SAND2014-15660PE

Exceptional service in the national interest

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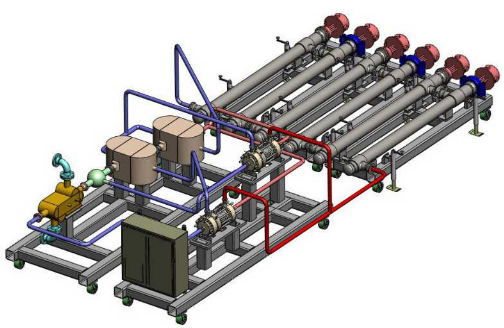

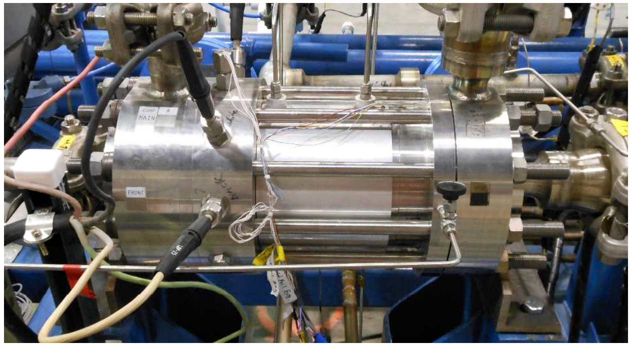

S-CO2 Brayton Cycle Development

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

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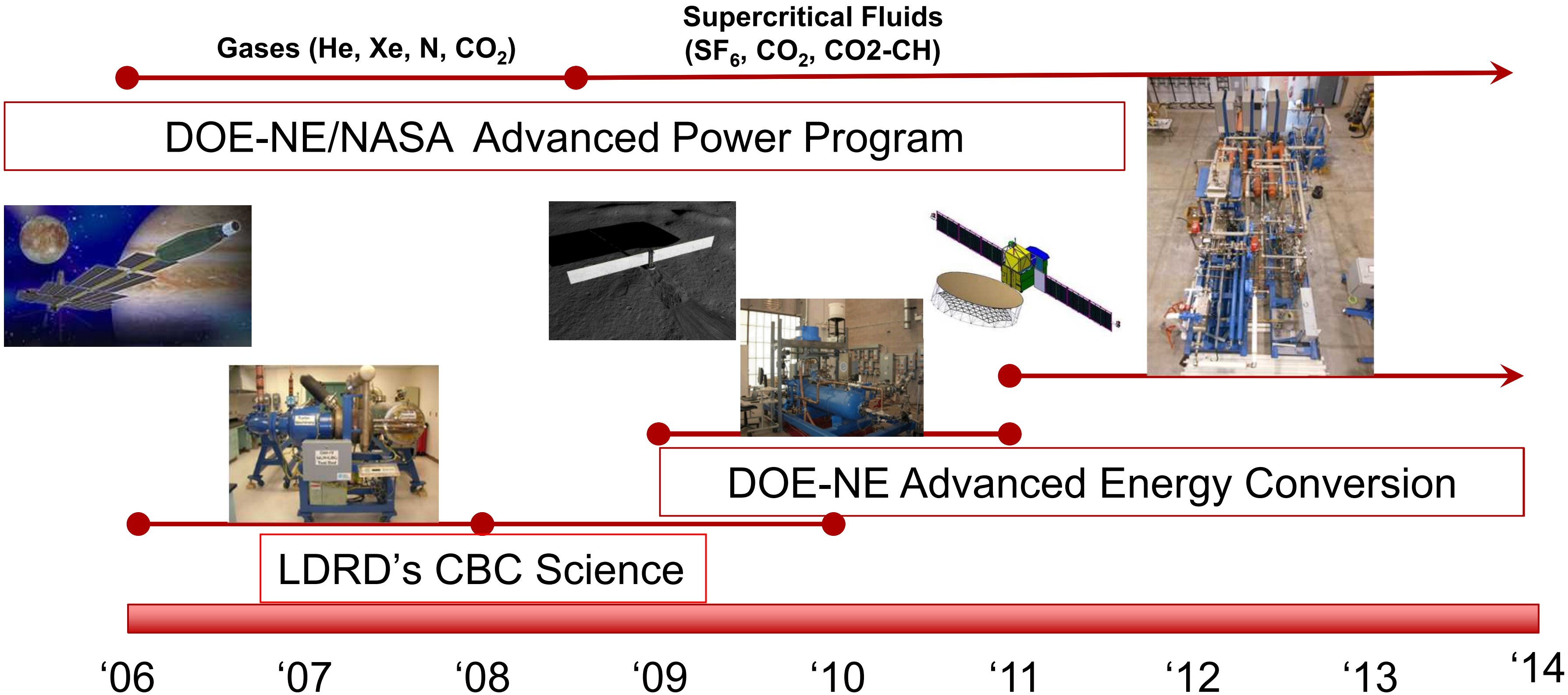
History of SCO_2 BC Program @ SNL

