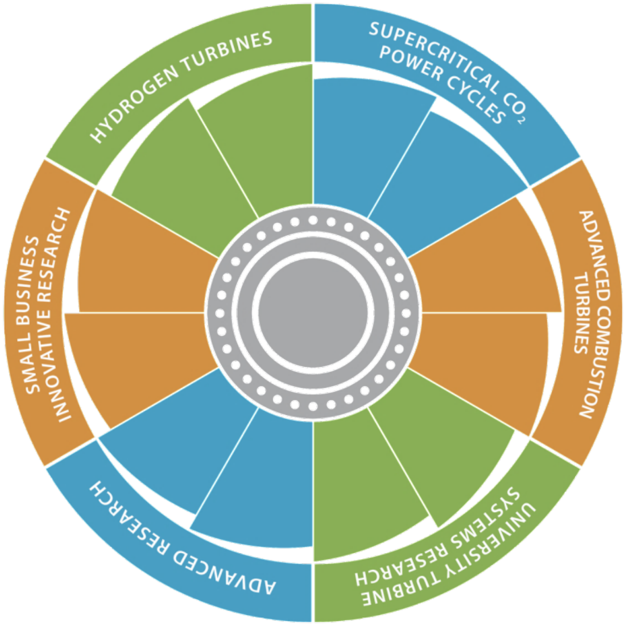


US DOE FE Advanced Turbine Program: Suggested Next Steps for UTSR

Richard Dennis, Technology Manager

Advanced Turbines, Advanced Energy Systems

DOE FE NETL

2014 UTSR Workshop
Purdue University; West Lafayette, IN
October 21 – 23, 2014

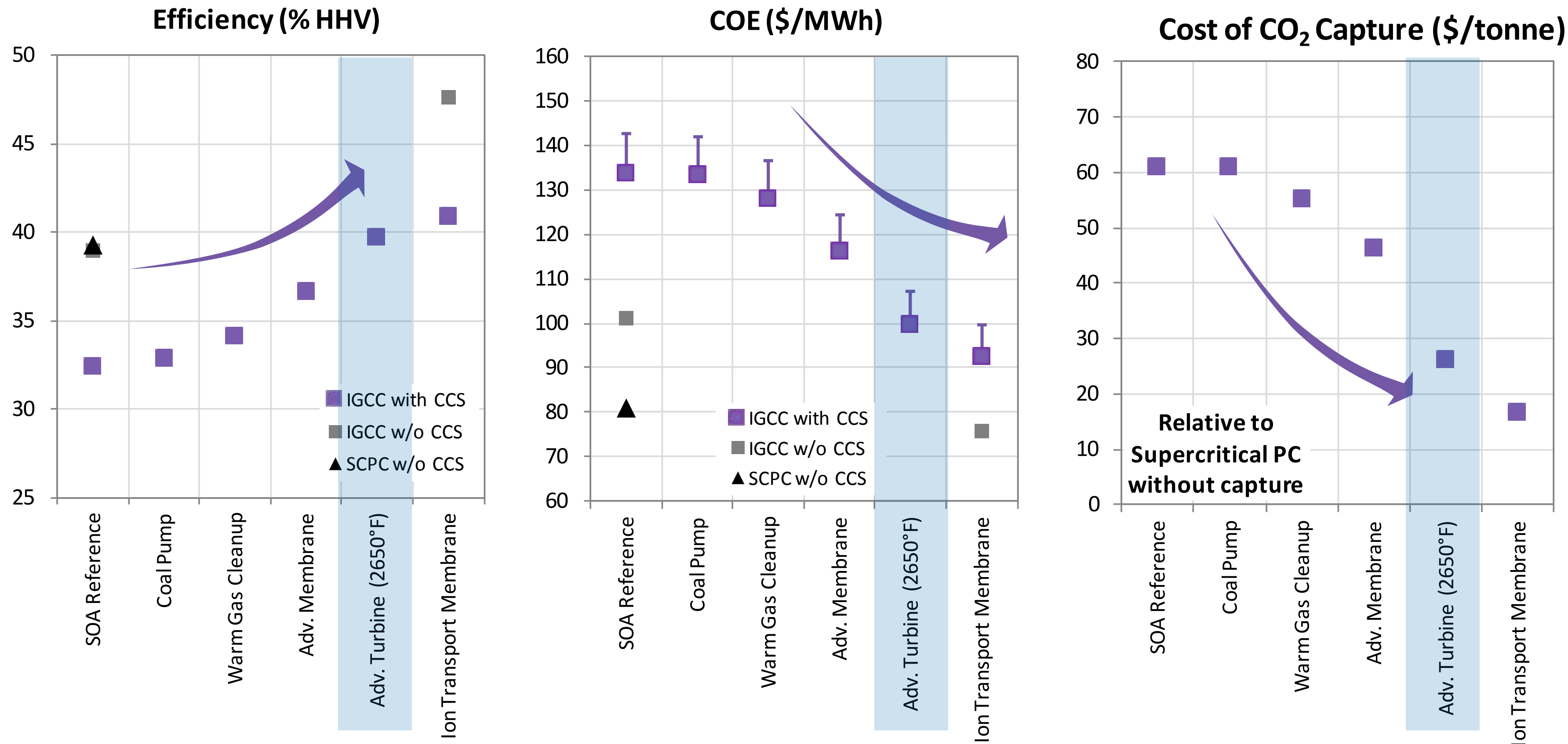
Presentation Outline

US DOE FE Advanced Turbine Program: Suggested Next Steps for UTSR

- **Drivers and approach**
- **Current R&D portfolio**
- **Results & key projects**
- **Next steps - future program path**

