DOE FE Advanced Turbines Program

2016 University Turbine Systems Research Project Review Meeting

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U.S. Department of Energy
National Energy Technology Laboratory

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Virginia Tech, Blacksburg, VA

Presentation Overview

- **Gas Turbines and the Power Generation Market**
- **Overview of DOE FE Advanced Turbines Program**
  - Program Goals and Budget
  - Combustion Turbines for 65 % Efficiency
  - Turbomachinery for SCO2 Power Cycles
- **Overview of DOE's Cross Cut Initiative SCO2 Power Cycle Program**
  - DOE SCO2 CCI
  - Projects
    - Advanced Recuperators
    - 10 MW SCO2 Pilot Plant
- **FE AT UTSR Request for Information**
- **Summary**

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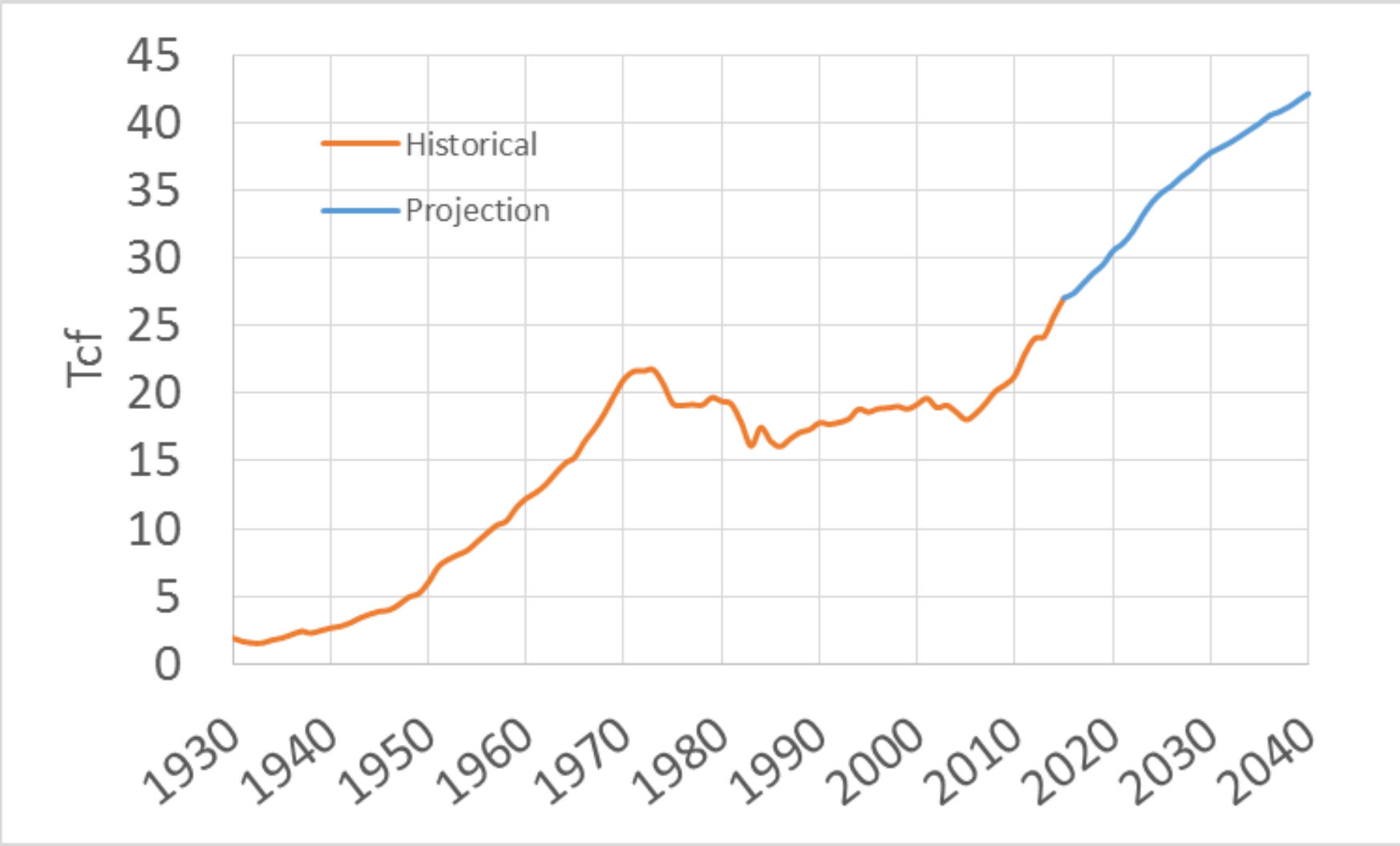
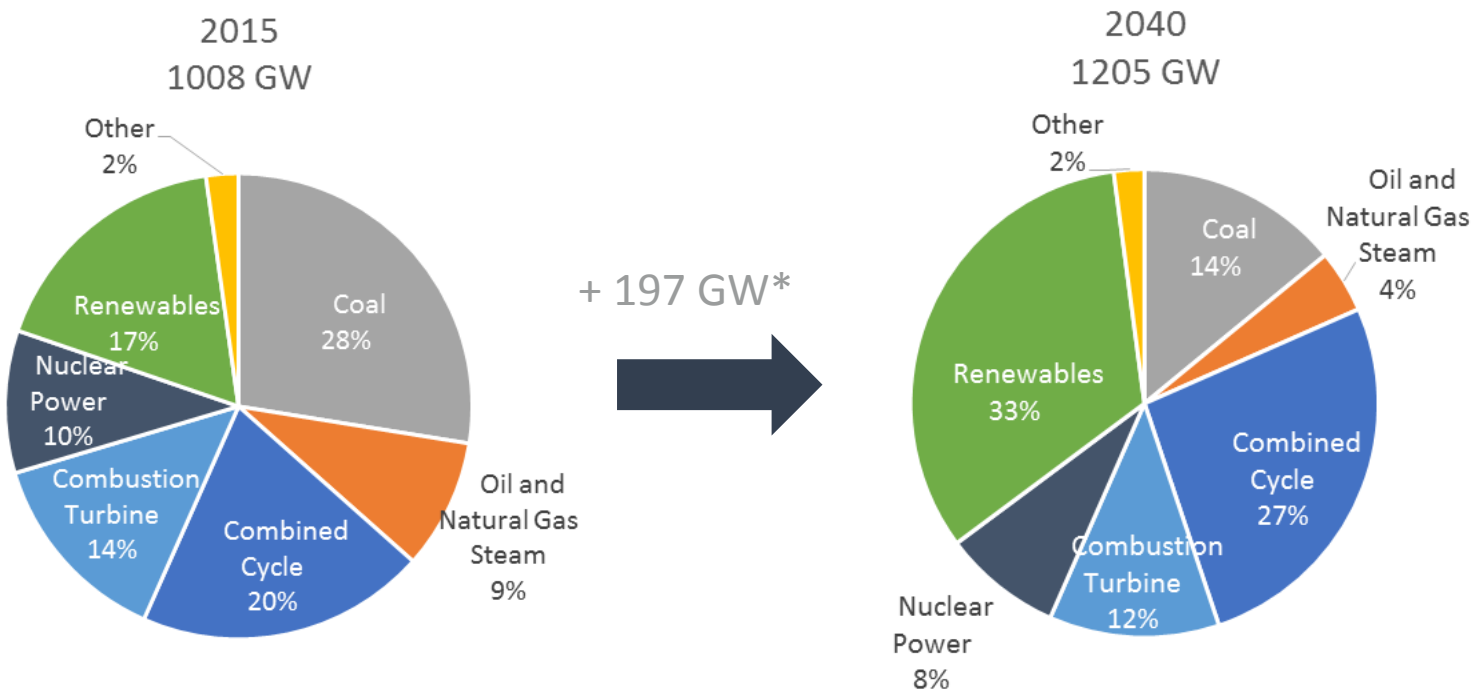
US Natural Gas, Dry Gas Production Historical and Projection