- 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.



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."

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)

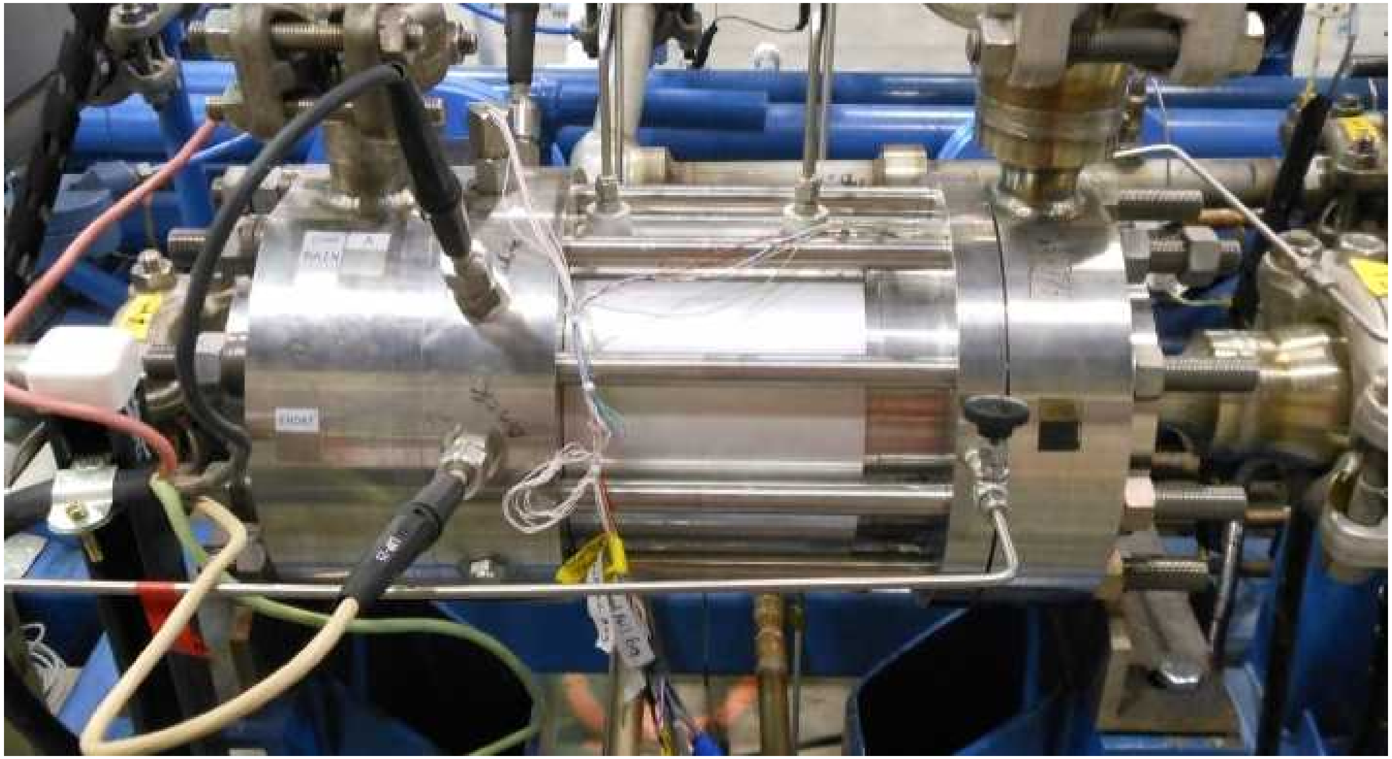
- TA under test since 4/2010
- Over 100 kW-hrs of power generated
- Operated in 3 configurations
  - Simple Brayton
  - GE Waste Heat Cycle
  - Recompression
- Testing of each component
- Verified cycle performance
- Developed Cycle Controls
- Developing maintenance procedures