R&D Driving Down the Cost of CO_2 Capture

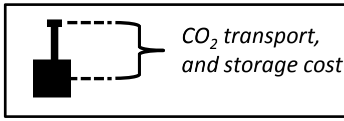
IGCC with Pre-Combustion Capture/H_2 Turbine



Advances in H_2 turbines including increases in firing temperature, output and compressor and turbine efficiencies, reduced cooling requirements, and addition of integration with the ASU provide:

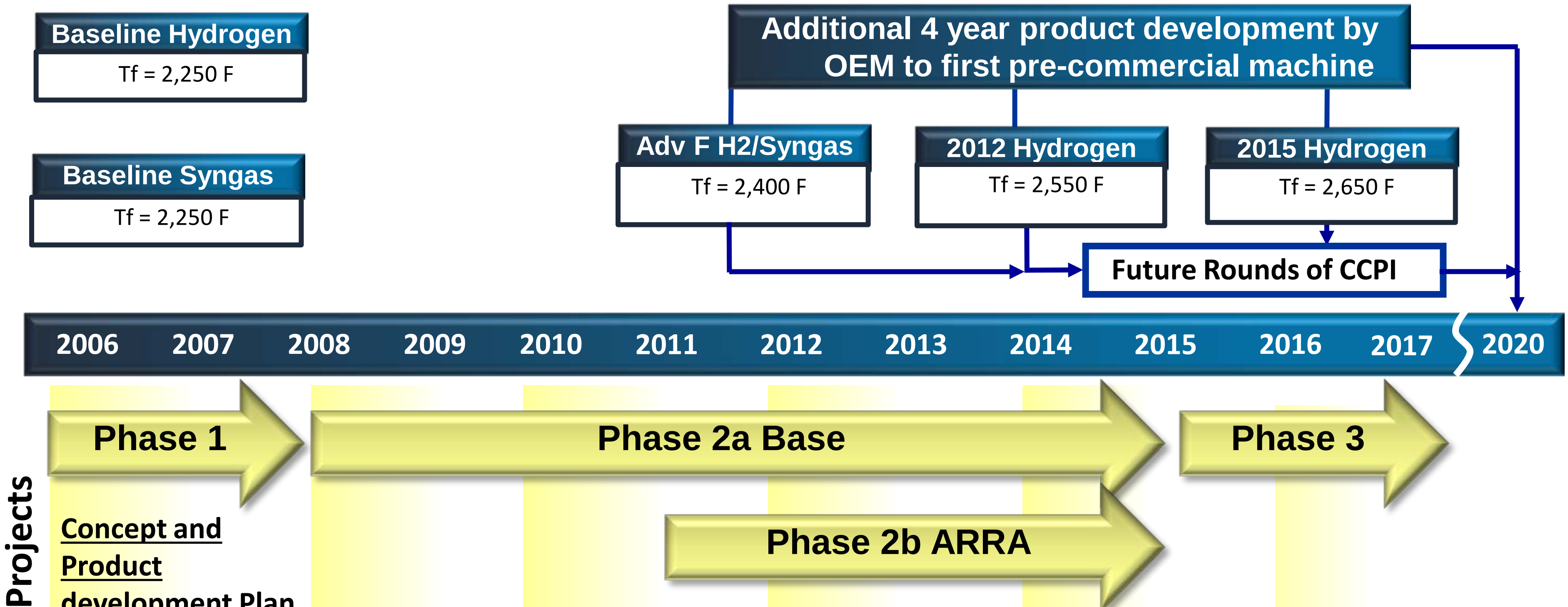
- **Efficiency improvements of 3 percentage points (4.3 percentage points vs. 2003 IGCC with 7FA)**
- **Cost of electricity (COE) reduction of ~15% and cost of capture reduction of ~$19/tonne**

H_2 turbines critical to IGCC pathway and achievement of CCRP goals



H_2 Turbine Development for IGCC with CCS

GE and Siemens H_2 Turbine Project Schedule



Concept and Product development Plan

- Conceptual design studies
- Go / No go lab testing
- Systems studies

Technology Development and Validation

- System studies
- Lab scale testing
- Bench / pilot scale testing
- Component design and testing
- ARRA funds bring in new technologies and enhance some existing efforts