Source: EIA

US Electricity Net Generating Capacity



- **CC & CT have net capacity addition of 121.6 GW**

* Net increase includes additions and retirements

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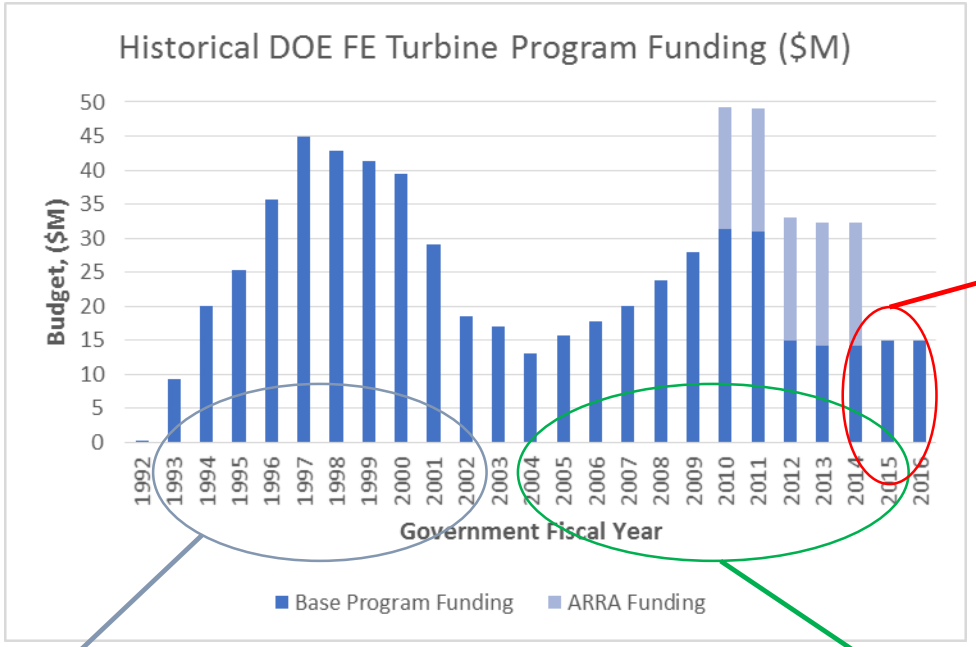
Advanced Turbines Program Goals

