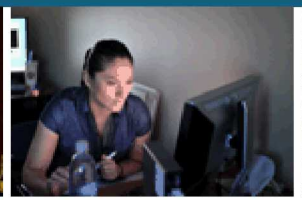
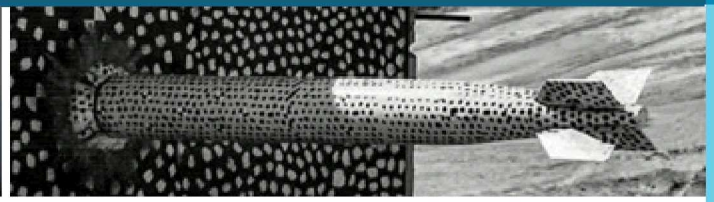
SAND2020-4724PE

Supercritical Transformational Electrical Production (STEP)





Program Status Summary and Path Forward

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Turbocompressor Development

Artist rendering ~ late 2017

Demonstrated performance ~ 2019

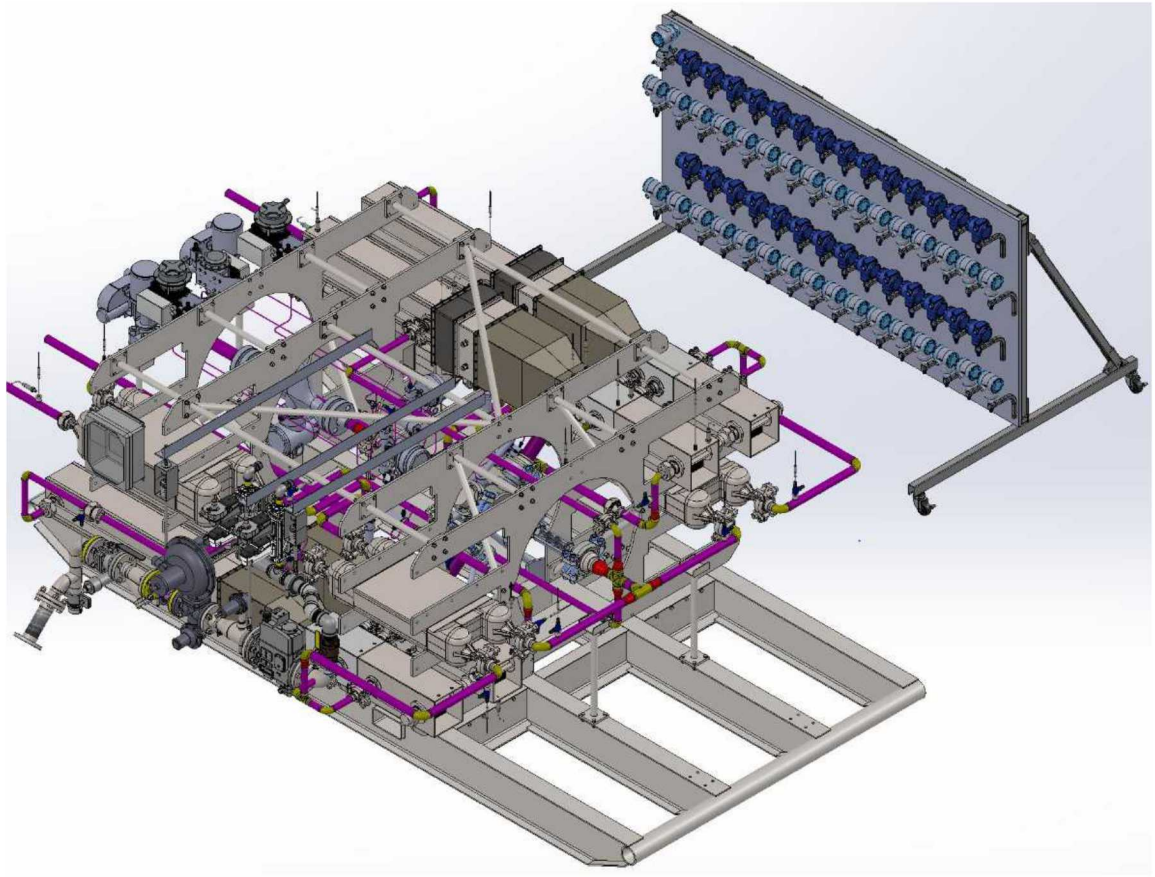
1 MWe Turbocompressor

Turbomachinery development platform at SNL

Successes:

- Demonstration of blowdown start method
  - 15 starts performed
- Rotor thrust balance achieved
  - After some initial thrust bearing rubs, thrust balance was achieved through valve control strategies
- Limits of SNL loop achieved
  - Maximum of 1000F @ 2000 psi achieved
- 67.5 hours achieved on unit
  - 51 hours at limits of loop
- Continuing to get operating hours on the unit

Proposed Test Rig

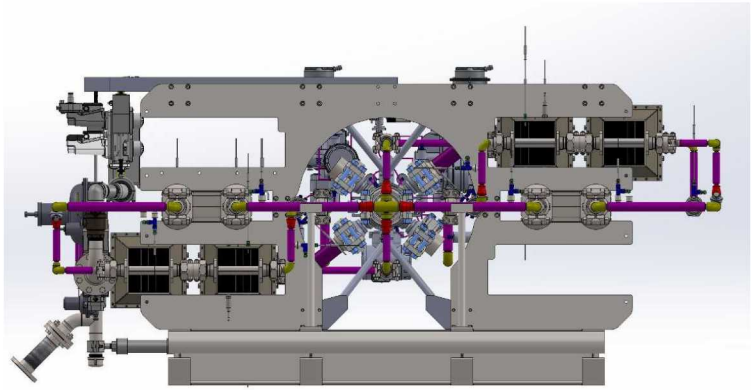


Goal:
Demonstrate performance of turbocompressor to full design conditions:

1382F @ 6222 psi

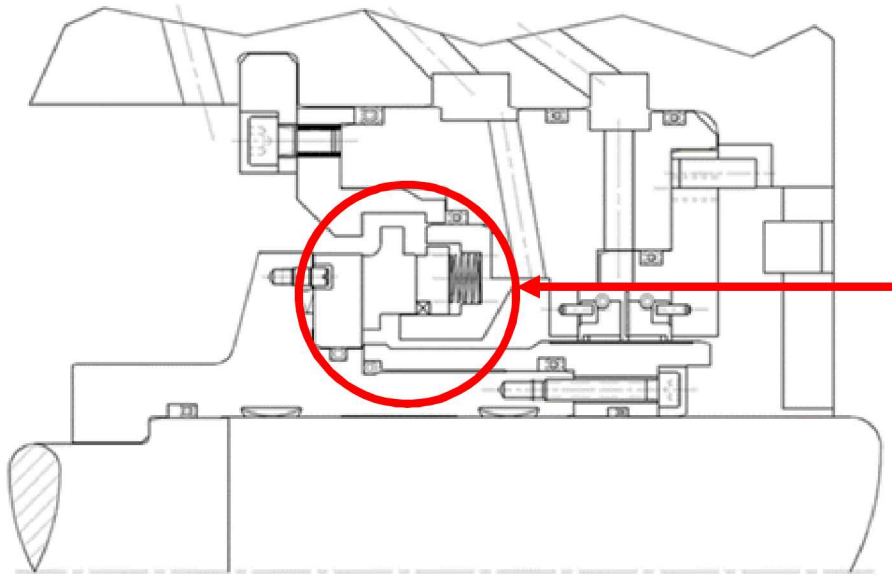
Utilize previously purchased turbocompressor with 4 combustor/heat exchanger trains

