Stretch Efficiency – Thermodynamic Analysis of New Combustion Regimes
(Agreement 10037)

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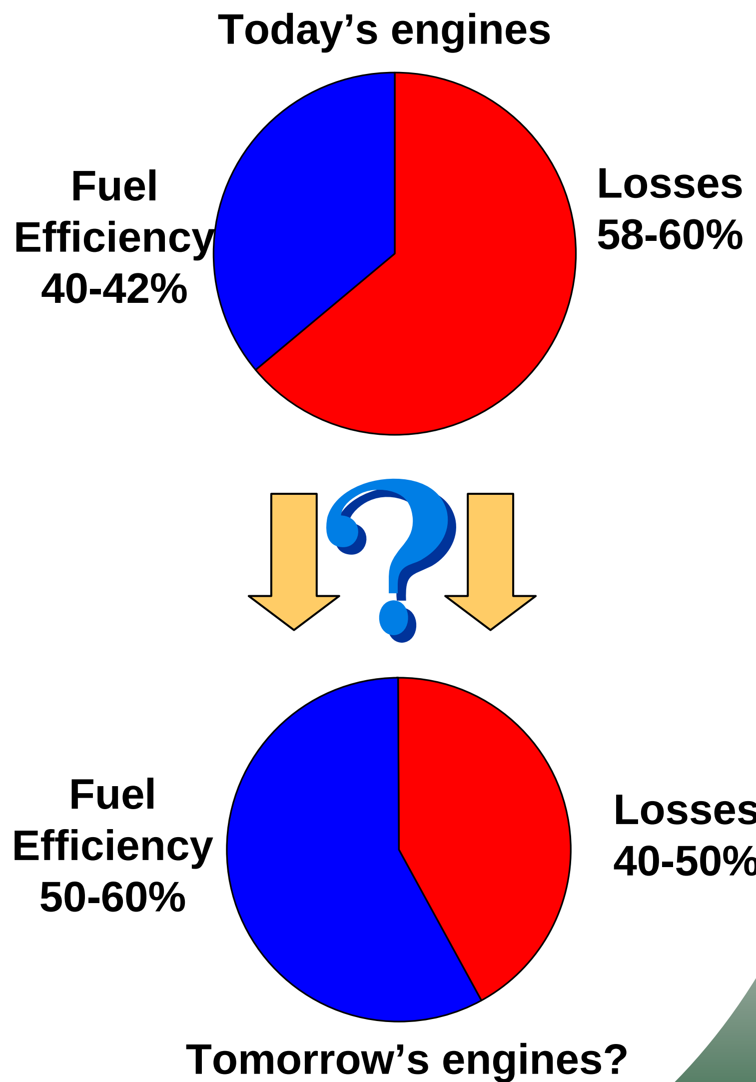
Vehicle Technologies
U.S. Department of Energy

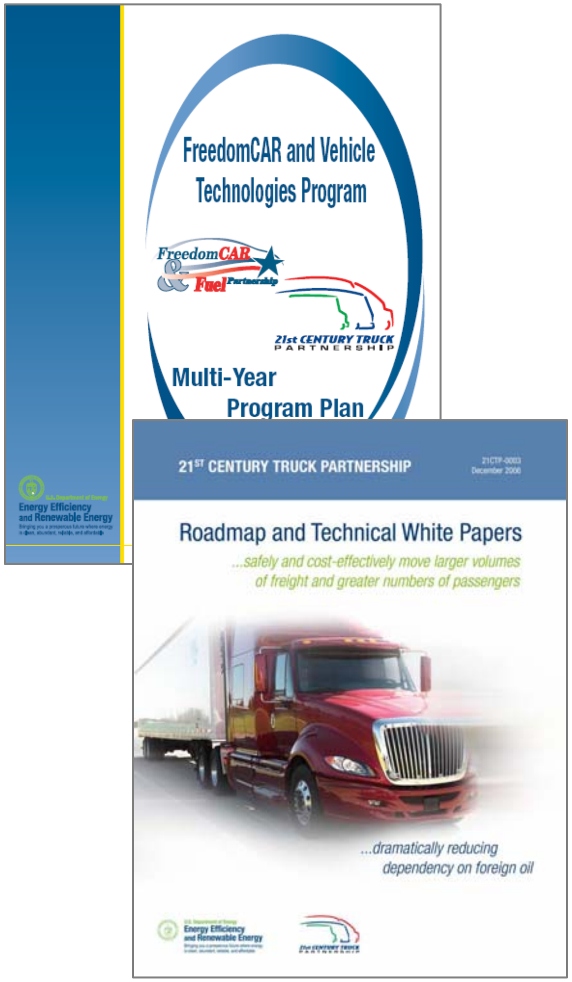
This presentation does not contain any proprietary or confidential information

