Combined Heat and Power Research and Development

FWP Number: CEED210, Project 19864, Agreement 19128

Oak Ridge National Laboratory

Project Period: Sept 2008 – Sept 2011

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Executive Summary

Comprehensive program addresses improved efficiency and optimization of CHP systems and components as well as expanded use of opportunity fuels

- **Combined Heat & Power Activities**
  - **Develop a state-of-the-art, large-bore, single-cylinder engine research facility**
  - **Thermodynamic evaluation of recip- and turbine-based CHP engines and systems**
  - **Advanced combustion studies**
  - Examine potential of advanced concepts such as closed Brayton cycle and super-critical CO_2 systems
  - Develop and evaluate advanced materials for engine valves and turbines
- **Fuel Flexibility: Contaminant (Siloxane) Mitigation**
  - Examine silica formation kinetics and characterize deposits
  - Development of a novel siloxane separation technique
  - Evaluation of low-cost siloxane sensor (with University of Tennessee)

Project objectives

- **Improve the efficiency and utility of CHP systems**
  - **Develop tools and methods for system-level design and optimization of CHP systems**
  - **Develop and evaluate strategies for real-time management of power-to-heat ratio to meet changing demands**
  - **Identify and assess opportunities to improve component efficiencies**
    - Thermodynamic analysis of engine data and CHP system modeling
    - Control to improve stability of lean-limit combustion and advanced combustion modes
    - Improved durability of high-temperature valve and turbine materials
  - **Evaluate how those improvements impact overall system performance**
    - *e.g.*, effect of low-temperature combustion strategies, improved turbo-machinery, etc on process heat production and system efficiency
  - **Fuel flexibility for increased utilization of opportunity fuels**
- **Dissemination of gained knowledge through publications and interactions with industry**

Project Management and Budget

- **FY 2011 budget for ORNL's CHP tasks: $1200k**
  - **FY 2011 budget for three tasks presented today: $700k**
  - **Total BA received for FY 2011 to date: $638k (of $1200k)**
- **FY 2012 budget: TBD**

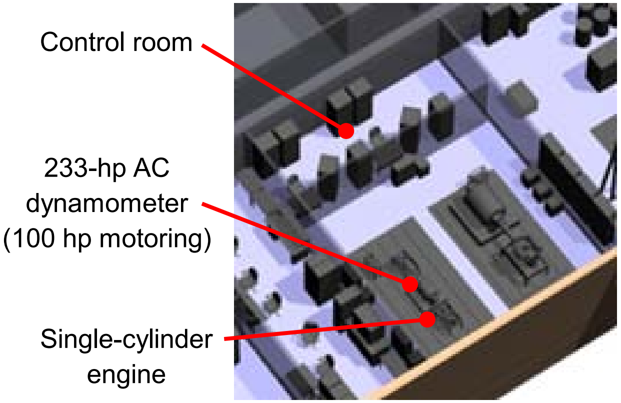
- **FY 2011 Milestones**
  - **Complete and publish advanced thermodynamic analysis of reciprocating engine examining areas for potential efficiency gains (Sept 2011)**
  - **Publish results from baseline and lean-burn studies on large-bore, single-cylinder engine (Sept 2011)**
  - **Publish results from valve materials study (Sept 2011)**

Discussion of each task

Task 1: Establishing a large-engine research cell at ORNL

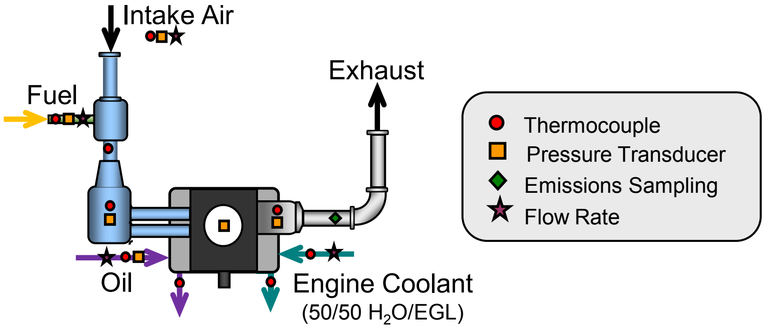
- **Internal funding used to develop state-of-the-art large-engine research cell**
  - 600-hp DC dynamometer
  - Dual-ended, 233-hp AC dynamometer (100 hp motoring)
  - Fuel-flexible operation: natural gas, diesel, and gasoline/ethanol
  - Cell commissioned in March 2009
- **Installed 3.0-L single-cylinder research engine based on Waukesha APG1000 (Phase I ARES engine)**
  - Designed and built by Digital Engines
  - Collaborated with GE Energy, Dresser Inc. on install and start-up
  - LabView®-based engine controls and data acquisition
  - Engine commissioned on 3 November 2010
- **Provides state-of-the-art research capabilities for large-bore, natural gas engines**