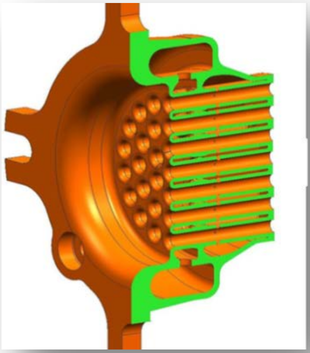
Design, Manufacturing and Testing of Pre-Commercial prototype (Phase 3 Not Awarded)

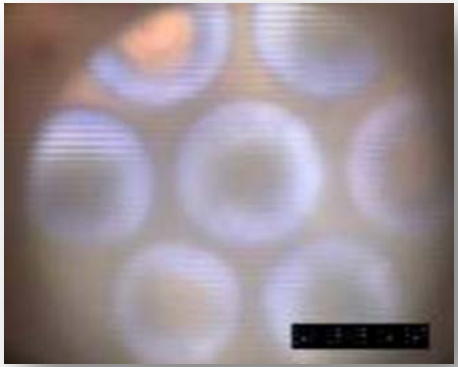
- Final component testing
- Detailed design
- Fabrication and assembly of machine
- Pre-commercial testing

GE Full-Scale H_2 Combustion Testing

Ready for Full Scale Pre-Commercial Deployment

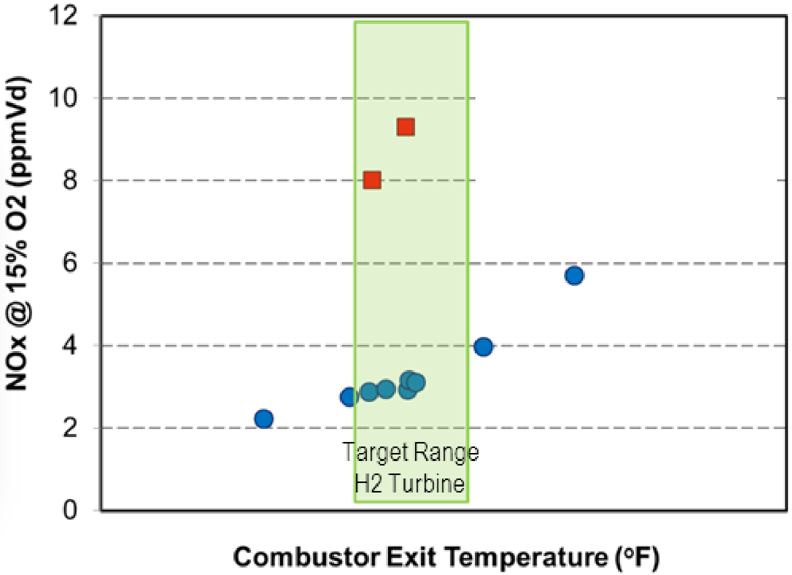
- **Tested at full F-class & advanced gas turbine conditions with various fuel blends including 100% H_2**
- **< 3 ppm NOx @15% O_2 at target temp. with N_2 diluent**
- **Primary manufacturing path identified**
- **Leading candidate for combustion systems in all future gas turbine commercial product lines**





High-Hydrogen

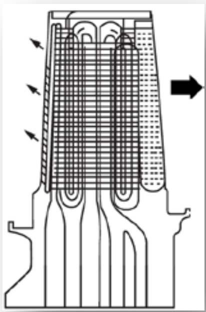
Improved, scaled-up MT Mixer for Full Can Testing



*Ref: Proceedings of ASME Turbo Expo 2012, June 11-15, 2012, Copenhagen, Denmark, GT2012-69913; DEVELOPMENT AND TESTING OF A LOW NOX HYDROGEN COMBUSTION SYSTEM FOR HEAVY DUTY GAS TURBINES, W. York, W. Ziminsky, E. Yilmaz **

Mikro Systems & Siemens Commercialize Advanced Cooling Technology for High Temperature Operation

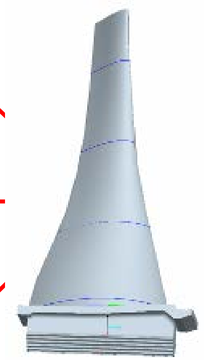
Ceramic Cores for Advanced Air Foils
Full Scale Engine Tests Completed



Innovative Designs
Siemens (DOE)

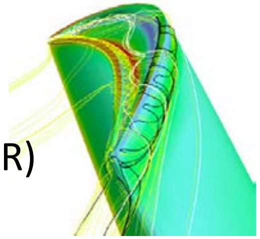
Innovative Manufacturing
Mikro Systems (DOE & SBIR)

NDE-GIS/IR Evaluation
Siemens (DOE)



4th Stage Air Foil

Model Test
Univ. of Pittsburgh (DOE)



CFD Analysis
Purdue Univ. (DOE & SBIR)

Hi-Temp/Press Rig Test
DOE-NETL

Casting Trials
(DOE & Mikro SBIR)

