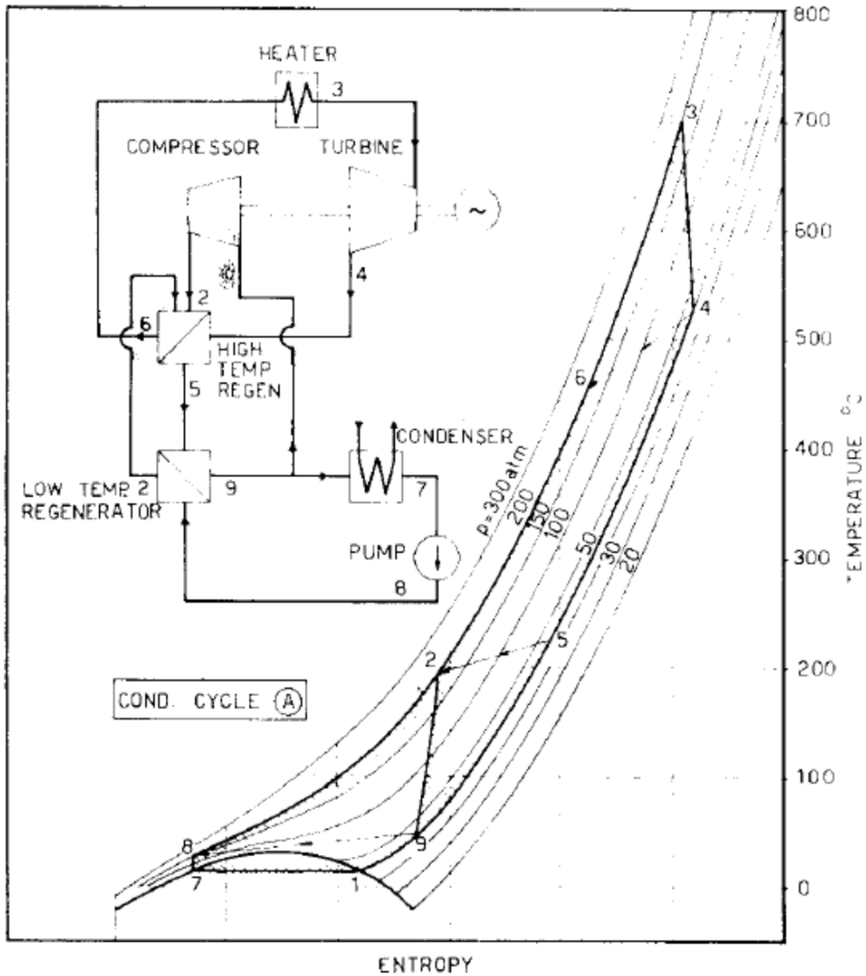
Air Brayton Cycles – Observations and Conclusions

- Significant history of successful and reliable operation of recuperated CBC's.
  - Air as working fluid
  - Large variety of fuels
  - Simple cycles only, but with compression intercooling
- Efficiency ceiling using air is relatively low, and steam cycle efficiencies improved over the decades, eventually rendering the air cycles noncompetitive.
- As a result, no air CBCs are operating today.

CBC Renaissance

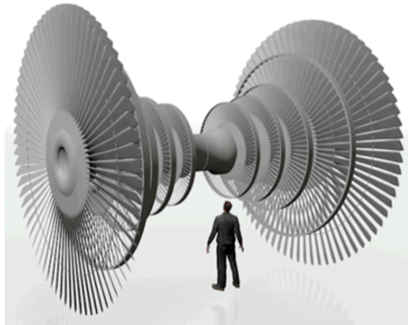
Science – Analysis

- Italian professor Angelino investigated cycle improvements and published conclusions in late 1960's.
- Focused on inefficiencies and working fluid.
- Identified recompression cycle (RCBC), using SCO2.
  - Cycle internal heat recuperation optimized.
  - Favorable CO2 critical temperature (88 ^{o}F, 31.4 ^{o}C, 304.4 K).