Floor plan of large-engine research cell at ORNL



3.0-L single-cylinder engine installation

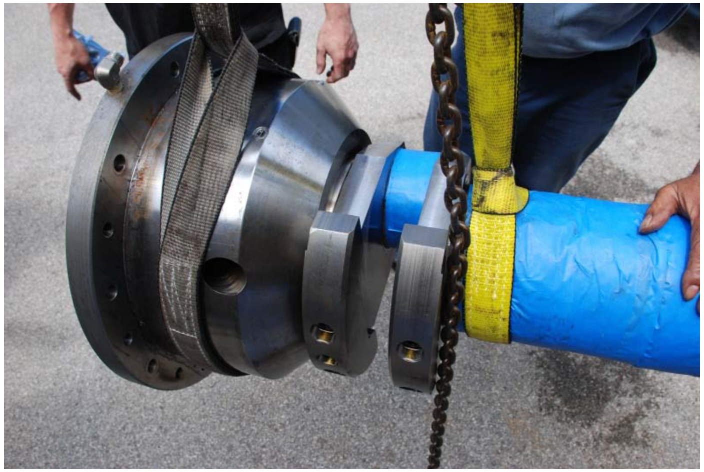
Extensive instrumentation to support detailed thermodynamic analysis



Status update on single-cylinder research engine

- **Unfortunately, after 19 hrs of fired operation, the front engine bearing seized on 23 March 2011**
  - Failure occurred approximately 20 min into initial operation at rated speed (1800 rpm)
  - Engine stopped within 7 s from 1800 rpm, overcoming 180 ft-lbf of engine torque, 200 ft-lbf of dyno torque and the inertia of a 900 lb flywheel
- **GE Energy, Dresser Inc. experienced two similar failures on their sister engine**
  - Same bearing failed
  - Tribology consultant attributed failure to thermal expansion mismatch between bearing carrier and crankshaft during warmup
  - We worked closely with GE Energy, Dresser Inc. during install and startup to develop pre-heating and oil-quality monitoring procedures in efforts to avoid similar failure
- **We plan to repair engine, address bearing lubrication issues, and return to operation this FY**
  - Engine disassembly and failure analysis have begun
  - Plan to consult with third-party tribologist
  - Redesign of bearing and lubrication systems
  - Modular design of engine should aid redesign efforts
- **Engine has attracted interest from multiple companies seeking to partner with ORNL on research efforts**

Front bearing seized on crankshaft

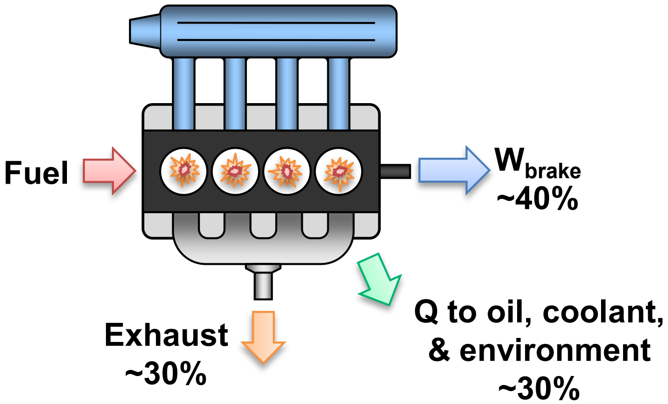


Task 2: Thermodynamic evaluation of CHP systems

- **Thermodynamic analysis provides a method for evaluating performance and potential opportunities for efficiency improvement in the engine and system as a whole**
  - First Law shows how fuel energy is used or lost throughout the system (common practice)
  - Second Law provides a relevant reference state to determine the actual work potential of the energy flows
- **System modeling supplements experimental data and provides additional insight into processes which are difficult to observe (*e.g.*, combustion, heat transfer, etc)**