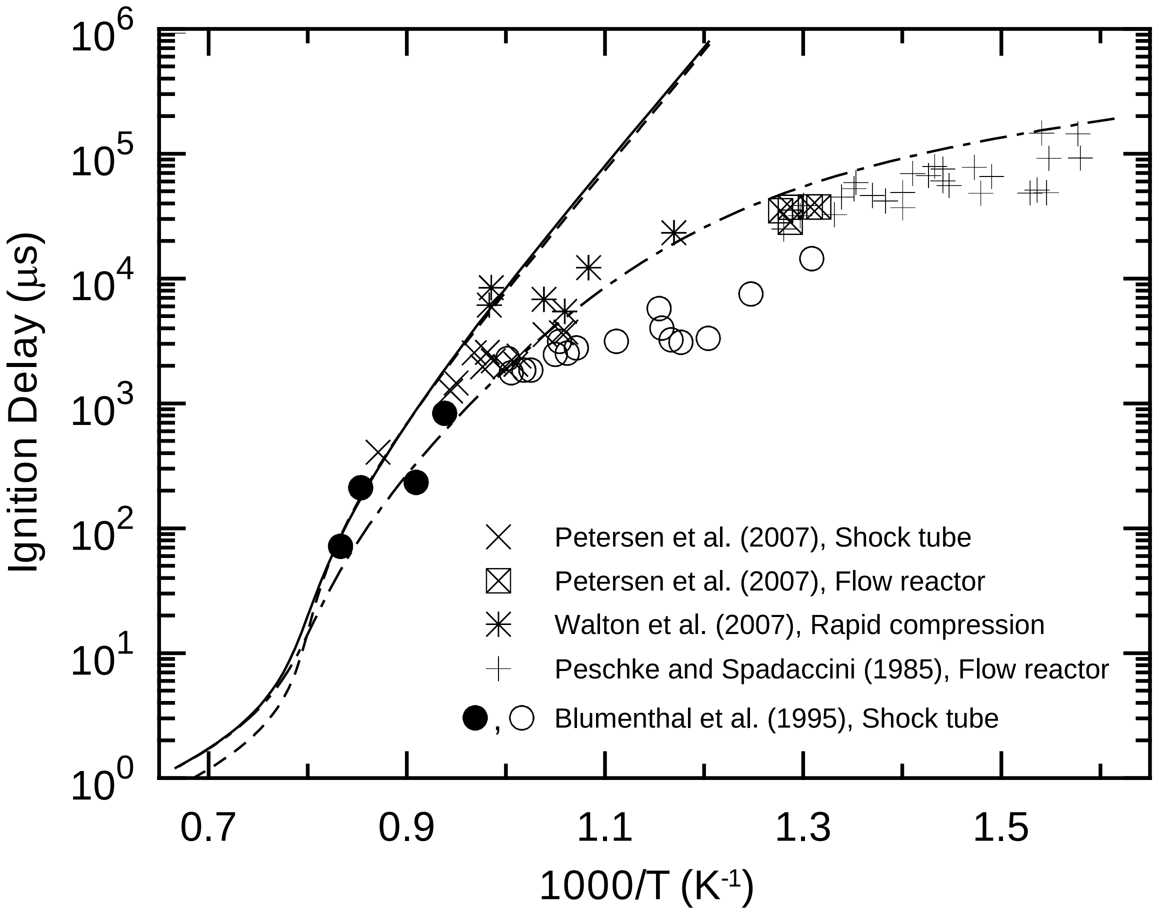
Siemens facility in Charlottesville, VA opened in 2013 for commercial production of airfoil ceramic cores for gas turbine blades and vanes using the TOMO^{SM} technology.

University Turbine Systems Research (UTSR)

Universities, Industry and government working on common R&D goals

- **Support DOE FE Hydrogen 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 network of universities, GT industry, and 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**

UTSR Addresses Complexities in Early Ignition Behavior with HHC/Syngas Fuels



Discrepancies persist between model predictions and measurements of ignition delay times (665ºF -1150ºF) across many test facilities

These discrepancies have been several orders of magnitude under certain conditions – calling into question both the meaningfulness of these lab experiments as well as the robustness of kinetics models

Path Forward for the Advanced Turbines Program

Additional Benefits & Market Applications

- **Advanced combined cycle turbine for hydrogen fuels**
  - Applicable to H_2 and natural gas
  - TIT of 3,100 ^oF
  - Adv. components: pressure gain combustion, advanced transition, air foils w/ decoupled thermal & mechanical stresses
  - Delivers another $20/T reduction in CO_2 capture cost
  - CC efficiency ~ 65 plus % (LHV, NG as bench mark)
- **Supercritical CO_2 based power cycles**
  - <u>Indirectly heated cycle</u> -> ~ 7 % pts. fuel-to-bus bar eff. improvement over SOTA PC (1,300 ^oF SCO2 TIT)
  - <u>Directly heated cycle</u> -> gateway to low cost CO_2 capture for coal based IGCC and NG