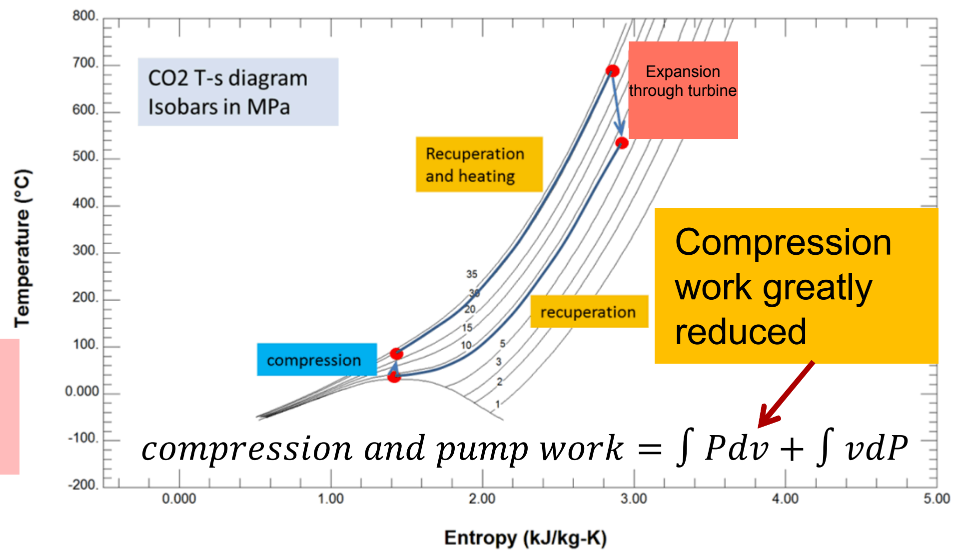
The Brayton Cycle and S-CO_2

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

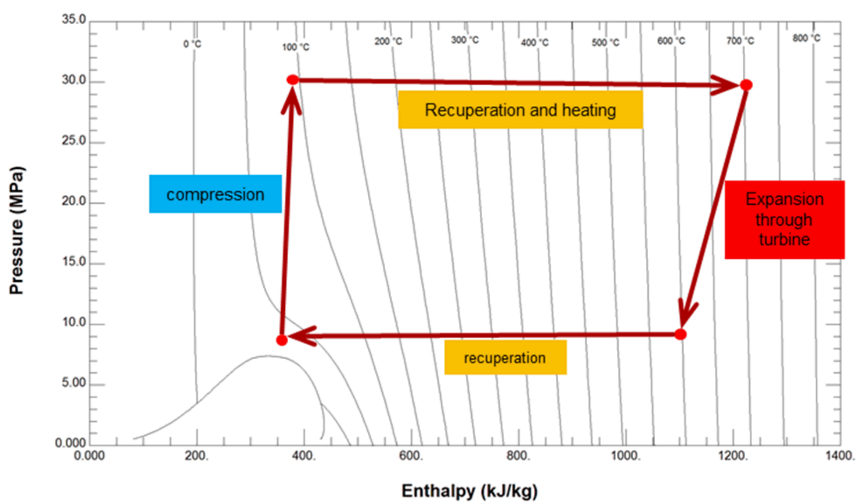


1 meter sCO_2
(300 MWe)
(Brayton Cycle)