Purpose: reduce petroleum consumption by improving fuel efficiency

- **Summarize understanding of ICE efficiency losses**
- **Identify promising strategies to reduce losses**
- **Implement proof-of-principle demonstrations of selected concepts**
- **Novel approach within OVT portfolio: focused on long term, high risk approaches for reducing fundamental thermodynamic losses in combustion**



Activity addresses multiple barriers to high efficiency ICEs



- **FCVT MYPP Technical Challenges & Barriers**
  - **"Engine efficiency improvement...and minimization of engine technology development risk are inhibited by inadequate understanding of…thermodynamic combustion losses..."**
- **21st Century Truck Partnership Roadmap Barriers to Achieving Efficiency Goals**
  - **"Relatively large thermodynamic losses in traditional combustion processes."**
- **FreedomCAR ACEC Tech Team Roadmap Barriers to Thermal Efficiency Goals**
  - **"Inherent exergy losses in conventional combustion processes. Among the largest losses in internal combustion engines, the availability destruction in rapid flame propagation may be only offset to a limited extent by LTC modes."**
  - **"Inadequate baseline for energy balance and availability (exergy) losses…. Understanding the losses is key...for achieving higher efficiency."**

No guidance received from previous reviews


U.S. Department of Energy
Energy Efficiency and Renewable Energy

FIRST SEMI-MEGA MERIT REVIEW REPORT

Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

FreedomCAR and Vehicle Technologies Program

2007 MERIT REVIEW & PEER EVALUATION REPORT

- **FY05-06: Project funding too small for formal review**
- **FY07: Project presented on a poster**
  - **Only scored by one reviewer**
  - **No reviewer comments given**

Approach incorporates thermodynamic analyses of ICE losses, demonstration of mitigation strategies, and concepts for ICE implementation

- **Phase I: Assembled team of expert collaborators to help clarify theoretical ICE efficiency limits based on literature and selected case studies**
  - **Identified most promising paths forward**
  - **Recommended specific topic areas for follow-on study**
- **Phase II: Develop and implement an experimental study to demonstrate more efficient combustion**
  - **Target: Reduce by half the 20-25% fuel efficiency loss in current engines due to combustion irreversibility**
  - **Intended to be proof-of-principle**
- **Phase III: Develop a concept for implementation of strategies from Phase II on an ICE**
  - **Intended to lead to practical application**