Example of typical energy usage for an IC engine

1st Law: Fuel energy usage



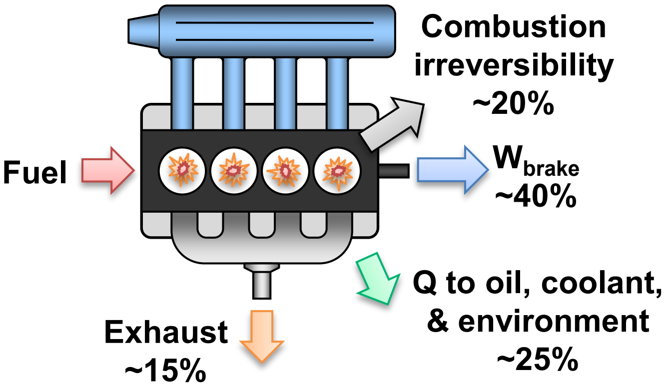
Fuel

W_{brake} ~40%

Exhaust ~30%

Q to oil, coolant, & environment ~30%

2nd Law: Fuel exergy usage



Combustion irreversibility ~20%

Fuel

W_{brake} ~40%

Exhaust ~15%

Q to oil, coolant, & environment ~25%

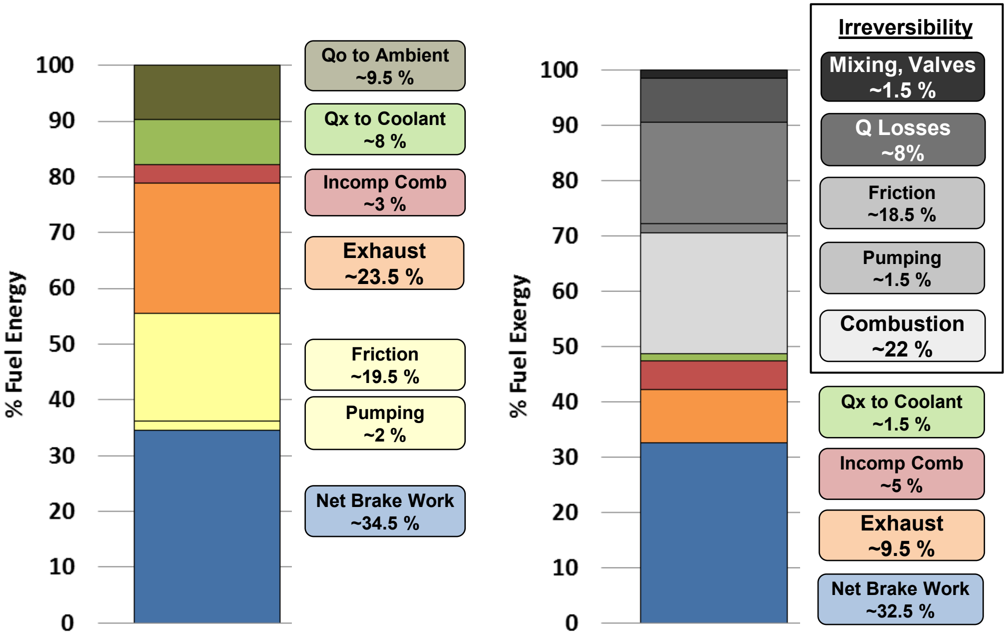
Working Definition: ***Exergy*** *(a.k.a. availability) is a measure of a system's potential to do useful work due to physical (P, T, etc.) and chemical differences between the system and the ambient environment.*

Thermodynamic analysis of IC engine data

- **Thermodynamic analysis of engine data provides insight to fuel energy usage**
  - Evaluate changes in energy distribution with operating strategy
  - Locate and quantify opportunities for efficiency improvement
- **Substantial detail can be obtained with standard measurements and a few assumptions**
  - Brake torque, temperatures, pressures (including in-cyl), air and fuel rates, exhaust composition, etc
- **Working with GE Energy, Dresser Inc. on more extensive analysis of engine and model data for APG1000**