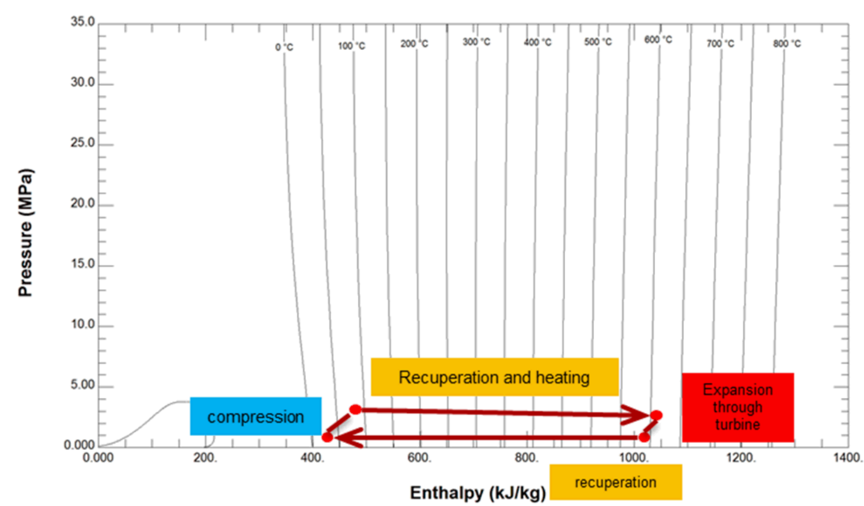
Small turbomachinery



$$compression\ and\ pump\ work = \int Pdv + \int vdP$$



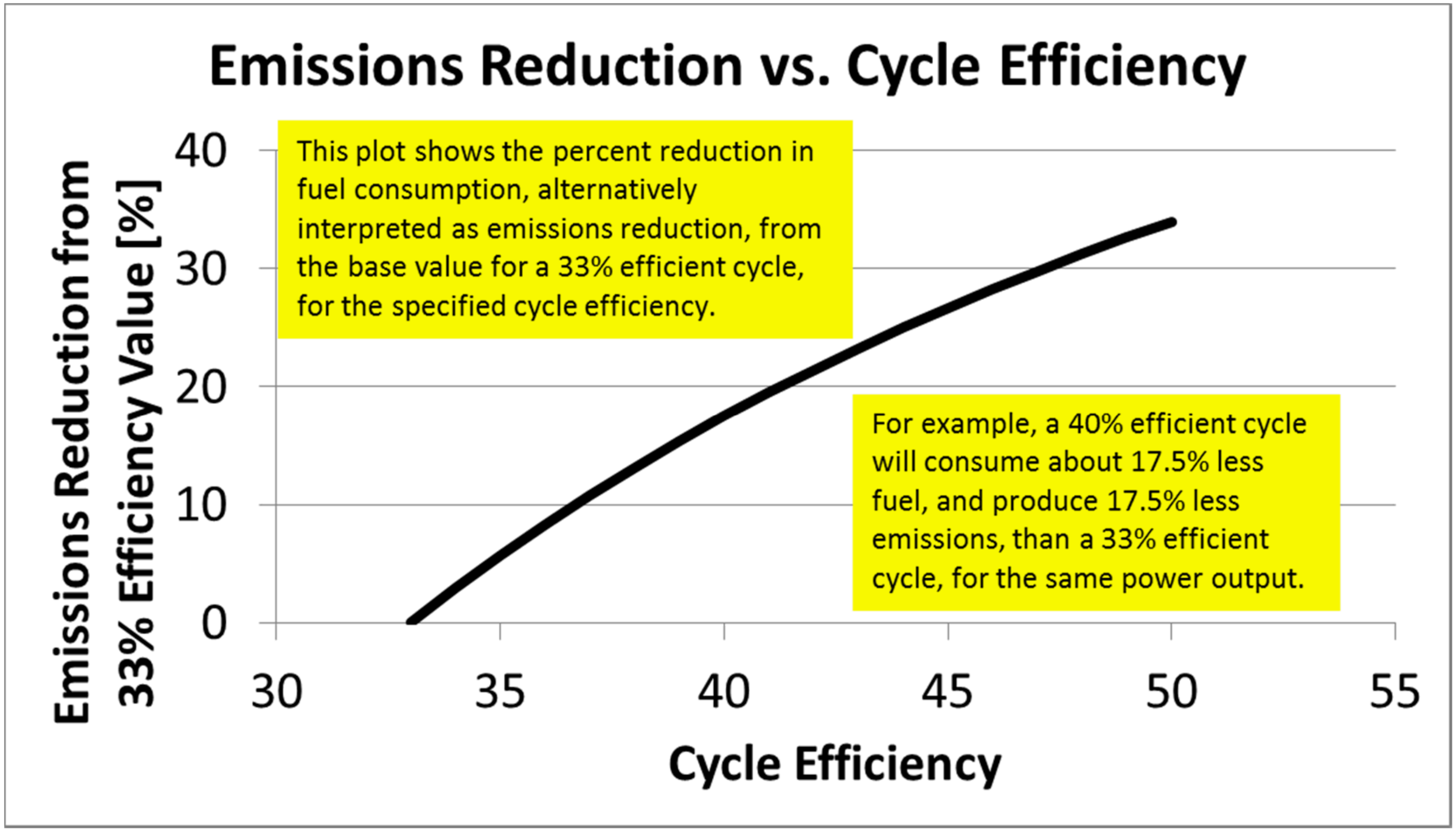
S-CO2 p-h diagram



Air p-h diagram