<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)



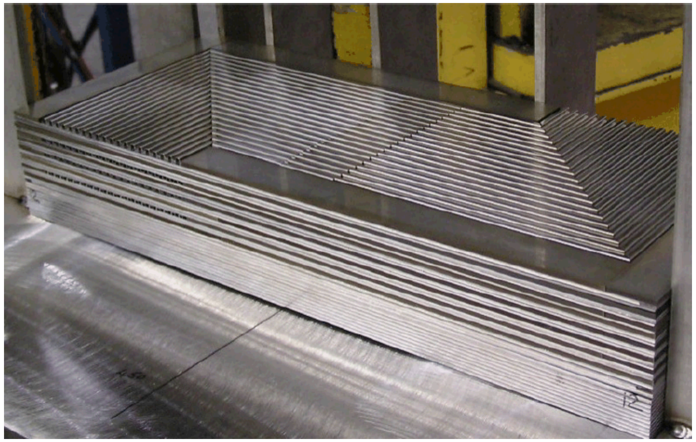
~24" Long by 12" diameter

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

High Temperature Recuperator

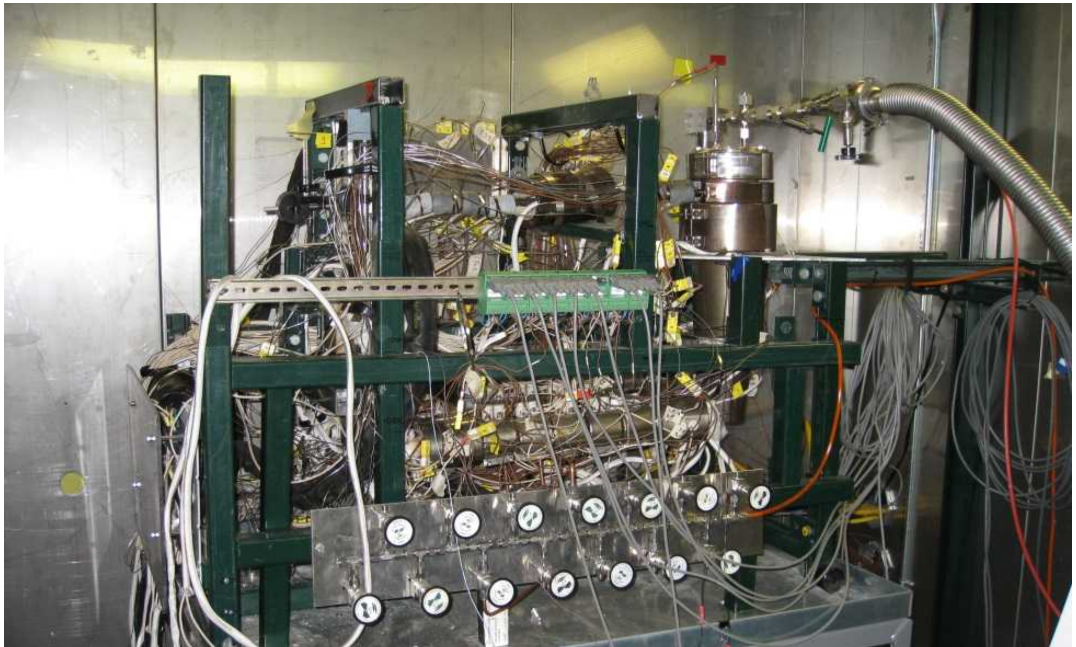
Low Temperature Recuperator

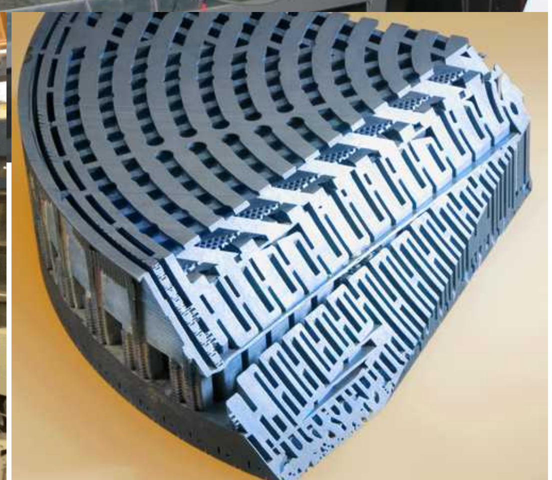