2025 Transformational Goals

- **Combustion turbine with 3,100 F TIT, 65 % CC efficiency (LHV)**
  - Bench marked against NG fueled combined cycle machines
  - Anticipate additional 20 % reduction in capture cost / 15 % COE reduction
- **Supporting goals for power cycles based on supercritical carbon dioxide**
  - Indirect SCO2 Power Cycles - Turbomachinery Efficiency
    - Develop / test expanders with efficiencies in the low 90s
    - Develop / test compressors with efficiencies in high 80s
    - Large 300 MW scale machines
    - Incumbent to beat: AUSC steam boiler / turbines cycles
  - Direct Fired SCO2 Power Cycles – SCO2 Combustion Turbine
    - Oxy-fuel (gaseous) combustion with CO2 dilution at high pressure
    - Combustor turbine integration
    - Large 300 MW scale machines
    - Incumbent to beat: F / H- class CC w/ post combustion carbon capture

Budget History and Major Accomplishments



AT Program (2014 – 2025)

- Full scale, full can combustion test at 3100F w/ < 25ppm NOx
- CMC nozzle design selected
- CMC combustor components down-selected from 50 concepts to 2
- Dry gas seal initial design completed for end seal in utility scale SCO2 expander

ATS Program (1992-2002)

- GE delivers most adv. 60% eff. NGCC
- Siemens produces adv. G-class components
- Focus on NG

H_2 Turbine Program (2005-2015)

- Solved H_2 combustion problem
  - Revolutionized combustion
- Advanced cooling architecture through advanced manufacturing

Note: ARRA funding came in one $ 90 M slug in FY 2010 and was spent over 5 FYs

Advanced Multi-Tube Mixer Combustion for 65% Efficiency

General Electric Co.

PROJECT NARRATIVE

- GE will develop and synthesize their multi-tube mixer combustion technology
- Goal of low NOx emissions up to 3100F while supporting load following grid needs
- Ultra-compact design that minimizes NOx formation and minimizes surface area to be cooled
- In-depth engineering analysis and design with minimal laboratory testing

BENEFITS

- Contributes to DOE goal of 65% combined cycle efficiency
- Enables robust fuel flexibility

PROJECT INFORMATION

- **Project Title:** Advanced Multi-Tube Mixer Combustion for 65% Efficiency
- **Award Number:** FE0023965
- **Project Duration:** 01/01/15 - 06/30/16
- **Key Technology:** Advanced Combustion Turbines
- **Location:** Schenectady, NY
- **FPM:** Mark Freeman
- **PI:** Willy Ziminsky
- **Project Performer:** General Electric Co.
- **Partners:** GE Power & Water, GE Global Research

GE FULL SCALE EARLY COMBUSTION HARDWARE

BUDGET

Total Award: $9,440,737

DOE Share: $6,608,516

Performer Share: $2,832,221

DOE Funding Plan

FY14	FY15	FY16	
$554,962	$125,000	-	Phase I – Fully funded in FY15
		$2,236,870	Phase II

Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle

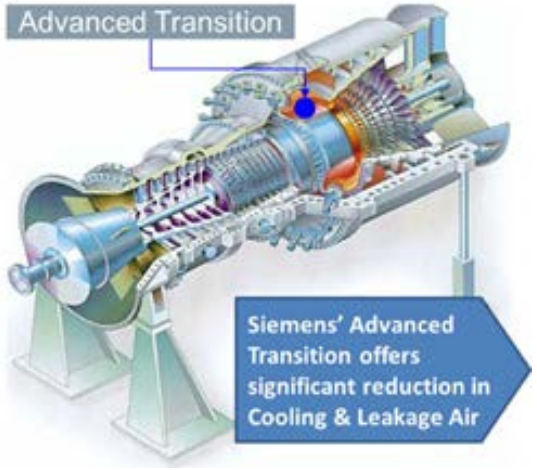
Siemens Energy Inc.

PROJECT NARRATIVE

- Siemens will develop a CMC based design for Siemens's Advanced Transition
- Deliverable is a design concept read for fabrication and test in a Phase II project
- Will utilize Siemen's patented Hybrid Oxide CMC system

BENEFITS

- Reduced cooling requirements enabling higher turbine inlet temperatures
- Contributes to DOE goal of 65% combined cycle efficiency



PROJECT INFORMATION

Project Title: *Ceramic Matrix Composite Advanced Transition for 65% Combined Cycle*

Award Number: FE0023955

Project Duration: 10/01/14 - 03/31/16

Key Technology: Advanced Combustion Turbines

Location: Orlando, FL

FPM: Seth Lawson

Project Performer: Siemens Energy Inc.

PI: Jay Morrison

BUDGET

Total Award: $8,118,348

DOE Share: $6,494,678

Performer Share: $1,623,670

DOE Funding Plan

FY14	FY15	FY16	
$649,454	$470,329	-	Phase I – Fully funded in FY15
		$1,725,000	Phase II

High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency

General Electric Co.