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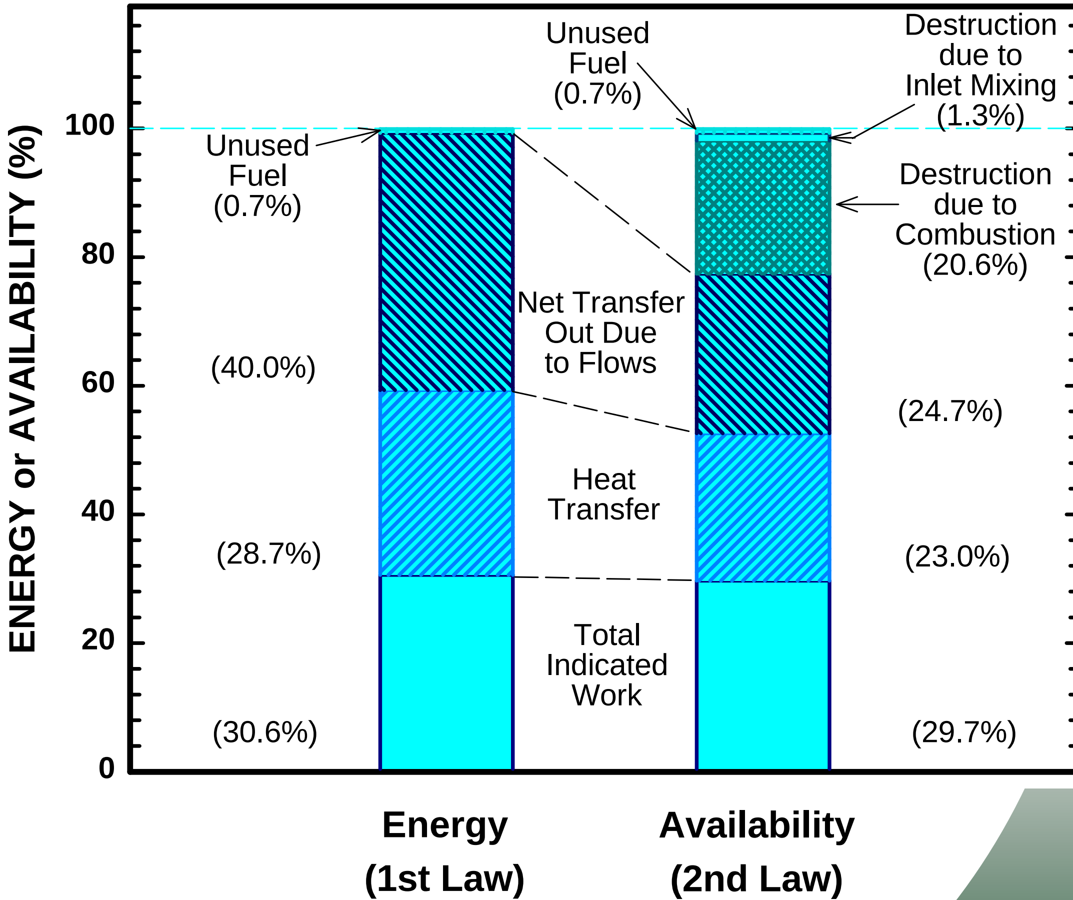
Phase I work focused on analysis of combustion losses and strategies to reduce those losses

- **Revisited constraints on efficiency with collaborators**
  - **Ben Druecke, Dave Foster, Sandy Klein, University of Wisconsin-Madison**
  - **Jerry Caton, Pramod Chavannavar, Texas A&M Univ.**
- **Consulted other widely recognized experts**
  - **John Clarke, Caterpillar, retired**
  - **Noam Lior, University of Pennsylvania**
  - **John Farrell and Walt Weissman, Exxon Mobil**
  - **Chris Edwards, Stanford University/GCEP**
- **Addressed following issues:**
  - **Identification and quantification of current inefficiencies**
  - **Clarification of physical constraints from 1st and 2nd laws**
  - **Identification of approaches to counteract inefficiencies**

Largest losses: wall heat transfer, unrecovered exhaust energy, and combustion irreversibility

- **Availability = energy available to produce work (exergy)**
  - **HC fuel availability ≈ heating value**
- **Wall heat transfer depends on materials and combustion details**
- **Utilizing exhaust availability requires cycle compounding**
- **Reducing combustion irreversibility requires fundamental changes to the combustion process**

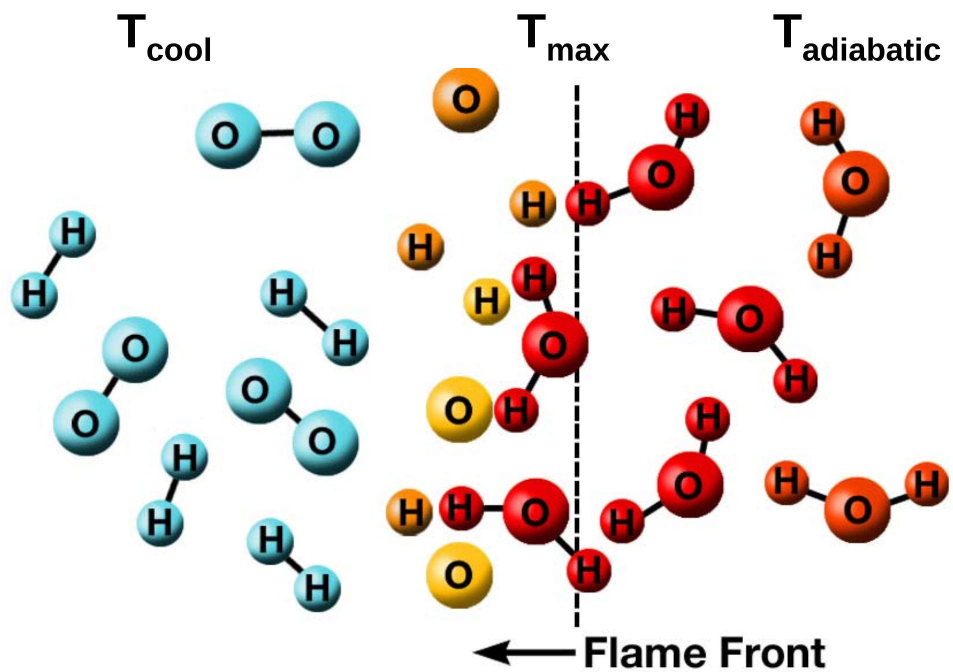
Octane-fueled spark-ignition engine (J. Caton, 1999)