Gas Water Chiller

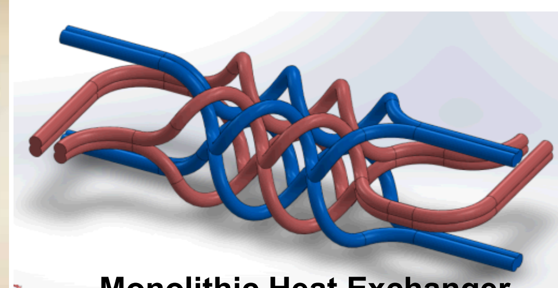


Prototype Sodium/CO2 PCHE

AdvSMR Energy Conversion Heat Exchanger Development



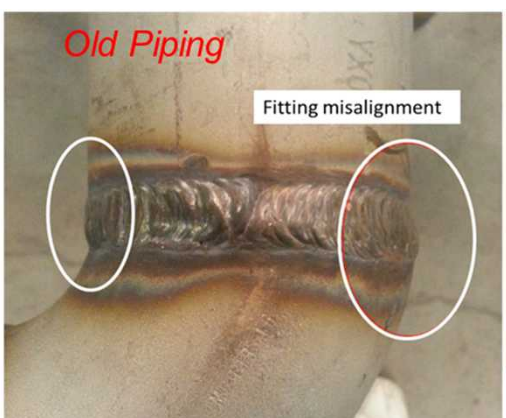


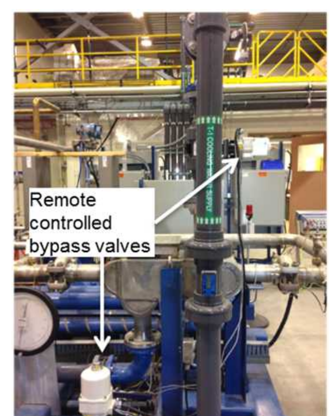


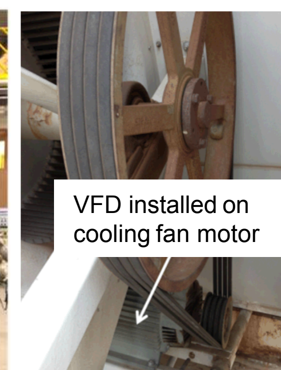
Monolithic Heat Exchanger Provisional Patent