Able to be upgraded with components necessary for electricity generation



Dry Gas Lift Off Seal Design

- **FY17 Seals design underway**
  - CFD, FEA and seal modeling

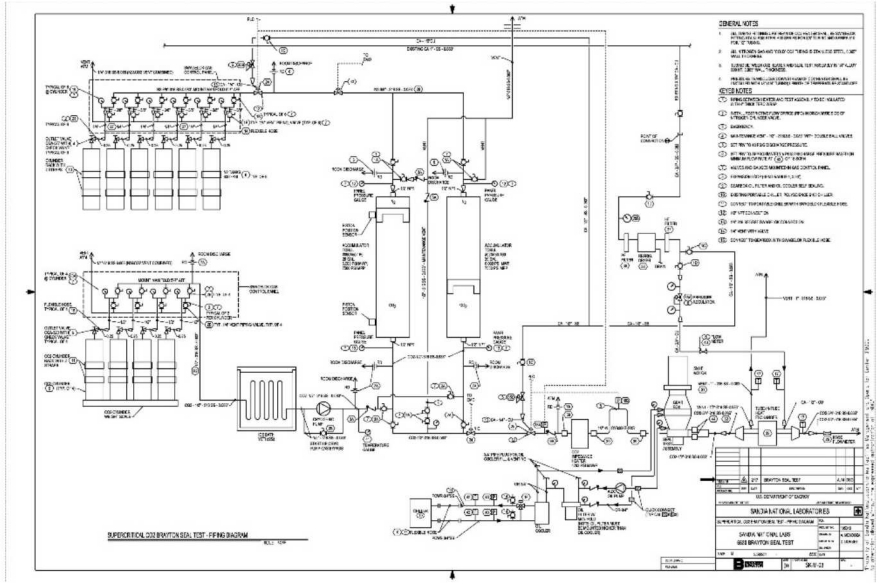


- **FY19 Seals have been manufactured on rev. 5**

Seals Test Rig Design

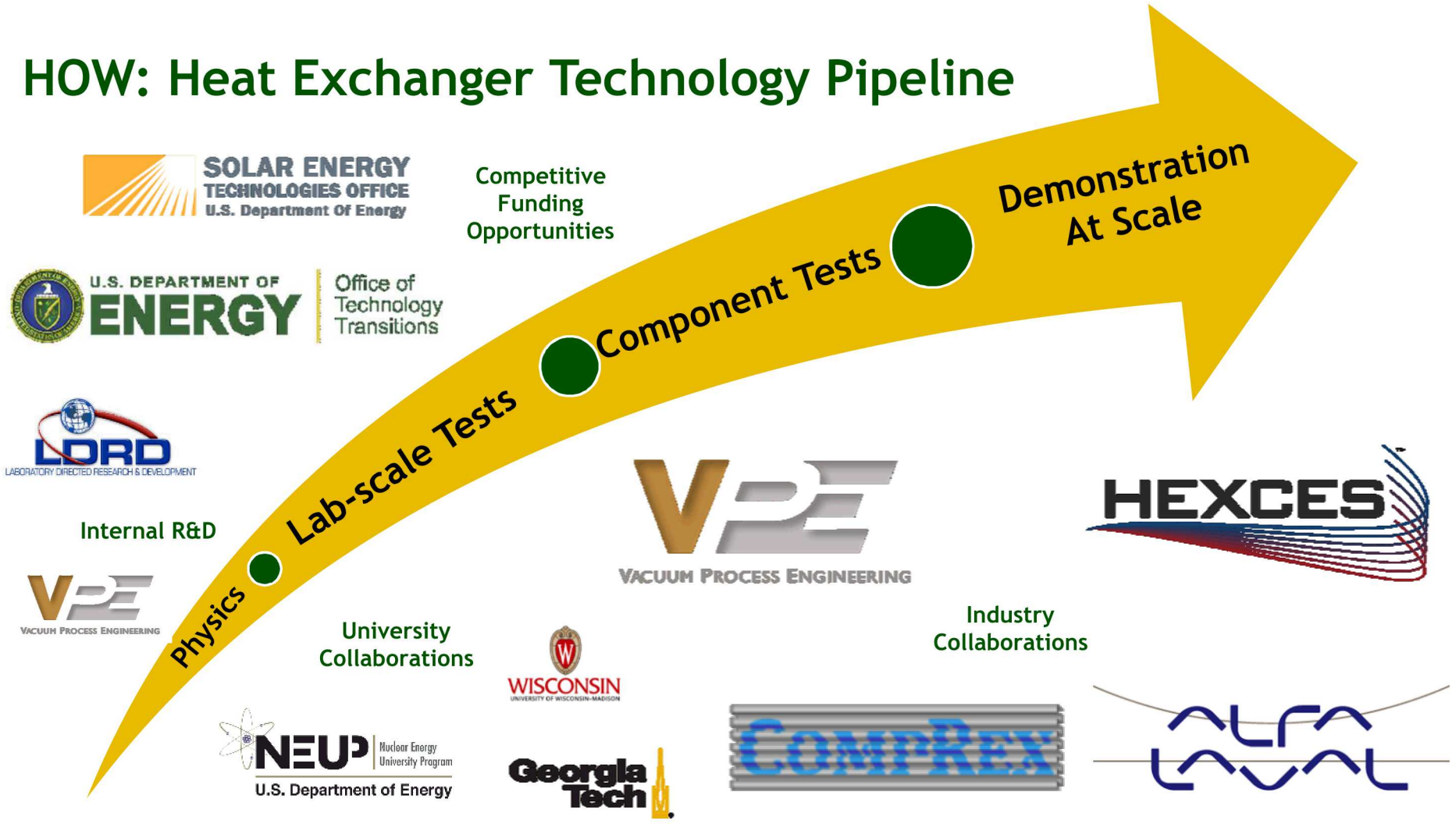
FY17 Design Started

- CFD, FEA, design and system modeling



- **FY19 Construction**

STEP Heat Exchangers



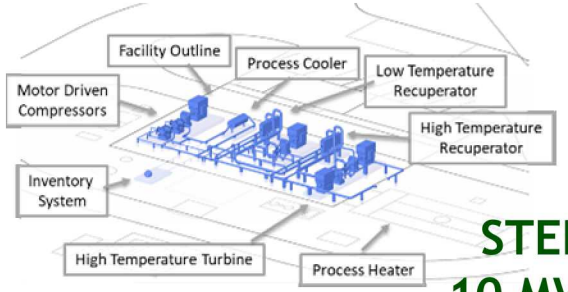
STEP Heat Exchangers

WHO: Advanced Heat Exchanger R&D Customer Base

VACUUM PROCESS ENGINEERING

COMPREX

Original Equipment Manufacturers



STEP
10 MWe

System-Level R&D Projects

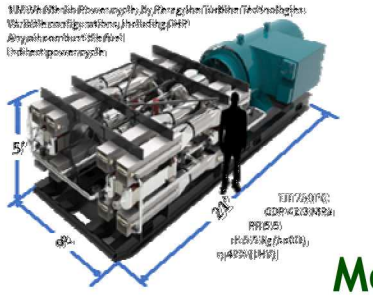
Echogen
EPS100

Commercial System Integrators

ALFA LAVAL

HEXCES

Gen3CSP
1 MWe



Merlin
1 MWe

High-Temperature Alloy Corrosion Behavior within Compact Heat Exchangers

Groups are operating under the assumption that the corrosion for alloy coupons will be the same as for alloys that have been processed into a heat exchanger

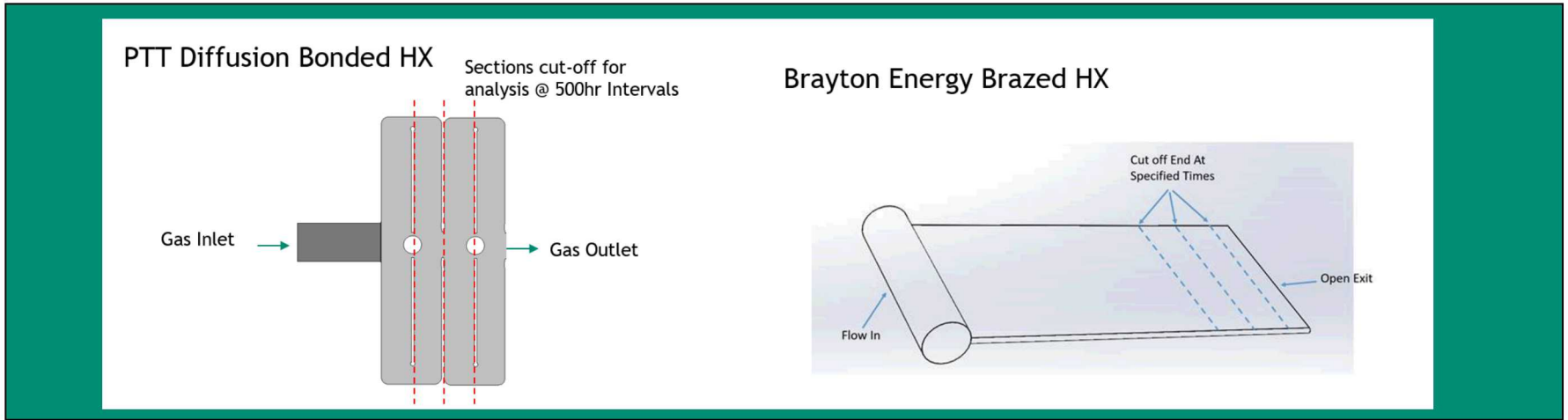
- There are chemical and thermal process during heat exchanger fabrication that may have an affect on high temperature corrosion behavior
- Alloy corrosion with a heat exchanger channel following high temperature exposure to CO_2 has never been examined