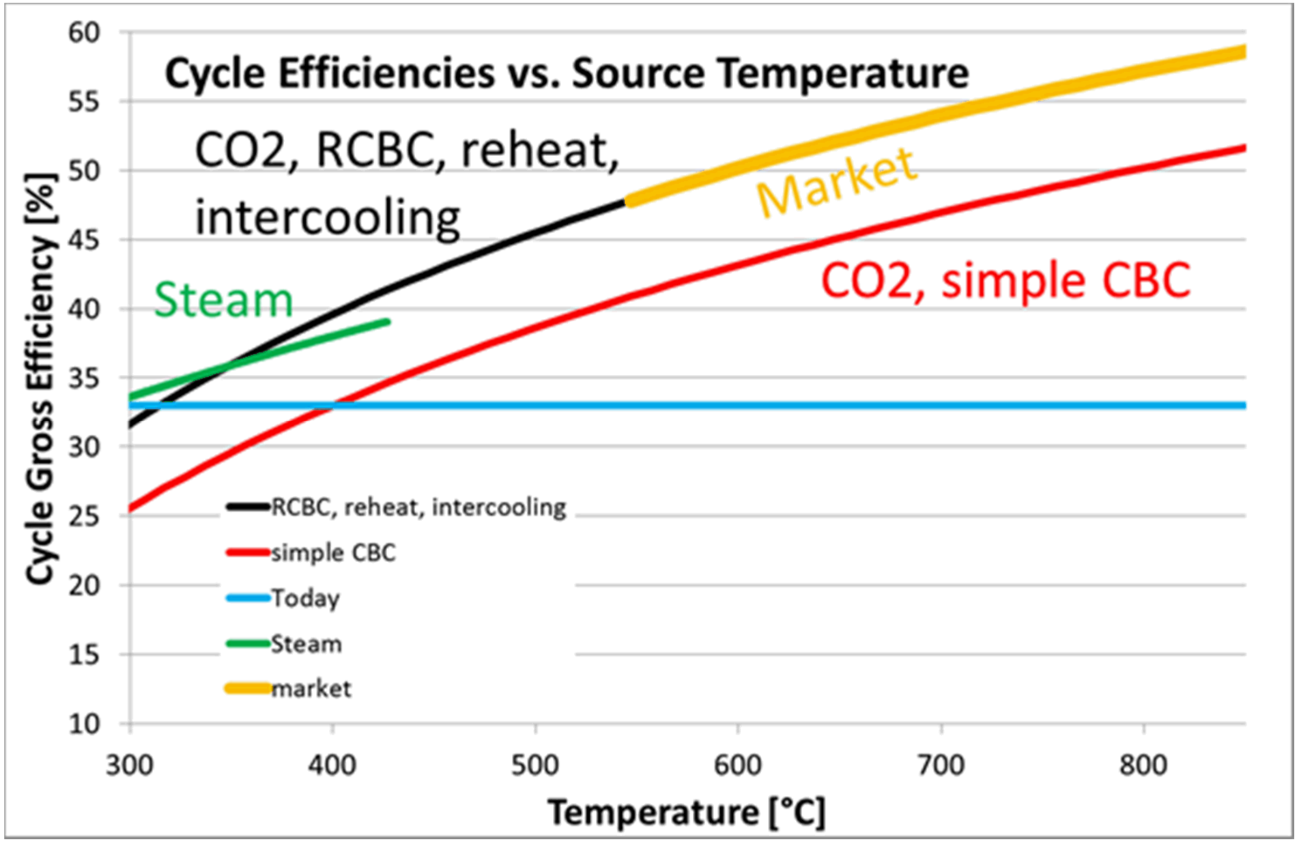
sCO_2 Benefits & Challenges

- Environmental improvement
  - Greenhouse gas reduction
  - Reduced water consumption
  - Dry cooling/suitable for arid environments