Targeted R&D Areas for Turbines Based Systems

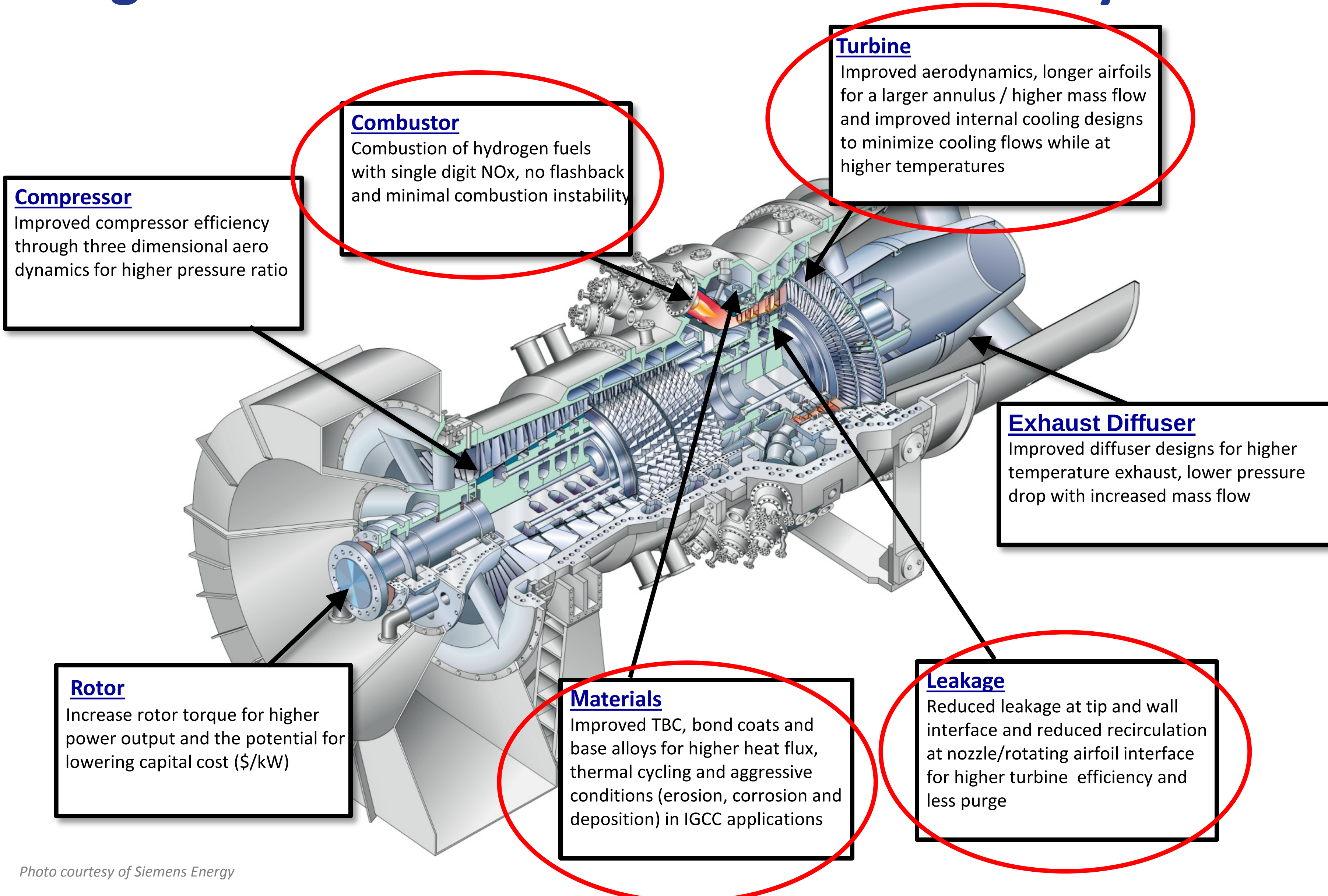
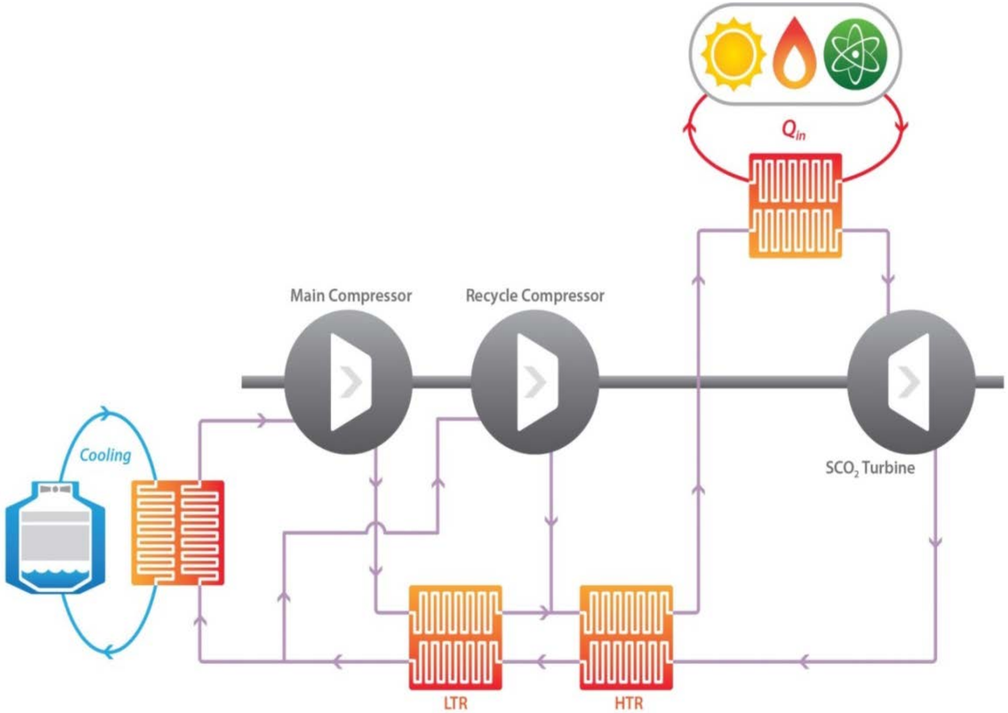