Series of experiments completed using small compact heat exchanger samples in order to fill this critical gap in understanding

Matrix of Heat Exchanger Samples Tested

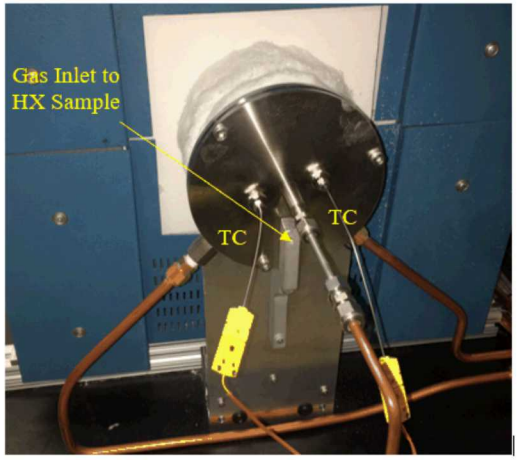
Company	HX Technology	Alloy	T, °C
Peregrine Turbine Technologies	Diffusion Bonded	I625	750
BraytonEnergy	Plate Fin Brazed	H230	750
BraytonEnergy	Plate Fin Brazed	I625	750

Evaluate samples for corrosion and hardness

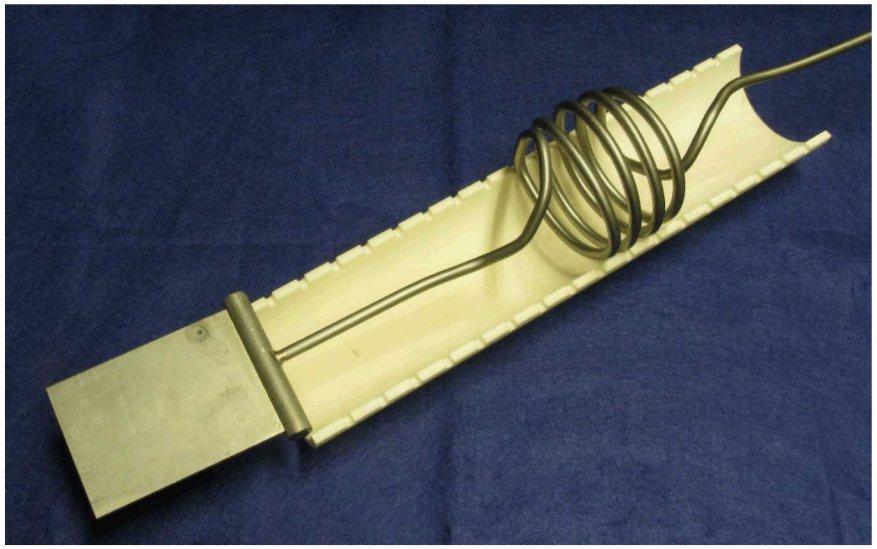


Experimental Setup for Heat Exchanger Experiments

Large Tube Furnaces used for Experiments



Brayton Energy Heat Exchanger Sample



Peregrine Turbine Technologies Heat Exchanger Sample

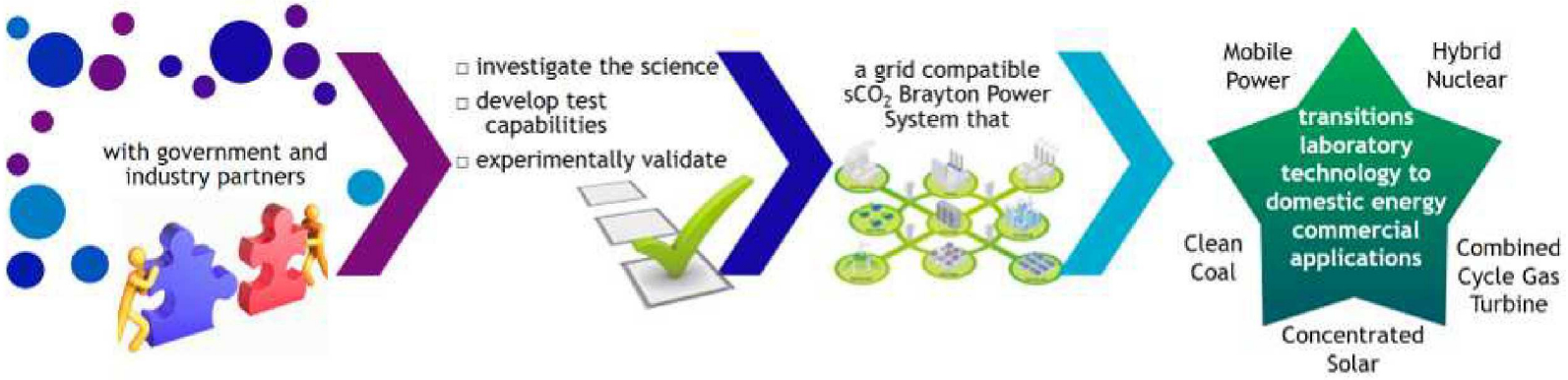
Brayton Team Mission & Objectives

"By the end of FY 2019, Sandia National Laboratories shall develop, with industry, **a fully operational 550°C 10 MWe R&D demonstration sCO2 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."