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**



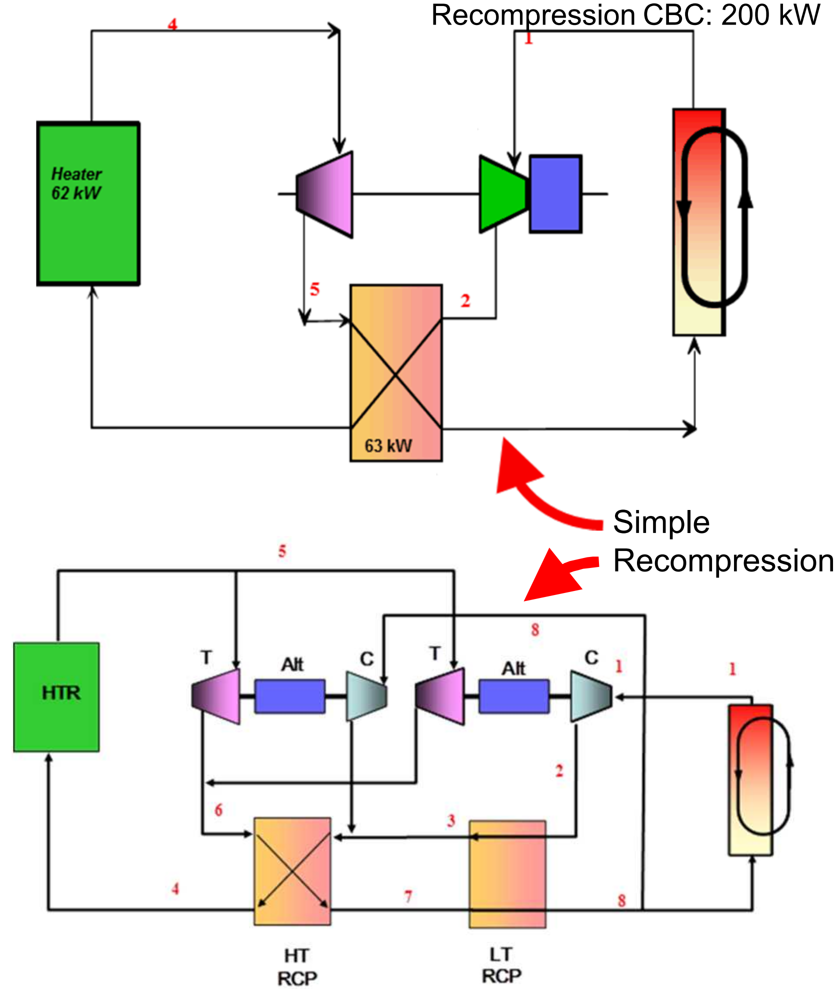




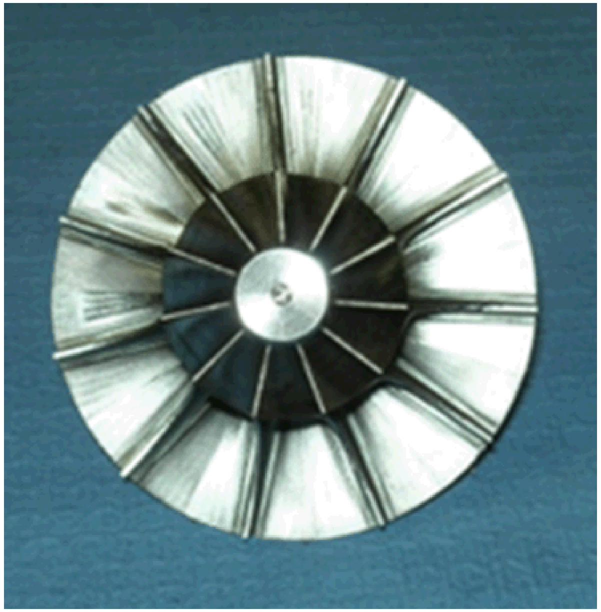
Test Summary and Operational Experience Closed Brayton Cycle (CBC) TA