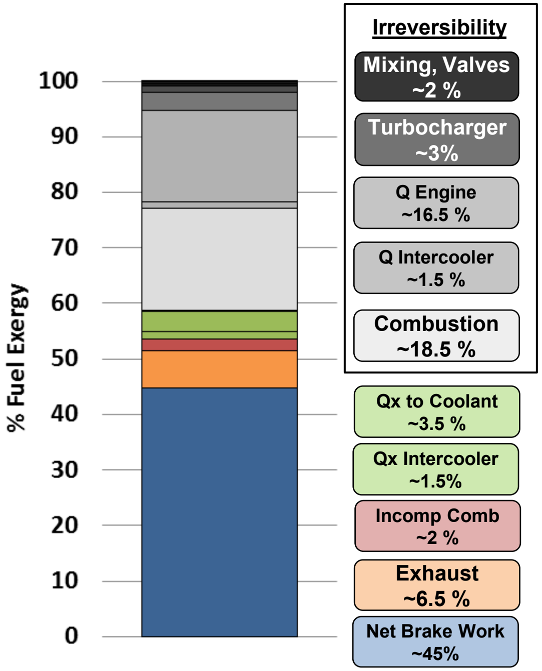
Example energy distribution based on data from single-cylinder engine
(1500 RPM, 7.25 bar BMEP)

1st Law Energy Balance **2nd Law Exergy Balance**



Example exergy distribution for APG1000
(@ different operating point)

2nd Law Exergy Balance



Efficiency limits of IC engines

- **IC engines are not limited by Carnot Efficiency**
  - **Theoretically, the maximum first law efficiency of an IC engine is** $\eta_{\max} \cong 100\%$
- **Practically, maximum efficiency is limited by a number of real-world concerns**
  - Work extraction efficiency
  - Material limits
  - Irreversible losses (friction, combustion irreversibility, etc)
  - Cost
- **Significant efficiency improvement will require addressing multiple loss mechanisms**

Loss Mechanism	Challenges and Opportunities	Assessment
Combustion Irreversibility	• Unrestrained combustion reactions far from chemical and thermal equilibrium • Requires radical changes in how combustion occurs • Some opportunities related to dilution and fuel selection	Difficult for near-term
Environmental heat loss	• Low-temperature combustion techniques • Adiabatic approach increases thermal exhaust energy for better energy transfer to turbocharger and/or other WHR hardware • Higher temperature operation requires improved materials and lubricants	• Low-temperature combustion approach complicated by stability concerns and use of natural gas • Adiabatic approach most effective in combination with thermal energy recovery
Friction and pumping	• Improved lubricants • More efficient valve technologies, fuel systems, etc	Opportunities for improved part-load performance
Exhaust energy	• Reductions in and/or better usage of exhaust energy requires fully expanded cycles, advanced combustion, improved turbo-machinery, and/or thermal exhaust energy recovery	Significant opportunities in waste energy recovery

Pushing the efficiency limits toward 60%

- **A recent *Engine Efficiency Colloquium* organized by ORNL with participants from industry, government, and academia addressed the subject of maximum practical engine efficiency**
  - *"The maximum BTE expected for slider-crank engines is about 60%, assuming that cost is not a constraint."*
  - *"Achieving BTEs > 60% will require radical changes to present engines, including cycle compounding, new engine architectures, and more constrained combustion reactions."*

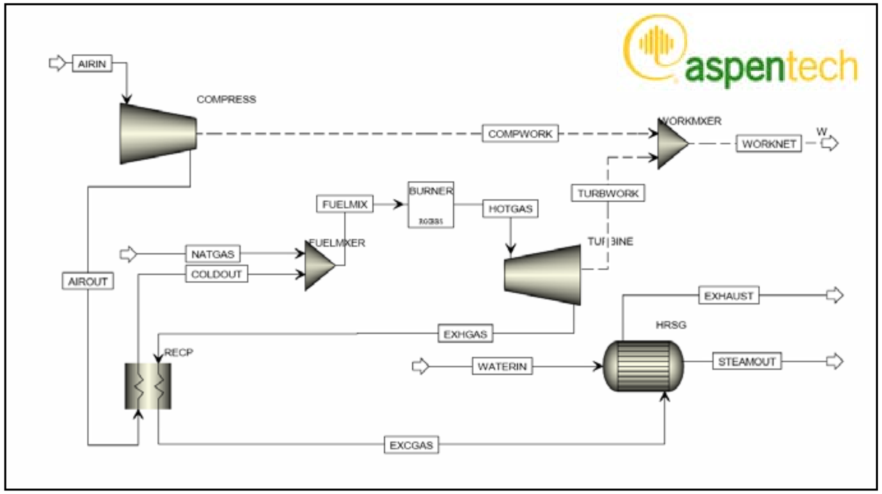
– Daw , et al. (2010) ORNL Report TM-2010/265