Combustion irreversibility is the least understood of the major losses

- **Irreversibility is caused by combustion reactions occurring far from chemical & thermal equilibrium (unrestrained chemical reactions)**
- **Molecular-scale gradients result in entropy generation,* reducing availability**
  - **internal heat transfer**
  - **molecular rearrangements**
  - **gradients in chemical potential**
- **Lost availability can never be recovered (2nd law)**

H_2 flame front



C.S. Daw, V.K. Chakravarthy, J. Conklin, and R.L. Graves, Intl. J. of H_2 Energy 31 (2006) 728-736

***See W. R. Dunbar and N. Lior, Sources of Combustion Irreversibility, Combustion Science and Technology, Vol 103, 1994.**

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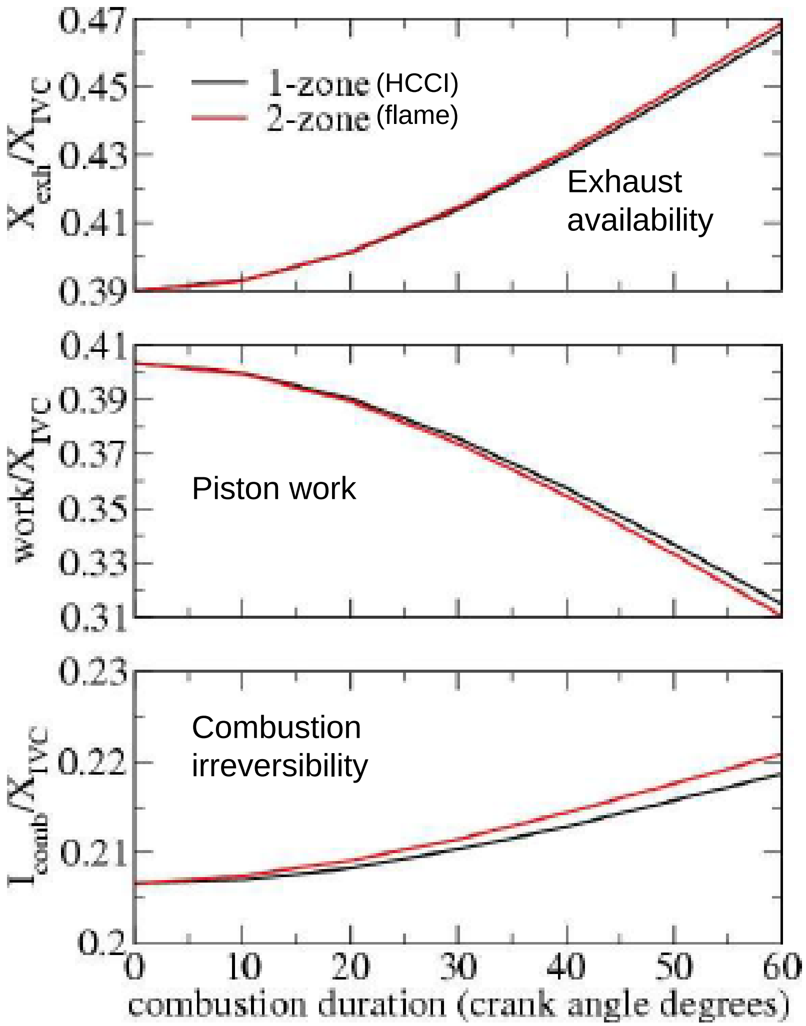
Combustion irreversibility is unchanged for HCCI and HCCI-like modes