PROJECT NARRATIVE

- GE will develop cooled high-temperature CMC nozzles (non-rotating airfoils)
- Leverages existing knowledge of CMC materials
- Phase I scope includes
  - Design and analysis of attachment configurations
  - Investigation of impingement and film cooling
  - Definition of sealing approaches, design of key sealing features, and analysis of sealing effectiveness
- Limited bench flow testing

BENEFITS

- Contributes to DOE goal of 65% combined cycle efficiency
- Revolutionary component architectures

PROJECT INFORMATION

Project Title: *High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency*

Award Number: FE0024006

Project Duration: 10/01/14 - 08/31/19

Key Technology: Advanced Combustion Turbines

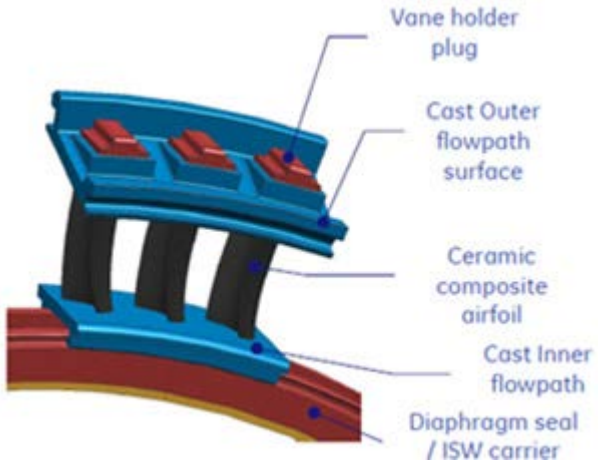
Location: Greenville, SC

FPM: Robin Ames

Project Performer: General Electric Co.

PI: John Delvaux

GE BAYONET NOZZLE ASSEMBL



BUDGET

Total Award: $9,537,331

DOE Share: $6,564,478

Performer Share: $2,972,853

DOE Funding Plan

FY14	FY15	FY16	
$219,499	$470,329	-	Phase I – Fully funded in FY15
		$1,725,000	Phase II

Rotating Detonation Combustion for Gas Turbines-Modeling and System Synthesis to Exceed 65% Efficiency Goal

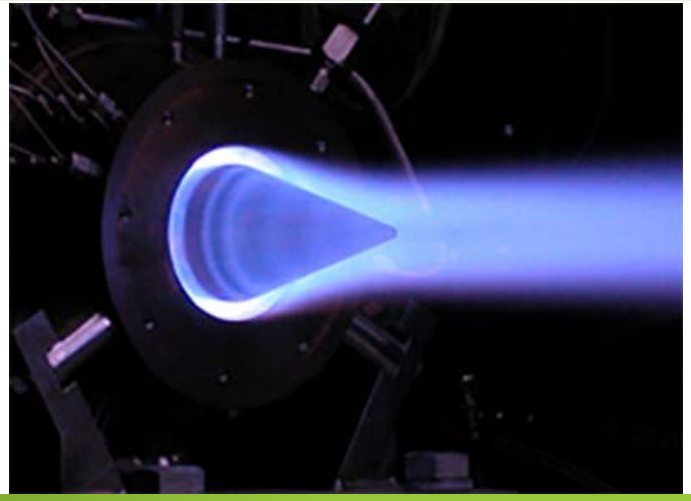
Aerojet Rocketdyne

PROJECT NARRATIVE

- Aerojet Rocketdyne, Inc. will develop, validate, and integrate a systems model for a rotating detonation combustor in a power plant systems model
- Initially creates a system simulation tool for integration
- Results of simulation will be integrated into systems model to define the path to configurations that exceed 65% efficiency

BENEFITS

- Contributes to DOE goal of 65% combined cycle efficiency
- Advances technology for combustion turbines for combined cycle applications



PROJECT INFORMATION

- **Project Title:** Rotating Detonation Combustion for Gas Turbines-Modeling and System Synthesis to Exceed 65% Efficiency Goal
- **Award Number:** FE0023983
- **Project Duration:** 10/01/14 - 03/31/16
- **Key Technology:** Pressure Gain Combustion
- **Location:** Chatsworth, CA
- **FPM:** Robin Ames
- **Project Performer:** Aerojet Rocketdyne
- **PI:** Glenn Havskjold

BUDGET

Total Award: $7,570,127

DOE Share: $6,054,678

Performer Share: $1,515,449

DOE Funding Plan

FY14	FY15	FY16	
$600,000	-	-	Phase I – Fully funded in FY14
		$1,747,517	Phase II

Development of Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders

General Electric Co.

PROJECT NARRATIVE

- GE and SwRI will develop expander shaft end seals for utility-scale supercritical CO_2 power cycles
- Conceptual design of a utility scale end seal capable of meeting the component-level and system-level objectives
- Thermodynamic optimization and preliminary design for a conceptual layout for a utility-scale sCO_2 power plant
- GE will develop face seals as a solution for end shaft sealing for SCO2 turbo expanders
- Conceptual design of a dedicated sCO_2 facility with enough fidelity to inform Phase II cost and schedule

BENEFITS

- Enables transformational goal of $10/metric ton CO_2 capture by 2035
- Thermodynamic cycle efficiencies of 50-52 percent or greater
- Reduced water consumption, reduced power block size and better thermodynamic integration with post-combustion CO_2 capture equipment

PROJECT INFORMATION

Project Title: *Development of Low-Leakage Shaft End Seals for Utility-Scale Supercritical Carbon Dioxide (sCO_2) Turbo Expanders*

Award Number: FE0024007

Project Duration: 10/01/14 - 08/31/19

Key Technology: Supercritical CO_2 Power Cycles

Location: Niskayuna, NY

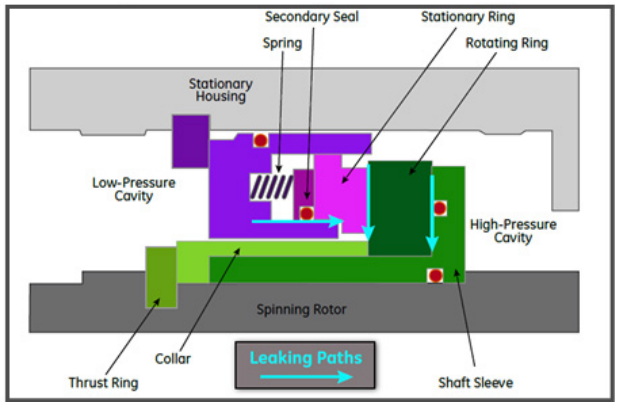
FPM: Seth Lawson

Project Performer: General Electric Co.