Photo courtesy of Siemens Energy

Supercritical CO_2 Power Cycles

Indirectly Heated Recompression Brayton Cycle

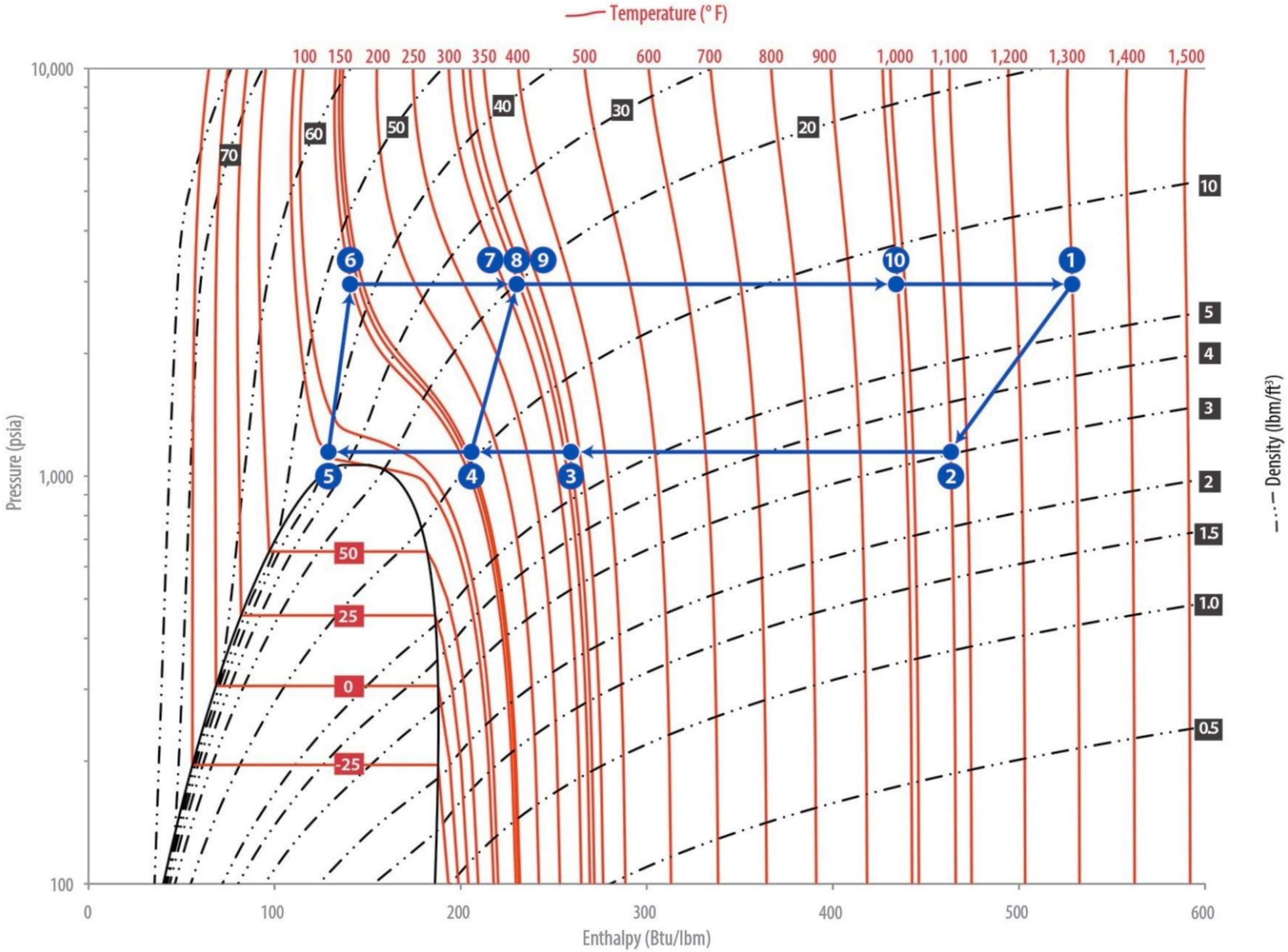
- **Thermal eff. > 50% possible**
- **~ 50% of the cycle energy is recuperated heat**
- **Low pressure ratio yields small turbo machinery**
- **Non condensing**
- **Ideally suited to constant temp heat source**
- **Adaptable for dry cooling**