- **This would be a very aggressive, stretch goal and costly**
- **Large (*e.g.*, ARES-class) engines stand a better chance of approaching this goal than smaller engines (such as transportation engines or small gen-sets)**
- **Will require balancing benefits (+) and drawbacks (–) of multiple approaches**
  - **Waste heat recovery (WHR)**
  - **Advanced, low-temperature combustion techniques**
    - \+ Lower heat loss and aftertreatment fuel penalty
    - − Lower WHR potential
    - − May require advanced controls to limit cyclic variability
  - **Advanced materials with low thermal conductivity and high durability**
    - \+ Lower heat loss and higher WHR potential
    - \+ Operation at higher cylinder pressures (increased piston work)
    - − Increased potential for knock and NOx production
  - **Improved turbo-machinery efficiency**
    - \+ Higher boost (especially at part load)
    - \+ Turbo-compounding
  - **Variable valve actuation for reduced pumping losses at part load**
  - **Dual-fuel combustion strategies?**
  - **Fuel reforming (to H_2 and CO) using exhaust heat (thermochemical recuperation)?**

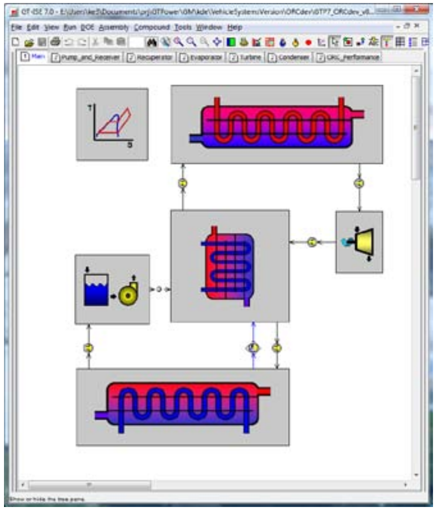
Modeling and analysis of recip- and turbine-based CHP systems

- **Models developed for state-of-the-art CHP systems using Aspen Plus® and GT-Suite®**
- **Evaluate combined system performance and assess opportunities for further optimization**
- **Evaluate strategies for managing power-to-heat ratio to meet demand**
- **Assess impact of strategies to improve power efficiency and/or reduce emissions on overall system performance and process heat production, for example…**
  - High-dilution (lean or high EGR) combustion strategies
  - Improved turbo-machinery performance for high-boost IC engines
  - Advanced materials for reduced heat loss
  - etc

Turbine-based CHP system modeling using Aspen Plus®



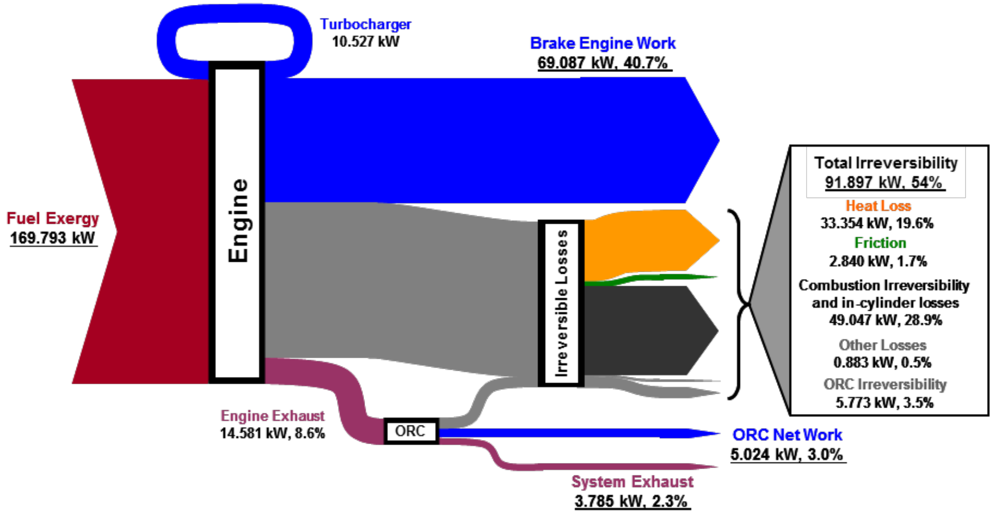
Reciprocating-engine-based CHP system modeling using GT-Suite®