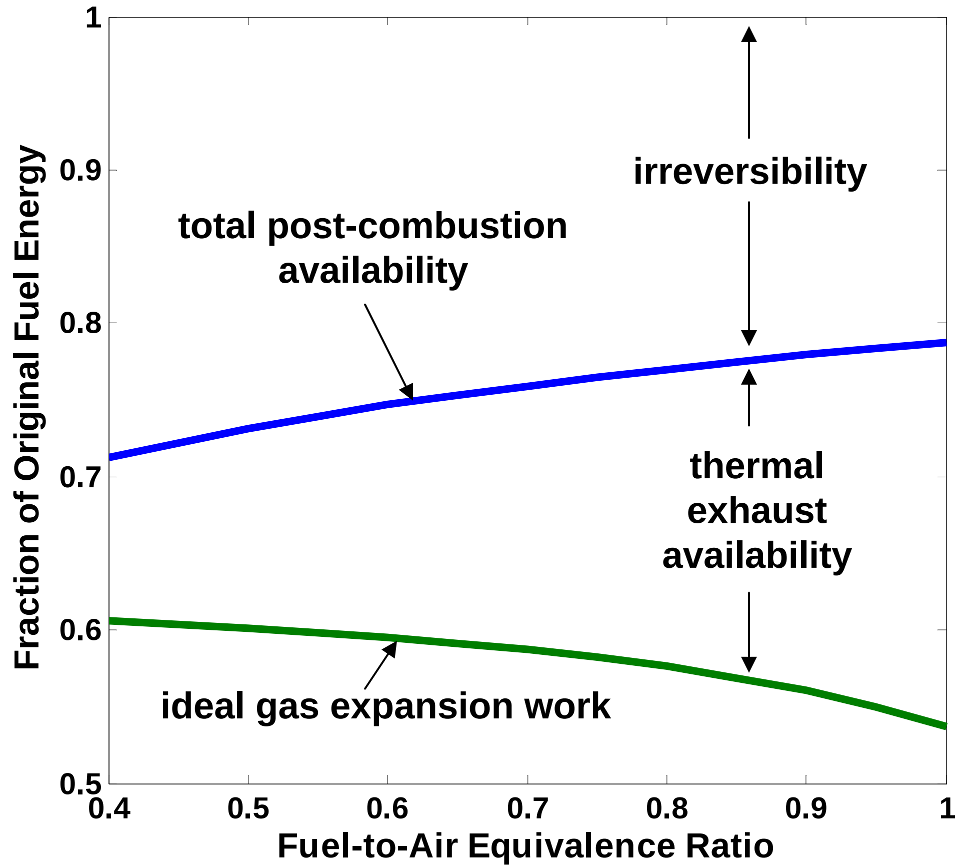
- **Comparison of conventional and HCCI H_2 combustion in adiabatic engine**
- **Even with homogeneous combustion (no macroscopic spatial gradients), irreversibility substantial**
- **Reactions still occurring far from chemical & thermal equilibrium (unrestrained)**
- **Entropy generation and availability loss effectively unchanged**



V. Chakravarthy, C.S. Daw, R. Graves, B. Druecke, D. Foster, S. Klein, "Second Law Comparison of Volumetric and Flame Combustion in an Ideal Engine with Exhaust Heat Recovery," Proc. Of Tech. Mtg of Central States Section of Combustion Inst., May 2006

Combustion irreversibility minimized by stoich. fueling, but at expense of reduced expansion work

- **Combustion irreversibility reduced for stoichiometric equivalance ratio**
  - **reactions still unrestrained but with fewer molecules**
  - **less dilution of reaction products**
  - **lower entropy generation**
- **Effect masked in traditional ICEs by reduced expansion work extraction for stoichiometric mixture**
- **Recovering higher availability from stoichiometric combustion will require cycle compounding**



Plot details:

- **ideal adiabatic combustion of iso-octane and air**
- **fully expanded otto cycle with initial compression ratio = 10**

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Most promising paths to higher efficiency identified

Lower impact paths:

- **HCCI, except as it:**
  - **reduces heat losses**
  - **enables stoich. combustion**
- **Lean-burn**
- **Matching reaction rates to work extraction**
- **CR>10**

Higher impact paths:

- **Staged combustion, with near-equilibrium reactions**
- **Stoichiometric combustion**
- **Reduced wall heat transfer**
- **Cycle compounding, especially with exhaust heat recovery**

Other observations:

- **Most opportunities for incremental improvements have already been pursued**
- **Large improvements will require globally integrated systems perspective (simultaneous optimization of combustion, heat transfer, work extraction)**
- **Optimized combustion engines are likely to be very different from today's single-stage piston engines**

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Phase II focused on demonstrating reduced combustion irreversibility

- **Target: Demonstrate a reduction of the fuel availability loss due to combustion irreversibility from ~20% to ~10% in a bench-top constant pressure combustor**

- **Strategy: Utilize techniques to restrain or stage the combustion process and carry out the reactions closer to equilibrium**
  - **CPER (Counterflow Preheating with near-Equilibrium Reaction)**
    - **idealized process for carrying out combustion in near-equilibrium fashion**
      - **fuel and air equilibrated at high temperature prior to mixing, minimizing "internal" heat transfer**
      - **heating of reactant streams by exhaust gas accomplished in counterflow preheaters to minimize temperature gradients**
      - **gas flows undergo reaction inside preheaters**
    - **difficult to achieve in idealized form due to high temperatures involved**
  - **TCR (Thermo-Chemical Recuperation)**
    - **utilizes exhaust heat to drive endothermic reforming reactions over an appropriate catalyst**
    - **stages the combustion process, enabling (partial) near-equilibrium reaction at much lower temperatures than CPER alone**