Recuperated Recompression Brayton (RCB) Cycle

CO_2 Pressure Enthalpy Diagram

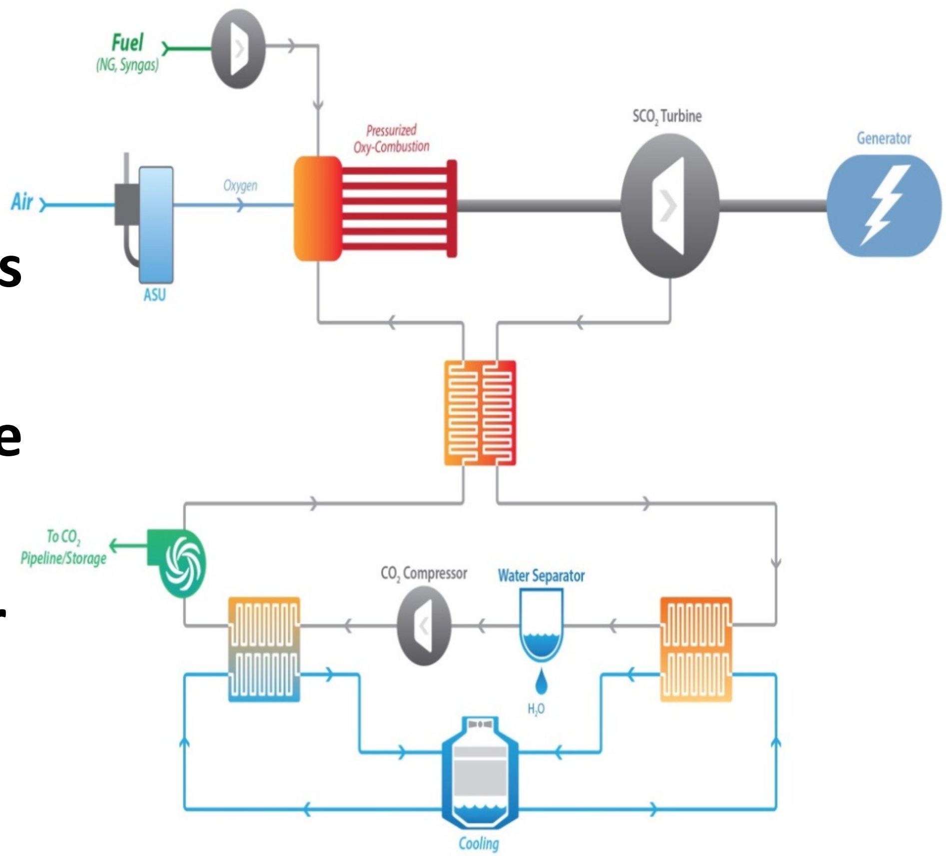
state points from previous slide



Supercritical CO_2 Power Cycles

Directly Heated Oxy-fuel Semi-closed Brayton Cycle

- **Directly heated cycle compatible w/ technology from indirectly heated cycle**
- **Fuel flexible: IGCC coal syngas or NG**
- **100 % CCS at storage pressure**
- **Water producer**
- **Incumbent to beat: Adv. F- or H-class NGCC w/ post CCS**
  - Nominally requires SCO2 TIT ~ 2,300 F or greater



Directly Heated Oxy-fuel SCO2 Power Cycle

DOE SCO2 Power Cycle Collaboration

- **SwRI workshop - SCO2 Power Cycle R&D, Feb 13 - 14, 2013**
- **NE RFI – SCO2 Brayton Cycle R&D Program; June 2, 2014**
- **EERE workshop – SCO2 Power Cycle R&D, June 23-24, 2014; Washington, D.C.**
- **2015 ENERGY & WATER APPROPRIATIONS BILL, August, 14**
- **4th. Symp. on SCO2 Power Cycles; Pitt., PA; Sept. 9 – 10, '14**
- **FE workshop – SCO2 Brayton Cycle R & D, Sept. 11, 2014**

2014 Advanced Turbine Funding Opportunity Announcement (FOA)

- **Objective: Competitively award applied R&D projects targeting innovative turbomachinery components. Two topic areas:**
  1. Adv. turbine components in CC applications capable of 65% or greater eff. (LHV) (bench mark)
  2. Supercritical CO_2 (SCO_2) based power cycles that are directly or indirectly heated in FE applications
- **The FOA utilized a two phase project approach:**
  - Phase I: Engineering & thermodynamic analysis / component validation. $500 k - $700 k DOE each
  - Phase II: Development / testing of components at lab. / bench scale. Anticipated awards: $2 M – $ 10 M DOE
- **Phase I awarded hard down-select to Phase II in FY16**