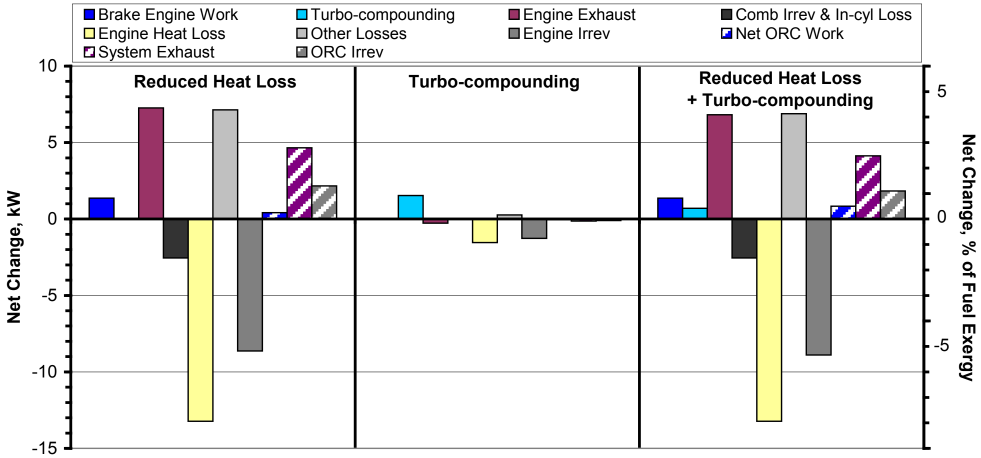
Modeling example for reciprocating-engine-based system

- **System consists of a state-of-the-art, light-duty diesel engine coupled with an organic Rankine cycle (ORC) for waste heat recovery for additional power**
- **Evaluated impact of engine efficiency improvement strategies on overall system performance**
- **Advanced materials to reduce heat loss**
    - Limited increase in engine power
    - Significant increase in engine exhaust temperature
    - Lower combustion irreversibility
    - *1.2% point increase in system performance*
- **Turbo-compounding**
    - ORC compensates by further lowering system exhaust temperature
    - *1% point increase in system performance*
- **Combined approach**
    - *~2% point increase in system performance*
- **Full results published**
    - **ASME ICEF2010-35120**
    - **SAE 2010-01-2209**

Exergy distribution for small diesel engine at peak efficiency with Rankine bottoming cycle for waste heat recovery



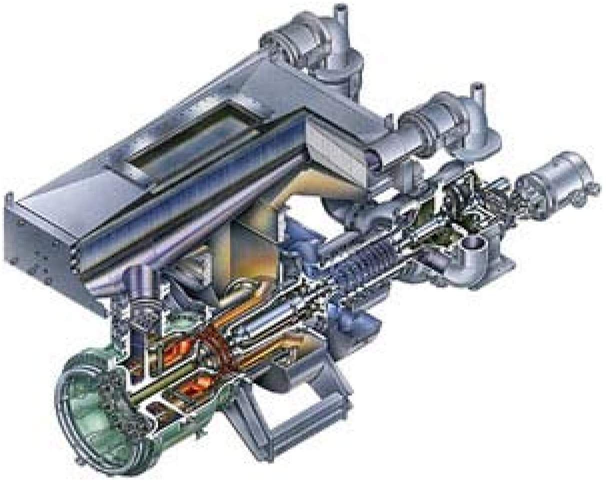
Net change in exergy distribution with efficiency improvement strategies



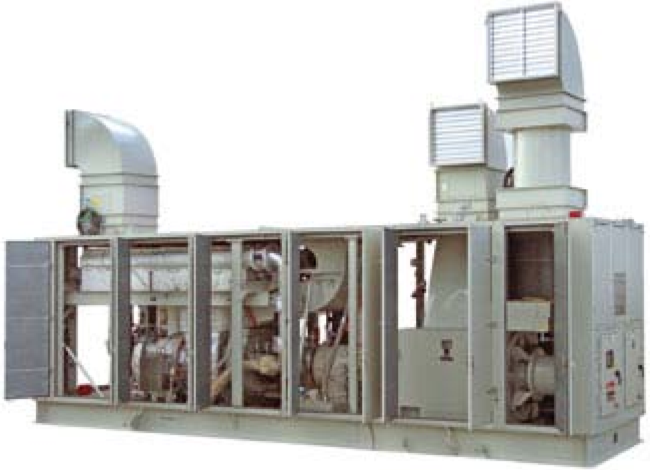
Turbine-based CHP system modeling and analysis