PI: Rahul Bidkar

Partners: Southwest Research Institute (SwRI)

DRY GAS SEALING TECHNOLOGY



BUDGET

Total Award: $8,617,402

DOE Share: $6,824,098

Performer Share: $1,793,304

DOE Funding Plan

FY14	FY15	FY16	
$699,757	-	-	Phase I – Fully funded in FY14
		$1,875,712	Phase II

High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion

Southwest Research Institute

PROJECT NARRATIVE

- The project team seeks to develop a high inlet temperature oxy-combustor suitable for integration with direct-fired supercritical CO_2 power cycles for fossil energy applications
- R&D evaluation of direct-fired sCO_2 oxy-combustor has involved system engineering design and thermodynamic analysis to assess plant efficiencies, verify operating conditions and optimize plant configuration in conjunction with technical gap analysis
- The Phase II effort seeks to build a 'first-of-a-kind' 1 MW test facility in order to evaluate the sCO_2 oxy-combustor technology in an integrated system (which enables both component- and system-level testing) to address/reduce technical uncertainties

BENEFITS

- Efficient power generation with integrated carbon capture at up to 99 % of generated CO_2
- Advances state-of-the-art in high pressure, high temperature combustor design

PROJECT INFORMATION

Project Title: *High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion*

Award Number: FE0024041

Project Duration: 10/01/14 - 03/31/20

Key Technology: Supercritical CO_2 Power Cycles

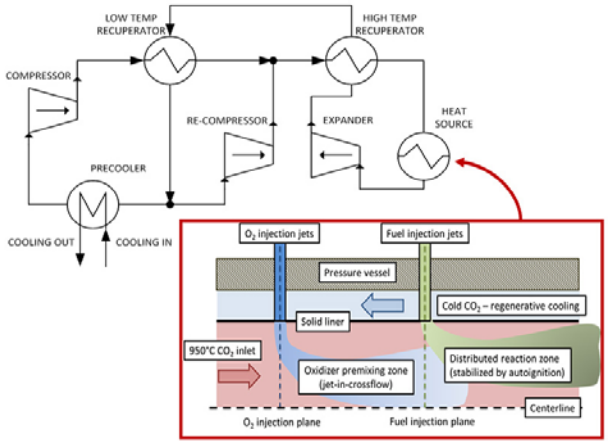
Location: San Antonio, TX

FPM: Mark Freeman

Project Performer: Southwest Research Institute

PI: Dr. Jacob Delimont

Partners: Thar Energy, GE Global Research, Georgia Tech, University of Central Florida



Autoignition-Stabilized Combustor Concept for Direct Fired Supercritical Oxy-Combustion Cycle

BUDGET

Total Award: $4,741,944 (Phase I plus Phase II)

DOE Share: $3,793,540

Performer Share: $948,404

DOE Funding Plan

FY14	FY15	FY16	
$600,000	-	-	Phase I – Fully funded in FY14
		$3,193,540	Phase II – Fully funded in FY16

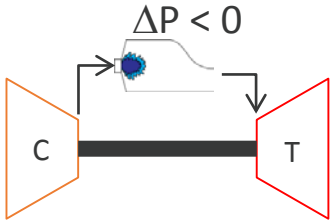
NETL Turbine Research

Goal **– Develop technology toward achieving the program goal of 3-5% points increase in efficiency.**

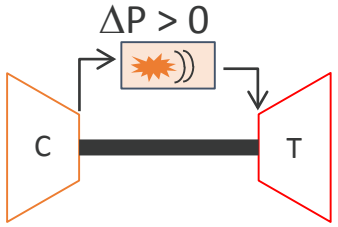
Approach **– Perform R&D in three important areas: Combustion, Heat Transfer and Advanced Cycles. Perform systems analysis to support research focus and verify performance targets.**

Pressure Gain Combustion

Improving efficiency through pressure increase across combustor.



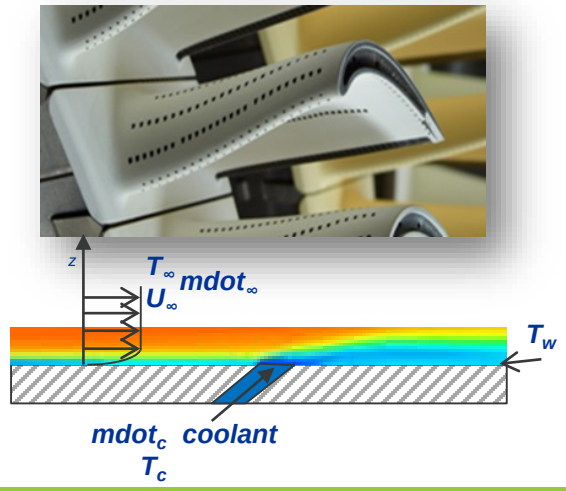
Conventional "**Constant Pressure** " Combustion has pressure loss across combustor