- 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



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

EPRI CRADA

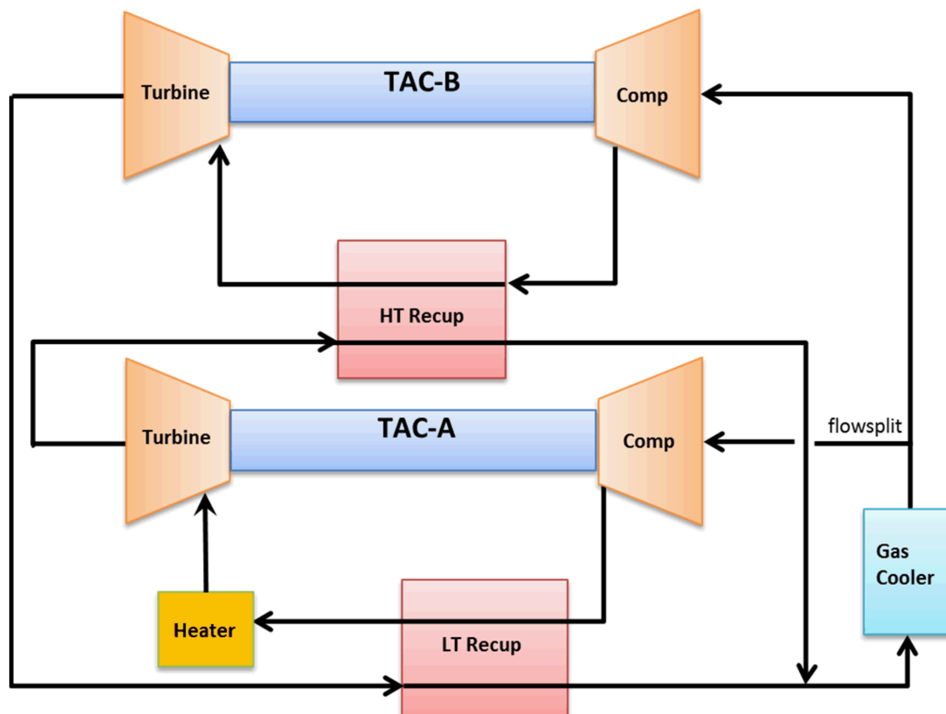
- EPRI initiated a CRADA in summer, 2013
  - Compare RCBC performance with selected cycles
  - Perform a literature search of various relevant topics
  - Future tasking expected in next budget cycle
- Primary Brayton cycle comparisons were compared with Advanced Ultra Supercritical Steam cycles.
  - 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.
- CRADA results and final report were completed on time and delivered to the satisfaction of the CRADA partner.
- 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