sCO2 Brayton Lab Vision Statement, 2014

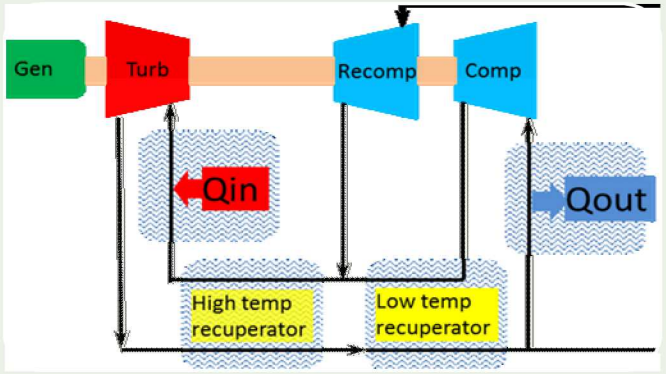
Sandia National Laboratories (SNL) Brayton Team mission states that "By October 2020, Sandia National Laboratories, **in collaboration with government and industry partners, shall investigate the science, develop the test capabilities, and experimentally validate a grid compatible sCO_2 Brayton Power System** that transitions laboratory technologies to domestic energy commercial applications."

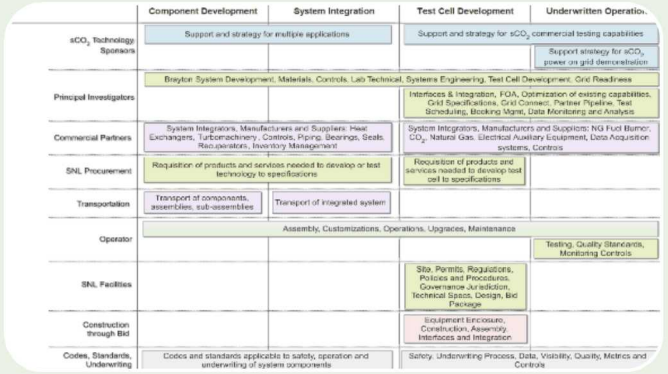
sCO2 Brayton Lab Vision Statement, revised June 2018



1. To support coordination and collaboration across labs and with industry
2. To lead R&D that ensures systematic identification and retirement of risks to ensure component readiness
3. To lead R&D that is inclusive of elements that increase the reliability and resiliency of electric power systems
4. To establish the foundations for successful commercialization of the technology

R&D Roadmap Lanes





RCBC Proof of Concept & Risk Retirement

- Ongoing since 2010, to Advance 10MWe, 750C component readiness through TRL and MRL management
- Includes Materials Development, Component Development, and Sub-Systems and Systems Integration
- Directly supports the 10MWe, 750C STEP Pilot Facility