"**Constant Volume**" Combustion incorporates a Pressure Gain with combustion

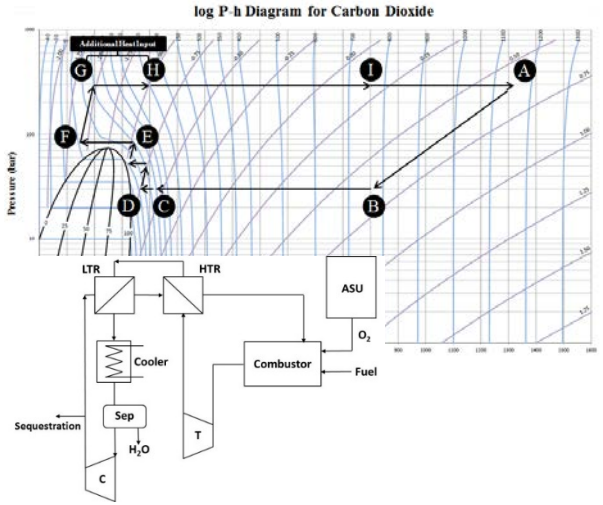
Aerothermal and Heat Transfer

Improving efficiency by increasing firing temperature and reducing cooling load.



Supercritical CO_2 Cycles

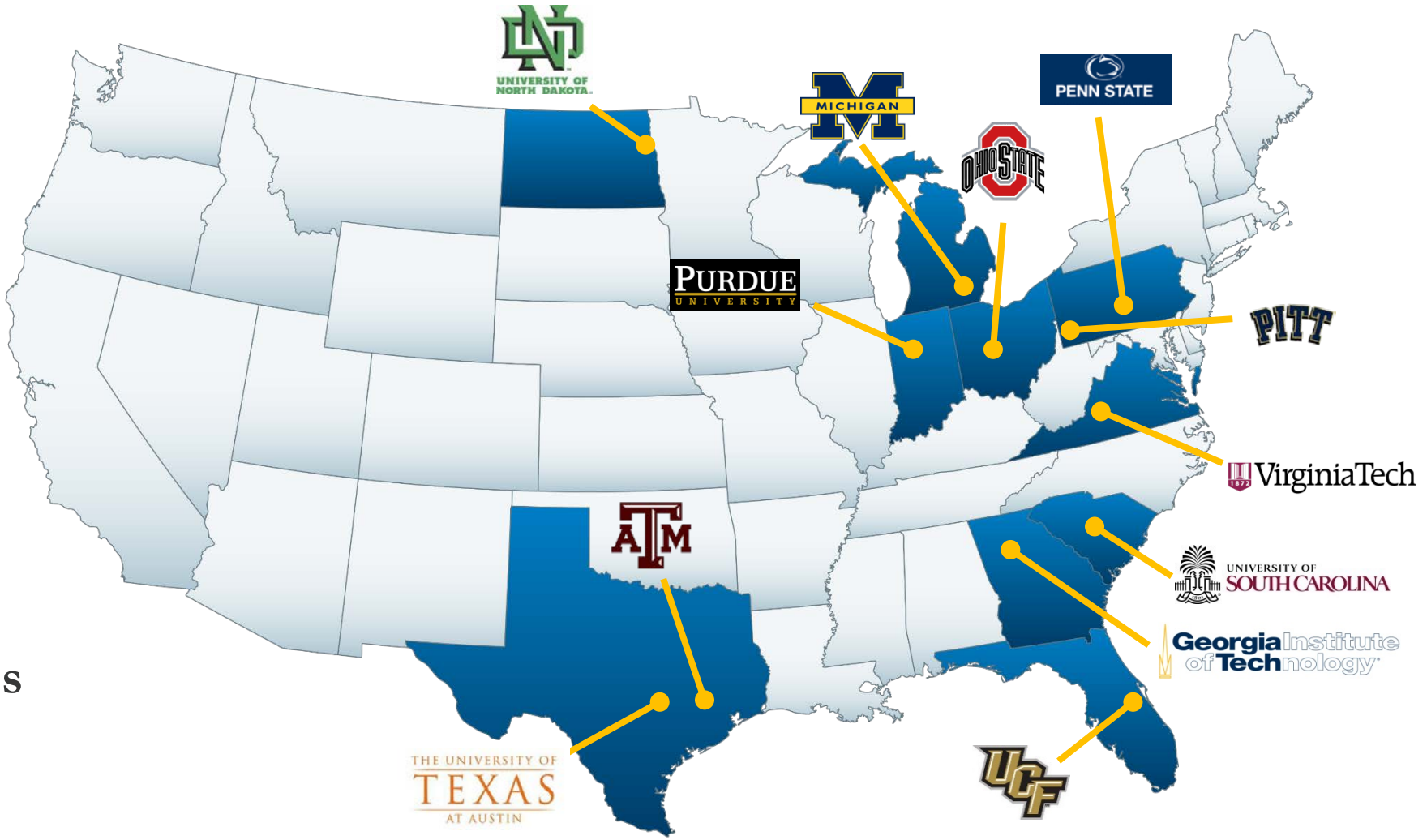
Improving efficiency through unique properties of supercritical CO_2 as a working fluid.