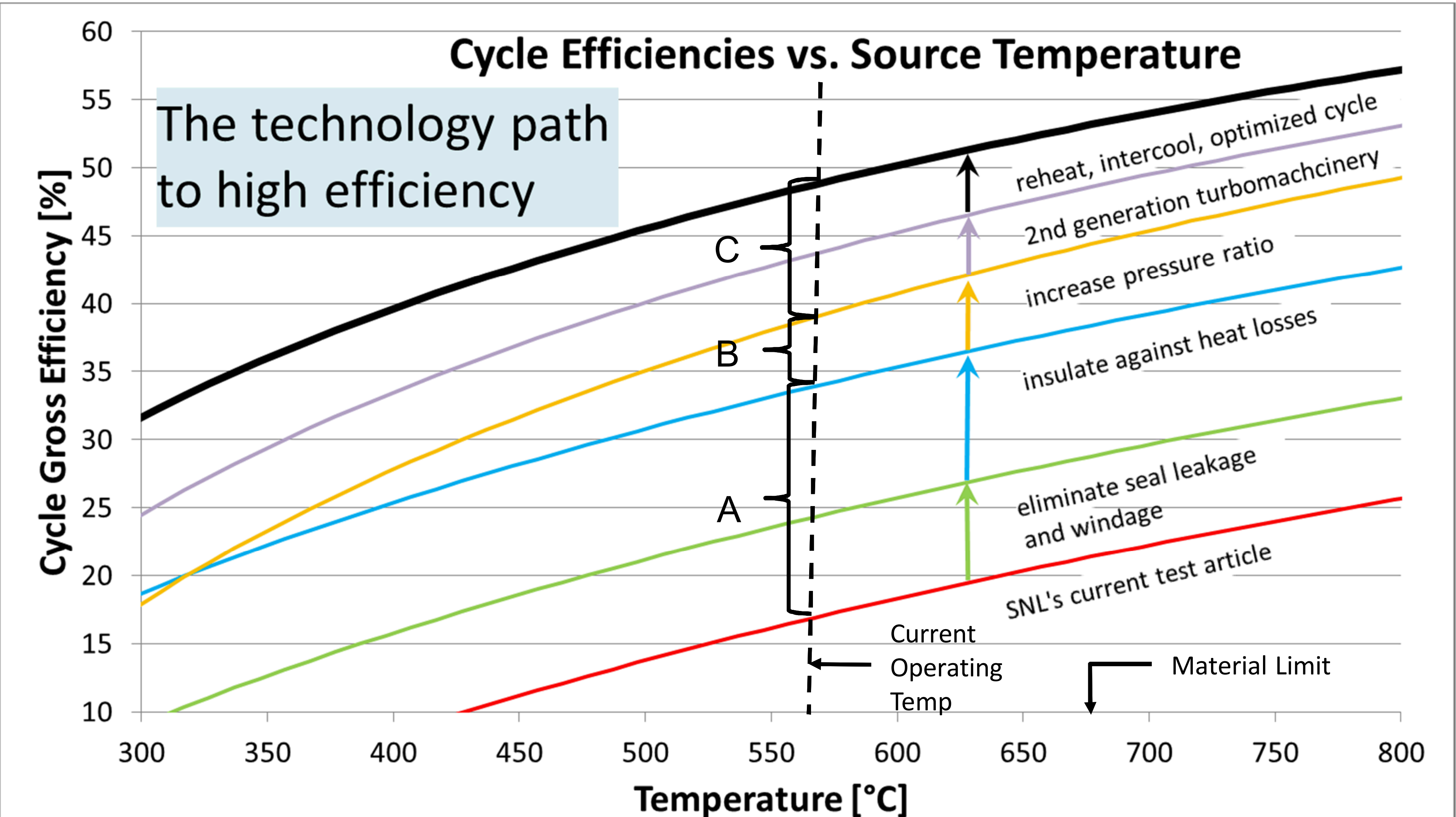
- **GE Global contracted with Sandia to test GE waste heat recovery concept.**
- **The Sandia TA re-plumbed to simulate the cycle – lesson learned**
- **Cycle and piping analyses and construction were accomplished in-house to determine feasibility and safety**
- **February 12, 2014 was the final test,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

Major GE testing achievements

System prestart		140212	140123	140121	140116	130313	121211	121129	121119	121114
Pressure	kPa	4885	4178	4600	4620	5180	2995	5170	4475	4578
Temperature	K	295.0	286.0	291.0	295.0	297.5	294.5	298.3	296.0	294.6
Density	kg/m^3					141	65.4			
Fill mass	kg	104.3	104.3		99.8			93.0	88.5	82.6
Test Duration	seconds	15370	5822	8480	5065	8220	11010	5312	10465	7696
Max system pressure	kPa	10430	10710	9460	9525	9650	4778	9110	9620	8880
TAC A										
Max speed	kRPM	40.5	43.5	44	38	40	37	38	45	47
Max compressor pressure ratio	-	1.4	1.398	1.318	1.265	1.32	1.151	1.236	1.32	1.32
Max comp to turb dP	kPa	200	215	180	140	145	70	155	225	178
Max flow rate	kg/s	2.25	2.15	1.72	1.75	2.08	0.63	1.625	1.825	1.675
Max compressor inlet density	kg/m^3	383	338	258	297	323	108	264	275	211
Max Turbine inlet temperature	K	657	720	757	650	680	739	628	695	595
Max power generation	kW	-16	-17.2	-10.3	-6.5	-8.5	0.8	-2.8	-8.5	-0.9
TAC B										
Max speed	kRPM	38.5	41.5	42	38	40	35	36	45	45
Max compressor pressure ratio	-	1.36	1.368	1.3	1.27	1.31	1.21	1.214	1.29	1.27
Max comp to turb dP	kPa	150	230*	225*	100	107	-	140	40	23
Max flow rate	kg/s	2.56	2.48	1.89	2.02	2.03	0.59	1.62	1.945	1.72
Max compressor inlet density	kg/m^3	383	338	260	297	323	108	265	270	211
Max Turbine inlet temperature	K	540	575	627	530	596	630	550	587	524
Max power generation	kW	-9	-9.5	-5.0	-2.0	-5.8	2.1	0	-3	3.9