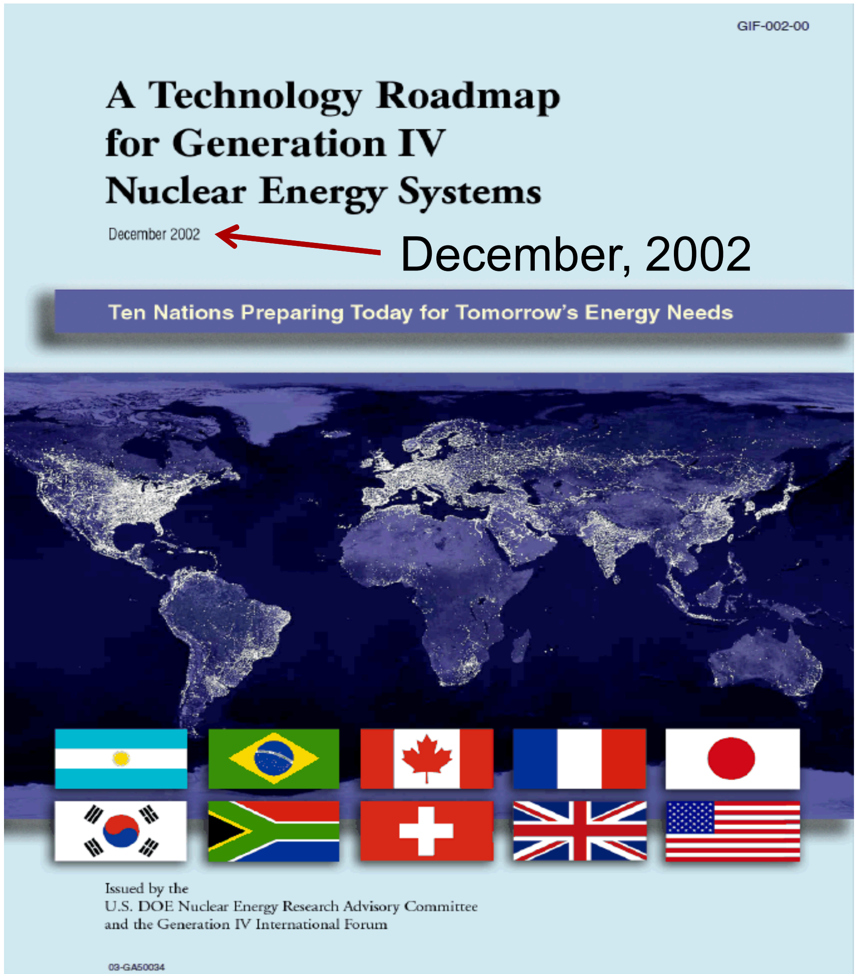
sCO_2 Benefits & Challenges

- Economic benefits
  - Smaller size relative to steam system – reduced capital cost
  - Increased efficiency – increased electricity production for same thermal input – lower cost of electricity ($/KW-hr)



Generation IV Technology Development

Sandia National Laboratories



Goals for Generation IV Nuclear Energy Systems

Sustainability–1 Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

DOE-NE formally recognized as early as 2002 that the SCO2 RCBC performance characteristics match up very well with small modular reactor operating conditions.

DOE Initiatives

- R&D at Sandia National Laboratories, 2006
  - Sandia R&D starts in 2005
  - DOE-NE begins investment in 2006 for SMR applications
  - Almost $15M invested in R&D at Sandia to date
- SunShot, 2012
  - Concentrating Solar Power at 700 ^{o}C
  - Achieve $0.06/kW-hr
  - SCO2 RCBC crucial to achieving goal
  - Largest single project at $16M
- Supercritical Transformational Electric Power (STEP), 2015
  - NE, FE, EERE
  - accelerate commercialization of SCO2 CBC
  - Cost-shared ~ 10 MWe demonstration program that all Offices would benefit from
  - Approximately $27.5M in first year.

Sandia Mission Statement

"By the end of FY 2019, Sandia National Laboratories shall develop 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."