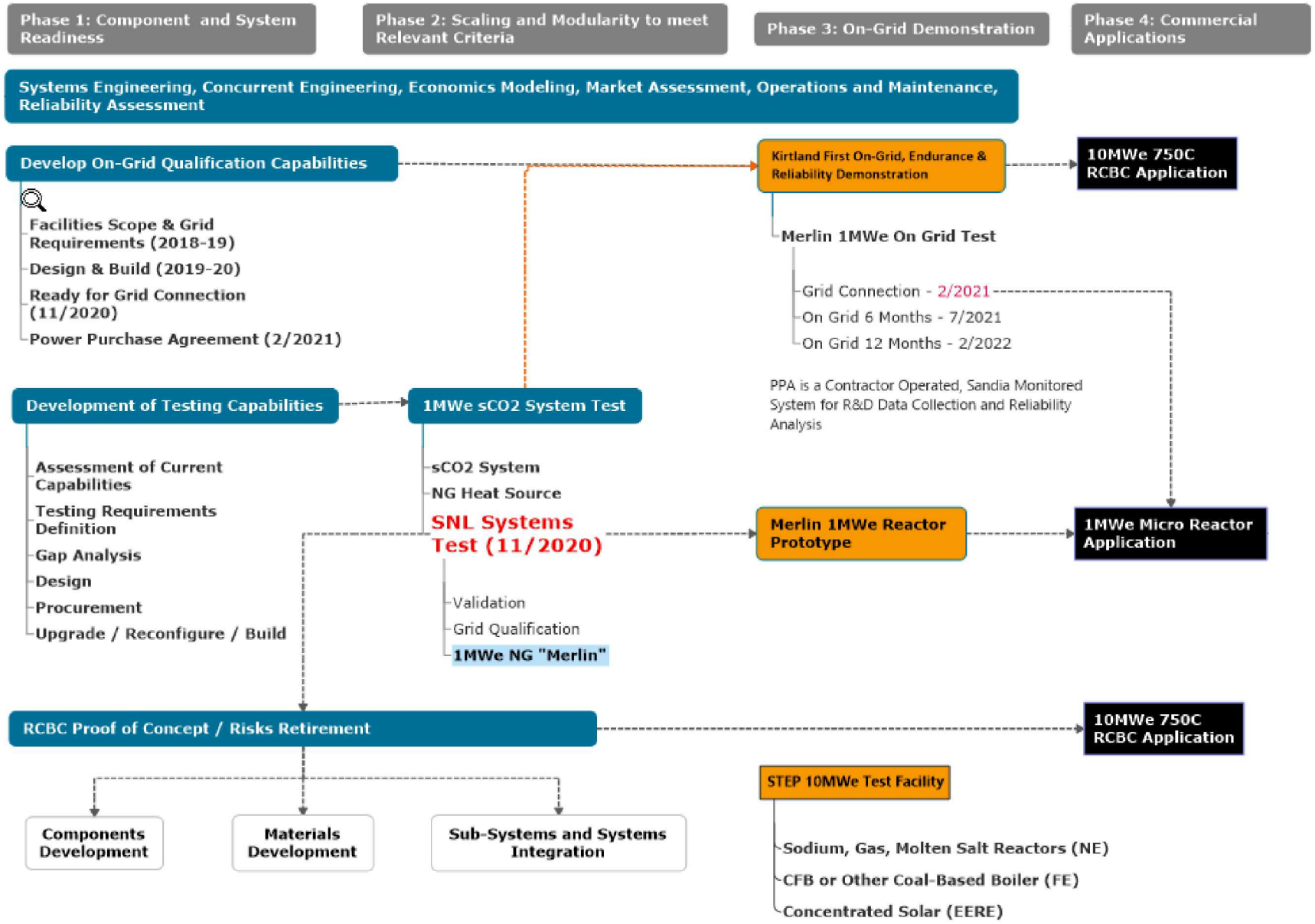
Component Testing Capabilities

- Assessment of current testing capabilities at SNL, and identification of gaps and needs to support effort.
- Identifies test requirements and test plans for qualification of commercial products, and develops capabilities to support those tests.
- Advances commercial readiness for a range of sCO_2 energy conversion systems and components

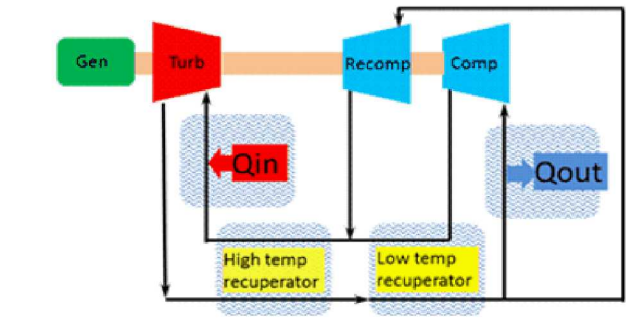
Grid Qualification Capabilities

- Scoping and Assessment of grid qualification requirements.
- Develops infrastructure to support grid qualification efforts, resulting in sCO2-generated power on the grid.
- Results in a smart micro-grid at SNL to demonstrate endurance and reliability of sCO2 power generated commercial systems.