Photo courtesy Siemens Energy

2014 Advanced Turbine FOA

Topic Area 1: 7 Awards - Turbine Components in CC Applications

- **Advanced components & combustors for 65 % efficiency**
  - High Temperature CMC Nozzles (GE)
  - Ceramic Matrix Composite Adv. Transition for 65% CC (SE)
  - Turbocharged Turbine with Adv. Cooling (FL Turbine Tech)
  - Adv. Multi-Tube Mixer Combustion for 65% Eff. CC (GE)
  - Low NOx Combustor Design for 65% Efficient Engine (SE)
- **Pressure gain combustion**
  - Rotating Detonation Combustion for Gas Turbines - Modeling and System Synthesis (Aerojet Rocketdyne, Inc.)
  - Combined Cycle Power Generation Employing Pressure Gain Combustion (United Technologies Research Center)

2014 Advanced Turbine FOA

Topic Area 2 (AT): 4 Awards - SCO2 Based Power Cycles

- **Turbo Machinery for Indirect and Direct SCO2 Power Cycles (AT- new)**
  - Low-Leakage Shaft End Seals for Utility-Scale SCO2 Turbo (GE)
  - Adv. Turbomachinery Comp. for SCO2 Cycles (Aerojet Rocketdyne)
- **Oxy-fuel Combustors for SCO2 Power Cycles (AT - new)**
  - Coal Syngas Comb. for HP Oxy-Fuel SCO2 Cycle (8 Rivers Capital)
  - HT Combustor for Direct Fired Supercritical Oxy-Combustion (SwRI)
- **Recuperators / Heat Exchangers for SCO2 Power Cycles (ACS - new)**
  - Low-Cost Recuperative HX for SCO2 Systems (Altex Tech. Corp)
  - Mfg. Process for Low-Cost HX Applications (Brayton Energy)
  - Microchannel HX for FE SCO2 cycles (Oregon State U)
  - HT HX for Systems with Large Pressure Differentials (Thar Energy)
  - Thin Film Primary Surface HX for Advanced Power Cycles (SwRI)
  - HX for SCO2 Waste Heat Recovery (Echogen / PNNL, SBIR)
- **Materials and Fundamentals (AT)**
  - Materials Issues for Supercritical carbon Dioxide (ORNL – on going)
  - Thermodynamic and Transport Properties of SCO2 (NIST -on going)

AT = Adv. Turbine program funding; ACS = Adv. Combustion Systems program funding

Advanced Turbines Program Portfolio

FY 2015 Project Participants

(new projects in Green and ending projects in Red — if not extended)

Hydrogen Turbines

GE Energy-ARRA, SC/NY
Siemens Energy-ARRA, FL

Advanced Turbine Components for CC

Aerojet Rocketdyne, CA
Florida Turbine Tech., FL
General Electric, NY
General Electric, SC
Siemens Energy, FL
Siemens Energy, FL
United Technologies, CT

Supercritical CO2

NIST, CO
ORNL, TN
8 Rivers Capital, NC
Aerojet Rocketdyne, CA
General Electric, NY
Southwest Research, TX
Echogen, OH (SBIR)

UTSR Program

Aero Heat Transfer

Ohio State, OH
U. North Dakota, ND
U. North Dakota, ND
U. Texas Austin, TX
Virginia Tech, VA

Combustion

Georgia Tech, GA	U. Calif. Irvine, CA	U. S. Carolina, SC
Purdue U., IN	U. Calif. Irvine, CA	U. Texas Austin, TX
Purdue U., IN	U. Michigan, MI	U. Texas Austin, TX
Texas A&M,TX	U. Michigan, MI	

Materials

Georgia Tech, GA	Stony Brook, NY	U. Conn., CT
Louisiana St., LA	Tenn. Tech, TN	U. N. Dakota, ND
Purdue U. , IN	U. Calif. Irvine, CA	U. Pittsburgh, PA

Advanced Research

Aero Heat Transfer and Materials

Ames Laboratory, IA
Florida Turbine Tech., FL
NETL/RUA*
ORNL, TN

SBIRs

Innovative Cooling Concepts

Florida Turbine Tech., FL

Manufacturing

Mikro Systems, VA
Mikro Systems, VA
QuesTek, IL

Thermal Barrier Coatings

HiFunda & UConn, UT CT
UES, OH
Mohawk, NY
UES, OH

*= single project with multiple activities; ARRA = American Recovery and Reinvestment Act;
UTSR = University Turbine Systems Research; SBIR = Small Business Innovative Research

Summary & Conclusions

Additional Benefits & Applications

- **Technical challenges addressed / resolved**
  - Solved: H_2 combustion with low single digit NO_x
  - Advanced components & concepts, materials, and manufacturing
  - H2 turbine at 2,650 °F TIT provides ~ $20/T reduction in capture cost ($60/T of CO_2 capture -> $ 40/T)
- **Current program is wrapping up**
- **Path forward for additional benefits & market applications**
  - Advanced Combined Cycle H2 Turbine (3,100 °F)
    - **Another $20/T reduction in CO_2 capture cost**
    - **High efficiency 65 % CC (LHV as a bench mark)**
  - SCO2 power cycles - Significant benefits for coal and NG w CCS
    - **Components and oxy-fuel combustion**
- **UTSR will have a role in this new path forward**