- **Aspen Plus used to model a state-of-the-art turbine-based CHP system for power and steam generation**
  - Evaluate opportunities for further optimizing system performance and power-to-heat ratio
  - Assess impact of power efficiency improvements on system performance
- **System based on a Solar Mercury™ 50 gas turbine**
  - State-of-the-art natural gas turbine system
  - Output: 4.6 MWe
  - Recuperated
  - 10-stage variable-vane compressor, 9.9:1 compression ratio
  - 2-stage reaction turbine
  - Ultra-lean-premix combustion
- **ORNL is also working with Solar Turbines on development of advanced turbine materials**

Cut-away schematic of Solar Mercury™ 50 turbine



Solar Mercury™ 50 turbine-based CHP installation

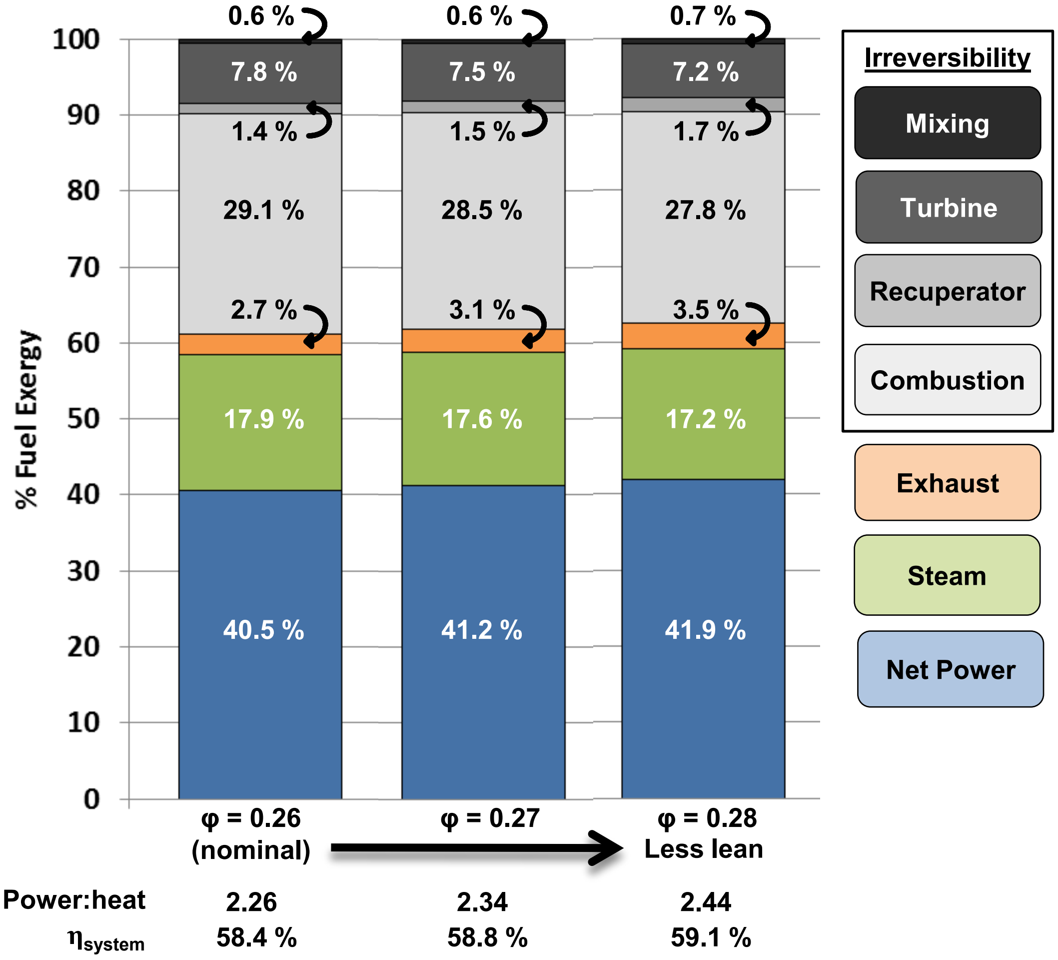


Images courtesy of Solar Turbines

Example results show effect of equivalence ratio on efficiency

- **Turbine-based CHP model recently completed**
- **Studies underway to assess impacts on system operation and evaluate opportunities for improvement**
- **Sample results presented here show impact of small changes in turbine equivalence ratio**
  - Increasing fueling increases power and overall system efficiency
  - Combustion irreversibility decreases with lower dilution – ~18.3 % at stoichiometry for natural gas
  - Ultra-lean operation desired to meet emissions regulations and limit turbine inlet temperature
    - Estimate potential efficiency improvement with advanced materials
    - Does efficiency benefits of less-lean operation outweigh burden of adding aftertreatment?
- **Additional studies underway (effects of pressure ratio, recuperator effectiveness, etc)**

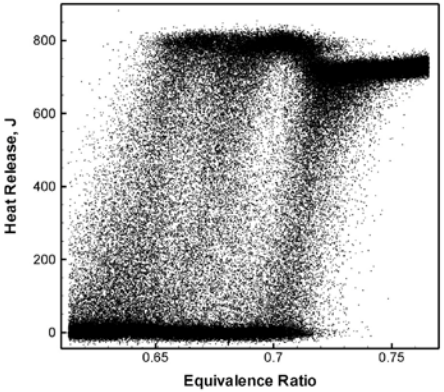
Model results showing equivalence ratio effects on exergy distribution for turbine-based CHP system



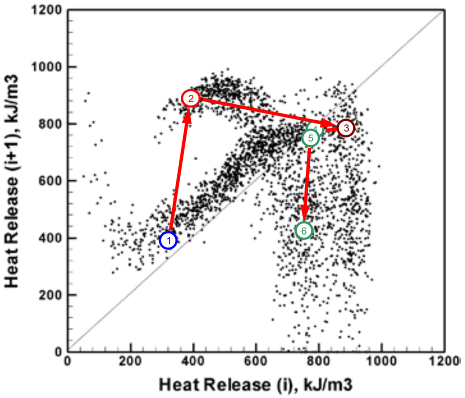
Task 3: Advanced combustion studies

- **Plans for this task involve ...**