University Turbine Systems Research Program

- **Support DOE FE Advanced Turbine Program goals**
  - Addresses scientific R&D to develop advanced turbines
  - Focused on coal-derived syngas, H_2, and other fossil fuels
- **Goals advanced by universities, GT industry, and DOE FE**
- **UTSR Industrial Fellowship funded by GT manufacturers**
- **UTSR projects established through competitive FOA**
  - open to all U.S. universities.
  - R&D topics support FE program and GT industry
- **Annual UTSR workshop facilitates technical communications with industry, academia, and DOE**
  - Open to the public, reviews of all UTSR and Advanced Turbines projects

2016 UTSR Program Participants



10 States

12 Universities

18 Projects

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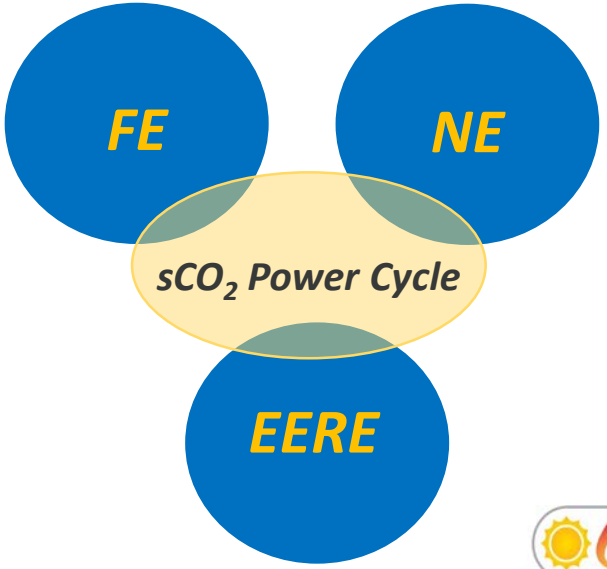
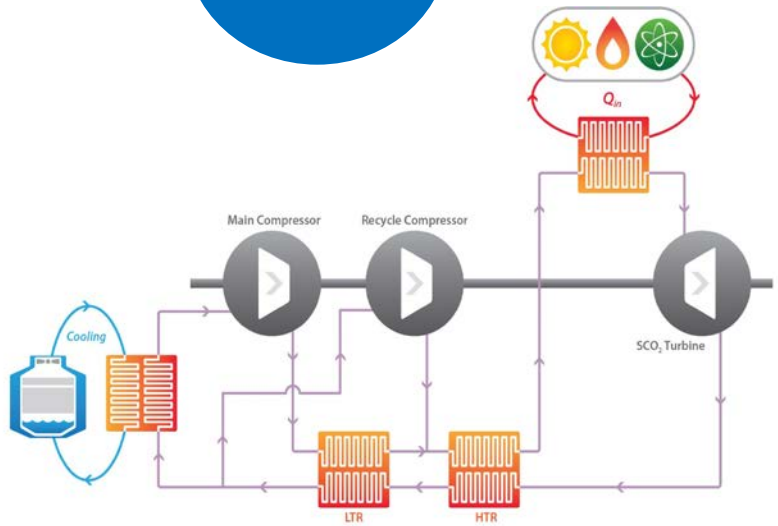
DOE SCO2 Crosscut Initiative

- **Nuclear Energy, Fossil Energy and Energy Efficiency and Renewable Energy collaborate on sCO2 power cycles**
  - Coordinate efforts to solve common application challenges
- **Mission:** Address technical issues, mature technology, reduce risks towards commercialization of the sCO2 power cycle
- **Design, build, and operate 10 MWe STEP (Supercritical Transformational Electric Power) indirect-fired sCO2 power cycle pilot-scale facility to demonstrate**
  - Component performance
  - Cycle operability
  - Progress towards a lower cost of electricity (> 50 % cycle eff.)
- **Base R&D portfolios within the three offices continue to address application specific development needs**





Technology Development of Modular, Low-Cost, High-Temperature Recuperators for sCO2 Power Cycles

Thar Energy LLC

PROJECT NARRATIVE

- The team will complete engineering assessments, recuperator development plans for multiple advanced recuperator concepts
- Phase I: Evaluate design, cost, performance. Down select most promising concept
- Phase II: Detailed design, fabrication of 47 MWth recuperator

BENEFITS

- Scalable recuperator design with optimal performance/cost ratio
- Operability at high temperature and pressure

PROJECT INFORMATION

Project Title: *Technology Development of Modular, Low-Cost, High-Temperature Recuperators for sCO2 Power Cycles*

Award Number: FE0026273

Project Duration: 10/01/2015 – 3/31/2019

Key Technology: STEP

Location: Pittsburgh, PA

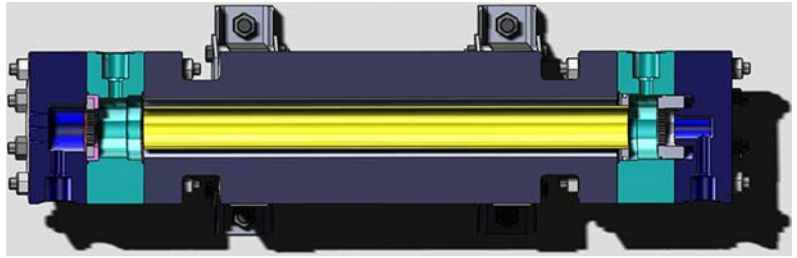
FPM: Seth Lawson

Project Performer: Thar Energy LLC

PI: Lalit Chordia

Partners: Southwest Research Institute, Oak Ridge National Laboratory, Georgia Institute of Technology