Updated STEP-NE Roadmap

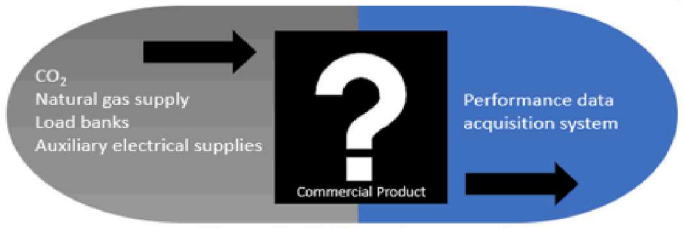


Concurrent Kirtland First Development Stages

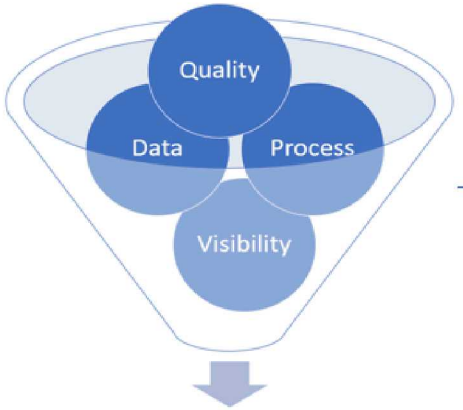


Component Development

System Integration



Test Cell Development

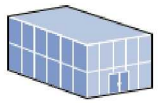


Underwritten Operation

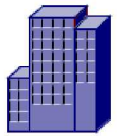
Kirtland First

- *Energy service provider*
- *Power purchase agreement*
- *24-7 operations*

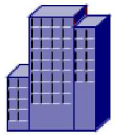
Consumers



Sandia National Labs



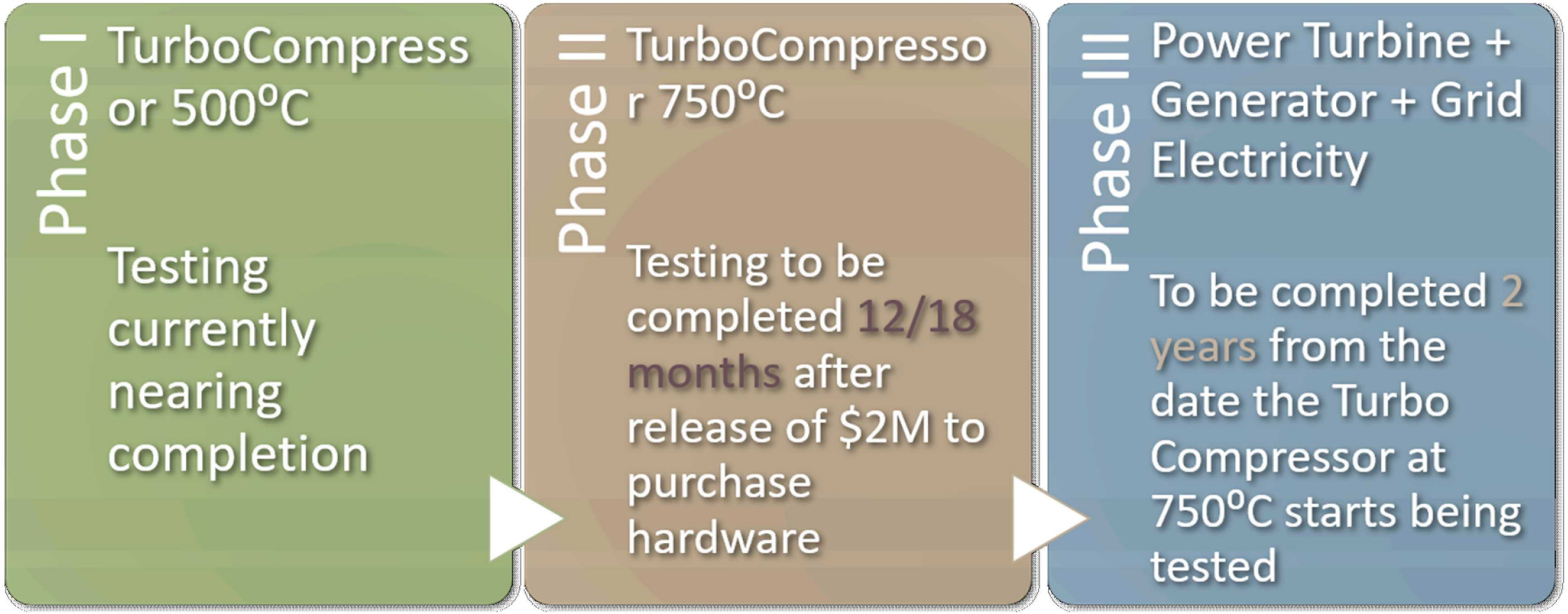
DOD KAFB



NNSA Operations

Technology Readiness and System Integration | System Qualification | Demonstration and Commercialization

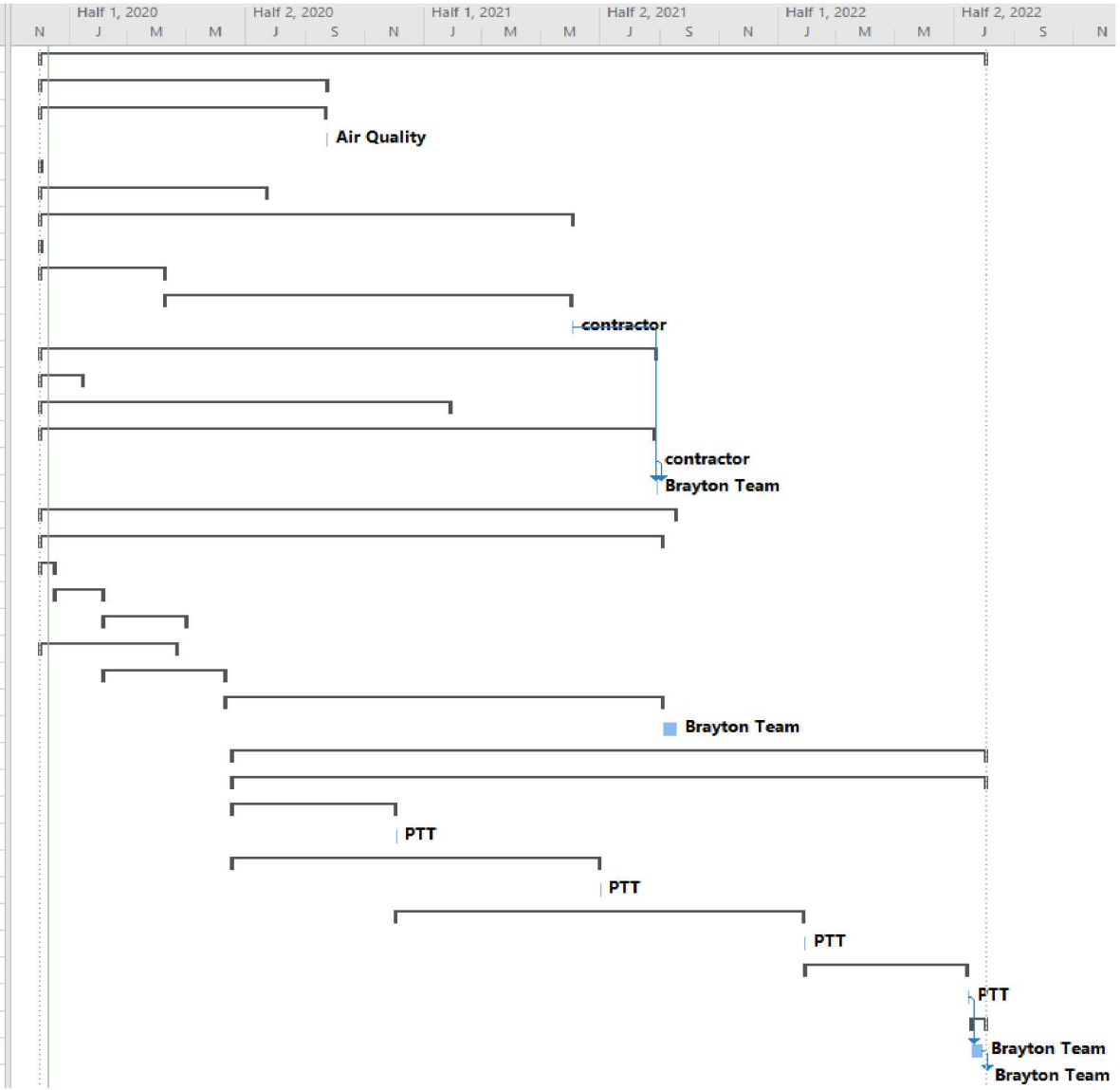
3 Phases to Commercialization



These three phases allow for the loop to be completed and tested, putting electrons on the grid. The prototype is a success and commercialization of 1 MWe system begins.