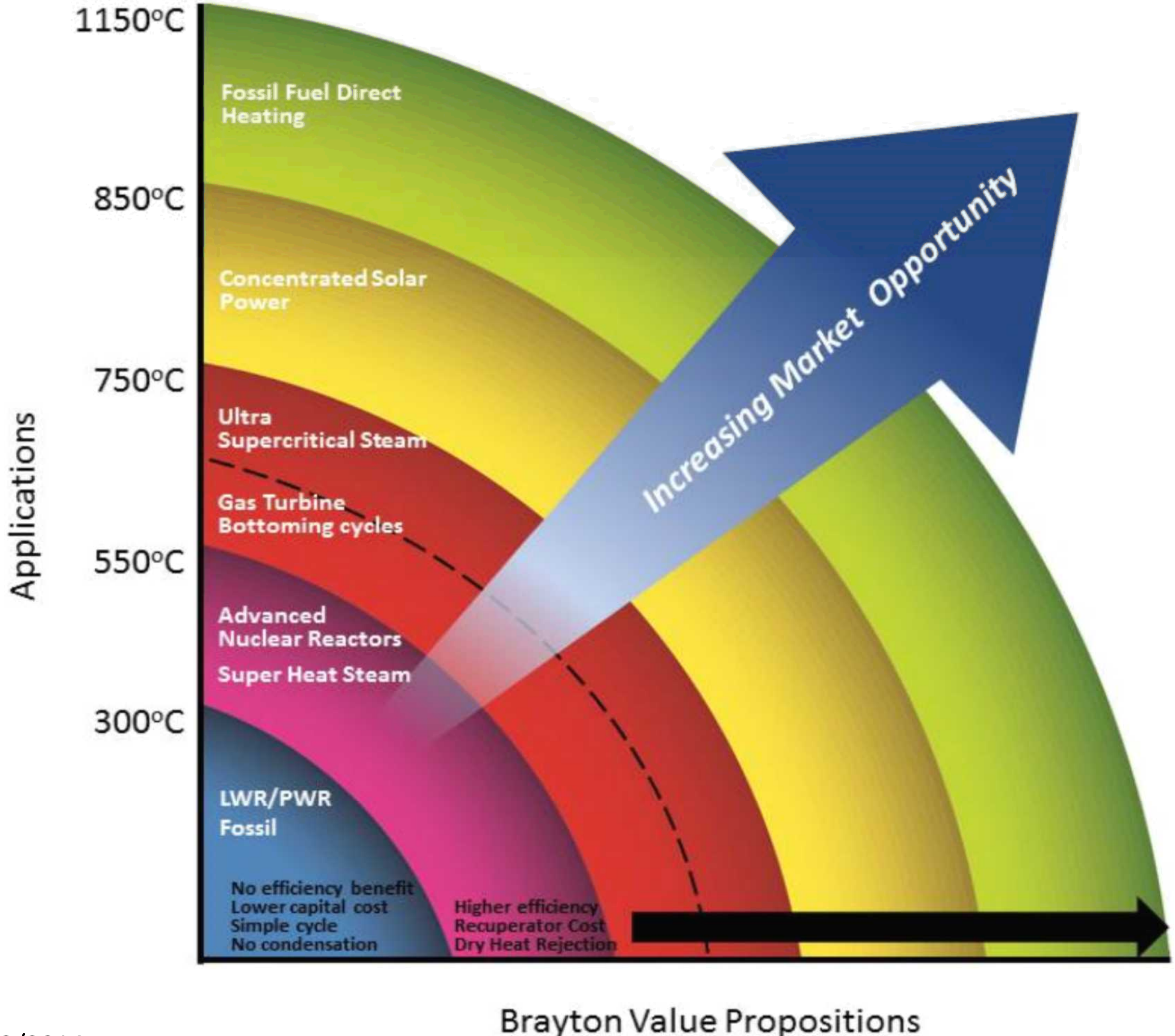


Pathway to High Conversion Efficiency



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