Microtubular heat exchanger layout



BUDGET

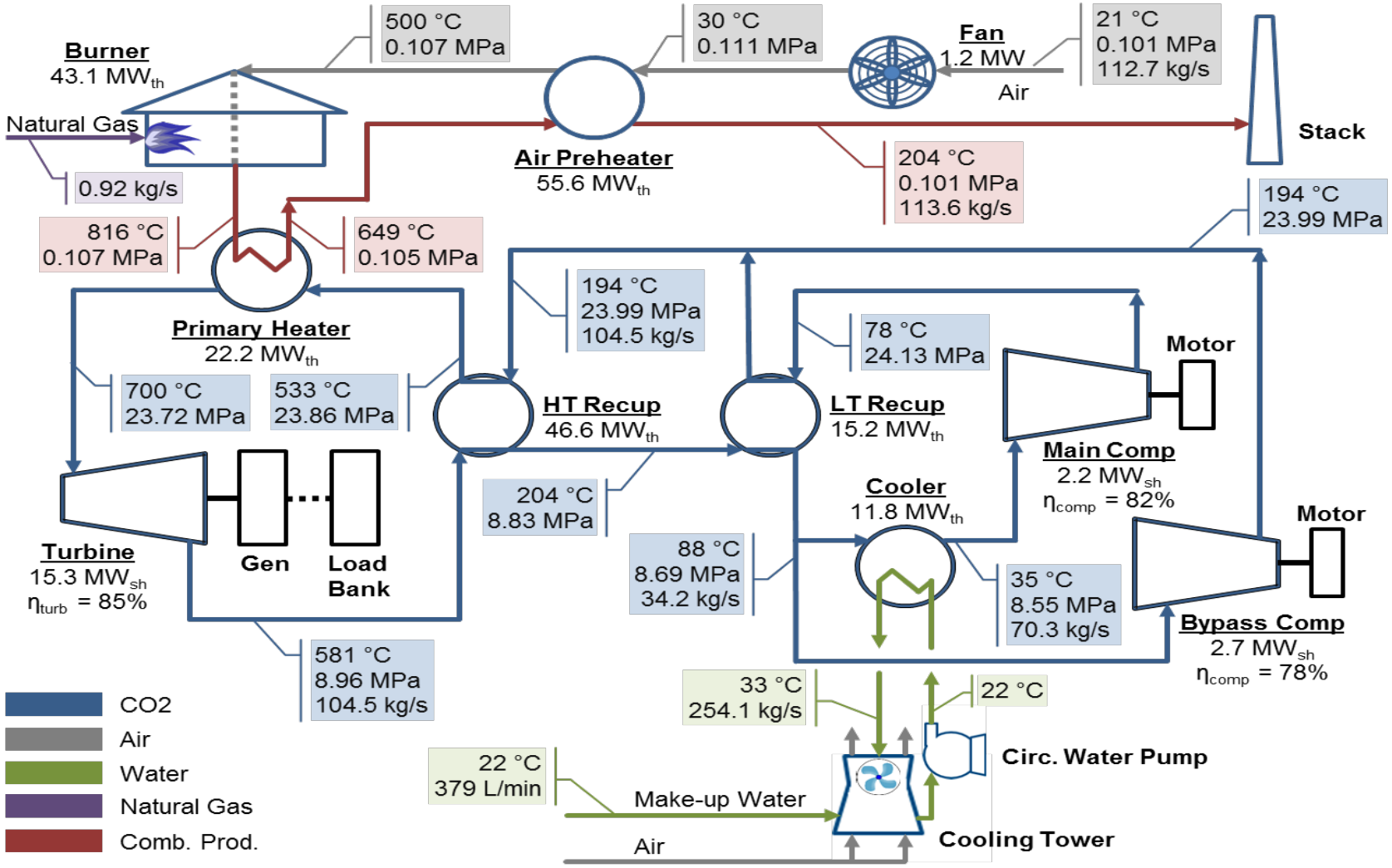
Total Award: $11,693,535.00

DOE Share: $9,344,826.00

Performer Share: $2,348,709.00

Baseline STEP Facility Layout 10 MWe Cycle Diagram

NETL Basis for Cost Estimate of STEP Facility



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Summary - UTSR Request for Information (RFI)

- **RFI issued on September 29 and closed October 24**
- **Purpose of RFI**
  - Obtain stakeholder input to formulate the next UTSR FOA
  - Identify technical R&D topics/subtopics that support:
    - Advanced gas turbine technologies for 65 % efficiency
    - Supercritical carbon dioxide based power cycles.
- **52 suggestions received outlining technical topics/subtopics**
    - Supporting advanced combustion turbines for 65 % efficiency
    - Supporting SCO2 power cycles
    - New areas were also suggested
- **Please join us Thursday (11/3/2016) 9 – 11 AM for a more detailed and collaborative discussion of these results to help shape the future of the UTSR program**

Summary

- Abundant and low cost natural gas has changed the power generation landscape
- Turbine based power generation is growing significantly
- The DOE Office of Fossil Energy Advanced Turbines (AT) Program is investing in advanced technology to support the 65 % CC efficiency goal and SCO2 power cycles
- UTSR is a significant part of the AT program
- Please join the UTSR RFI discussion on Thursday morning