  - Exploring the stability limits of the single-cylinder engine during lean and advanced combustion operation
  - Evaluating the potential to increase stability through intelligent control
- **ORNL has extensive experience in characterizing and controlling complex, unstable combustion processes to achieve efficiency and emissions reductions benefits**
  - Extending operation near stability limits
  - Transition and stabilization of low-temperature combustion modes
  - Avoiding misfire and abnormal combustion events

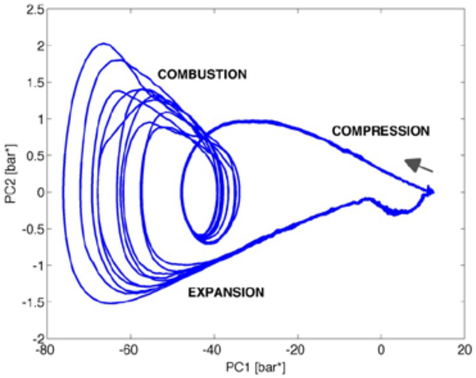
Example of unstable lean-limit SI operation



Complex but short-term predictable patterns observed in spark-assisted HCCI



Phase-space reconstruction for predicting instability



- **We are adapting plans for the remainder of FY2011 while the single-cylinder engine is repaired**
  - One option is evaluation a novel modeling strategy that builds on our existing understanding and ability to predict high-dilution combustion performance

Summary and Future Work

Comprehensive program has been established and is addressing challenges of improving component- and system-level performance of future CHP systems

- **State-of-the-art, single-cylinder research engine installed and commissioned at ORNL**
  - Engine suffered a bearing seizure
  - Failure assessment and redesign and repair efforts are underway
  - Goal is to return to operation this FY
- **Thermodynamic evaluations are providing insight to efficiency opportunities on a component and system level**
  - Presented assessment of practical IC engine efficiency limits
  - Evaluating IC engine data for efficiency opportunities
  - Continuing to exercise CHP system models
- **Combustion studies on the single-cylinder engine will resume following engine repairs**
  - Shifting focus to proposed modeling study for remainder of FY 2011

Questions?

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