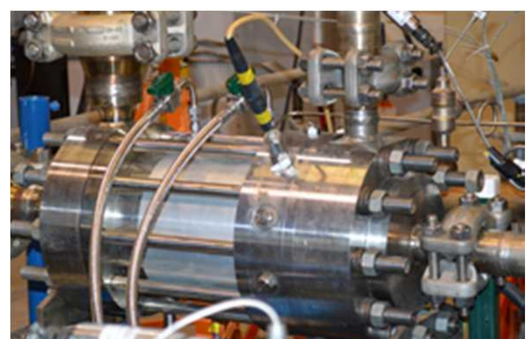
- Implies active pursuit of partners
- Demonstration project at Sandia
- Pilot plant project site TBD

Sandia National Labs Leadership

Sandia National Laboratories

- World's first and only operating Recompression closed Brayton cycle
- Highly versatile infrastructure
- Demonstrated ability to test various configurations, including proprietary industry concepts.

Each of 2 TACs designed to generate maximum of 125 kWe



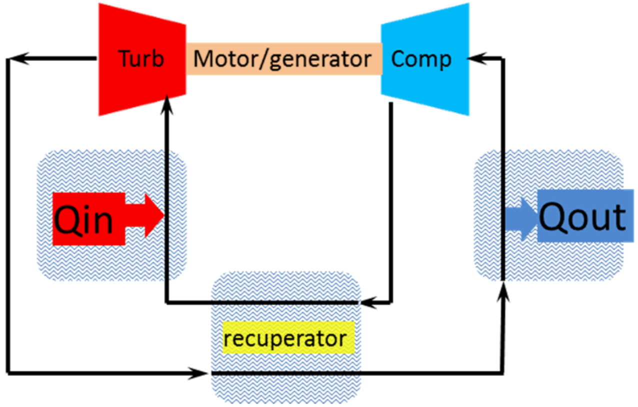
Heat source 780 kW

3 extremely efficient PCHE recuperators

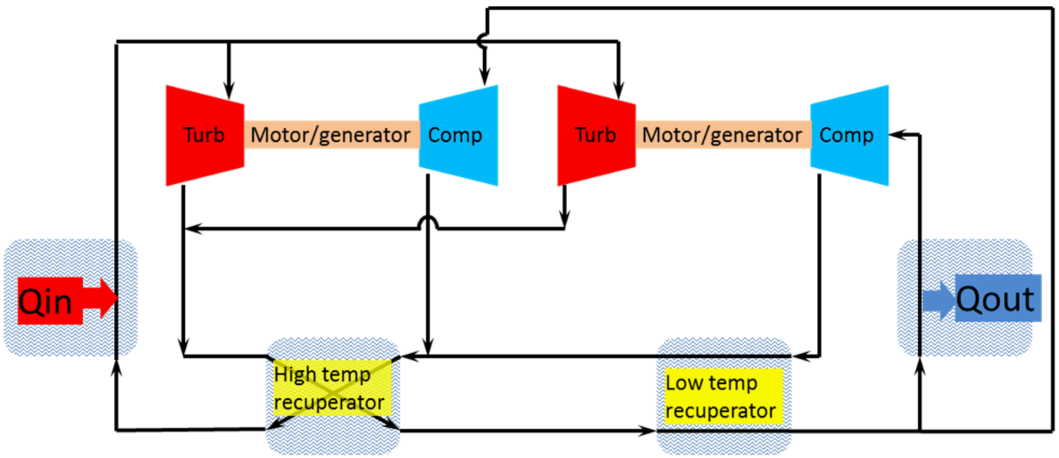
R&D at Sandia

- Two primary cycles of interest
  - Simple → best for low grade waste heat sources.
  - Recompression → best for closed heat sources, such as nuclear reactors and concentrated solar thermal cycles.
- Variety of investigations
  - Solar transients
  - Mixtures
  - Dry cooling
  - Industry proprietary cycles
- Operational experience and cycle insights develop with each test.