Project Schedule - DRAFT

Task Name	Duration	Start	Finish	Resource Names
Executing, Monitoring and Control	696 days?	Mon 12/2/19	Mon 8/1/22	
Permits and/ External Approvals	212 days	Mon 12/2/19	Tue 9/22/20	Brayton Team
Air Quality	211 days	Mon 12/2/19	Mon 9/21/20	Air Quality
Receive Permit	1 day	Tue 9/22/20	Tue 9/22/20	Air Quality
Experimental Enclosure	1 day	Mon 12/2/19	Mon 12/2/19	facilities
Safety Dcoumentation	167 days	Mon 12/2/19	Tue 7/21/20	Brayton Team
Grid Qualification Test Cell Construction	393 days?	Mon 12/2/19	Wed 6/2/21	Brayton Team
Design Test Cell	1 day?	Mon 12/2/19	Mon 12/2/19	B&P
Test Cell Bidding and Contracting Process	93 days?	Mon 12/2/19	Wed 4/8/20	facilities
Construction begins	299 days	Thu 4/9/20	Tue 6/1/21	contractor
Test Cell Construction Complete	1 day	Wed 6/2/21	Wed 6/2/21	contractor
Experimental Enclosure Construction	455 days?	Mon 12/2/19	Fri 8/27/21	Brayton Team
Design Enclosure	32 days	Mon 12/2/19	Tue 1/14/20	B&P
Enclosure Bidding and Contracting Process	303 days?	Mon 12/2/19	Wed 1/27/21	facilities
Construction begins	453 days	Mon 12/2/19	Wed 8/25/21	contractor
Enclosure construction complete	1 day	Thu 8/26/21	Thu 8/26/21	contractor
Validation of Test Cell with Enclosure	1 day?	Fri 8/27/21	Fri 8/27/21	Brayton Team
Phase 1: Initial Buildout to 750C	469 days?	Mon 12/2/19	Thu 9/16/21	PTT
Design Point Core Turbine Test Rig	459 days?	Mon 12/2/19	Thu 9/2/21	PTT
Rig Specification Negotiated	11 days	Mon 12/2/19	Mon 12/16/19	PTT
Rig Design	36 days?	Tue 12/17/19	Tue 2/4/20	PTT
Heater Module Verification	61 days	Wed 2/5/20	Wed 4/29/20	PTT
Control System	101 days?	Mon 12/2/19	Mon 4/20/20	Brayton Team
Core Test Rig	90 days	Wed 2/5/20	Tue 6/9/20	PTT
Ship Rig to Sandia	322 days	Wed 6/10/20	Thu 9/2/21	PTT
Rig Acceptace Test	10 days	Fri 9/3/21	Thu 9/16/21	Brayton Team
Phase 2: Generation System	554 days?	Wed 6/17/20	Mon 8/1/22	PTT
Merlin Series 1MW sCO2 Power Generation System	554 days?	Wed 6/17/20	Mon 8/1/22	PTT
Gen 2 Procurement & HX Verification	120 days	Wed 6/17/20	Tue 12/1/20	PTT
Gen 2 Verification Report	1 day?	Wed 12/2/20	Wed 12/2/20	PTT
Power Turbine	270 days	Wed 6/17/20	Tue 6/29/21	PTT
Power Turbine Verification Report	1 day?	Wed 6/30/21	Wed 6/30/21	PTT
NG Validation System	300 days	Thu 12/3/20	Wed 1/26/22	PTT
System Acceptance Test Report	1 day?	Thu 1/27/22	Thu 1/27/22	PTT
Application Certification @ SNL Test Facility	120 days	Fri 1/28/22	Thu 7/14/22	PTT
UL Application Certificate	1 day?	Fri 7/15/22	Fri 7/15/22	PTT
Field Testing	11 days?	Mon 7/18/22	Mon 8/1/22	PTT
Validation System Grid Connected	10 days	Mon 7/18/22	Fri 7/29/22	Brayton Team
Execute Field Test Schedule	1 day?	Mon 8/1/22	Mon 8/1/22	Brayton Team



Projected Project Costs

- **Building of the Grid Qualification Test Cell**
  - Facilities estimated **$2.038 Million** for purchase of equipment and construction for installation of the test pad.
  - Does not include Brayton team labor.
- **Experimental Enclosure for Grid Qualification Test Cell test equipment**
  - Additional cost in addition to the Grid Qualification Test Cell .
  - Approximately **$200K** for enclosure design.
  - Unknown total cost to build (determined by design).
  - Does not include Brayton team labor costs.
- **Peregrine Test Rig**
  - Buildout of Core Test Rig **$2 Million**.
  - Does not include SNL Brayton team support costs.
- **Peregrine Merlin Series 1MW Power Generation System**
  - Estimated cost between **$5 Million and $7 Million**.
  - Does not include SNL Brayton team support costs.

Parallel Path Forward