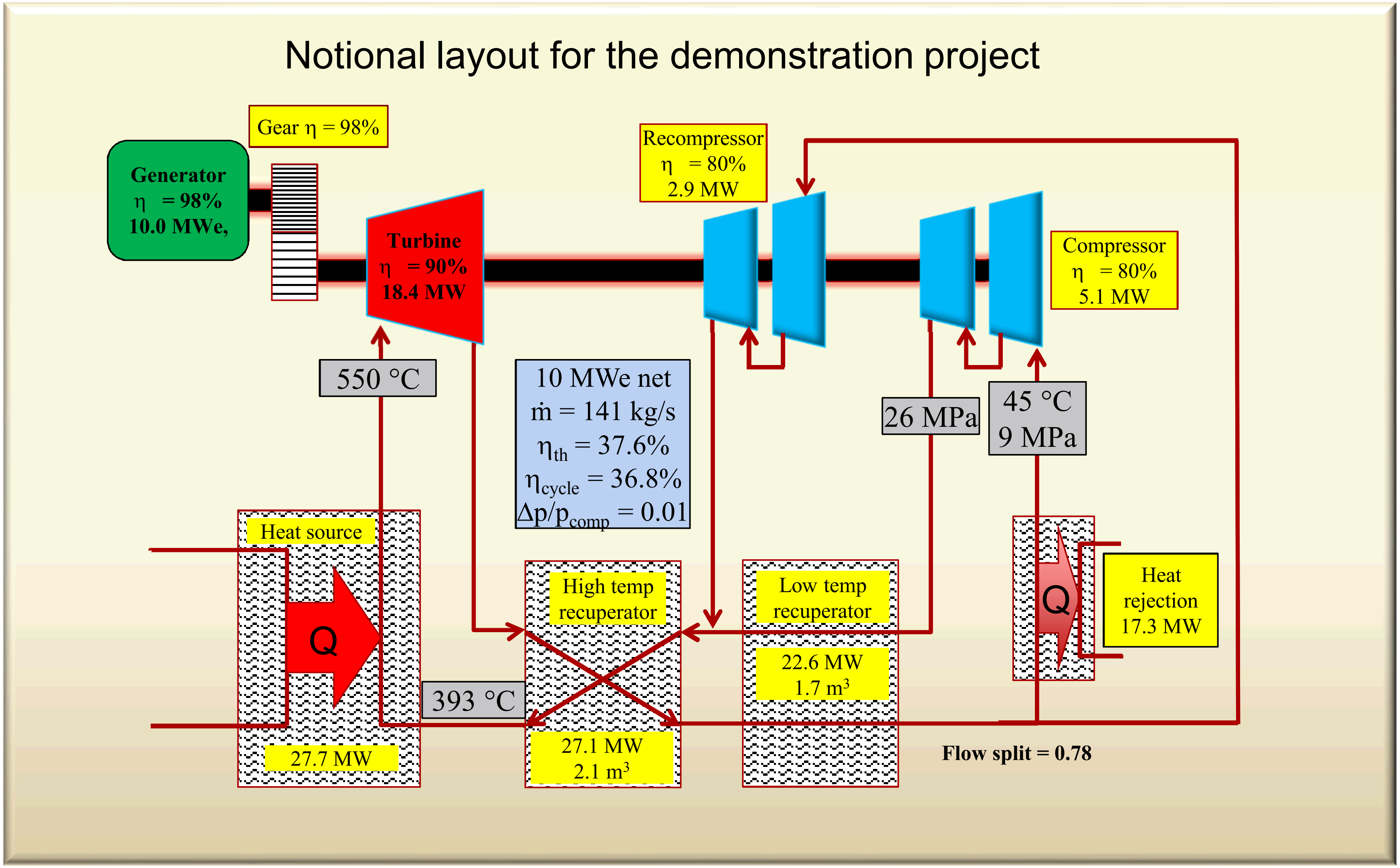
Simple cycle



Recompression cycle



10 MWe Net SCO2 RCBC with Dry Cooling



Summary

- The closed Brayton thermal-to-electric power conversion cycle has existed for 75 years.
- Theoretical analyses show that a revolutionary improvement in performance is possible with particular configurations and working fluids.
- DOE-NE has invested heavily in R&D of the RCBC for SMR applications at 550 ^{o}C.
- Optimal configurations exist for any heat source.
- Other offices and organizations have recognized the potential, and seek ways to accelerate commercialization.
- SNL has the world’s only RCBC, and continues to advance the technology through testing and engaging external interests.
- The CBC community is largely in agreement about the need for and general characteristics of a ~10 MWe demonstration system.
- The only obstacle of note preventing a demo is funding (~$30M).