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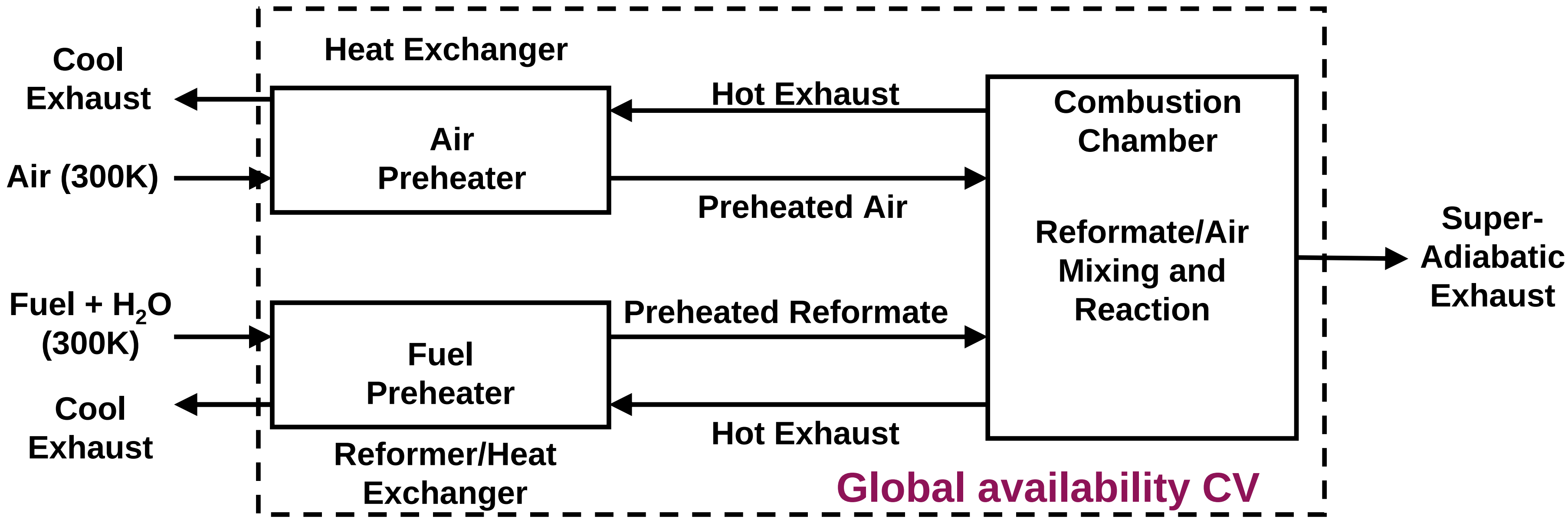
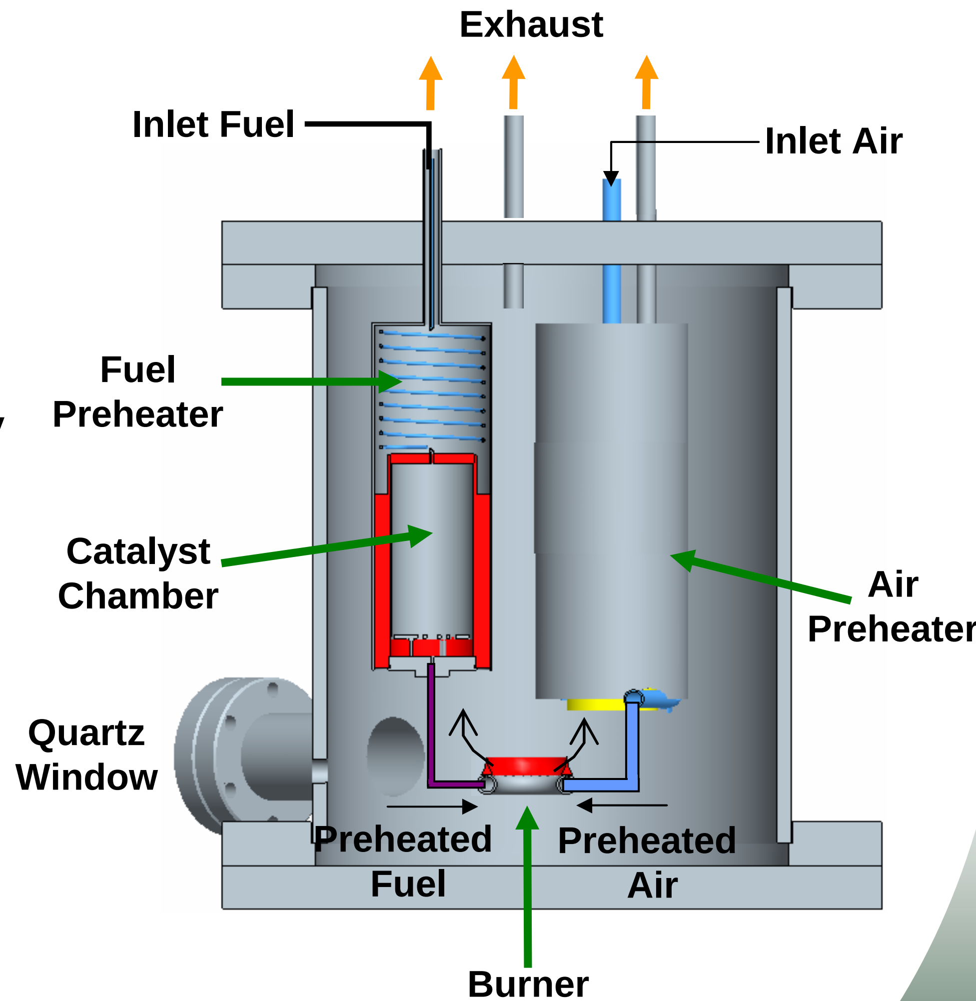
Conceptual schematic of CPER-TCR combustor



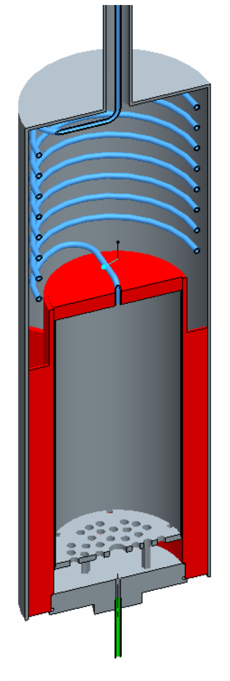
- **Combustion process redistributed into stages:**
  - **Air preheated with counterflow exhaust (thermal recuperation)**
  - **Fuel reformed and preheated with counterflow exhaust (thermo-chemical recuperation)**
- **Near equilibrium reforming and small ΔT heat transfer reduce entropy and increase output availability, generating super-adiabatic exhaust**

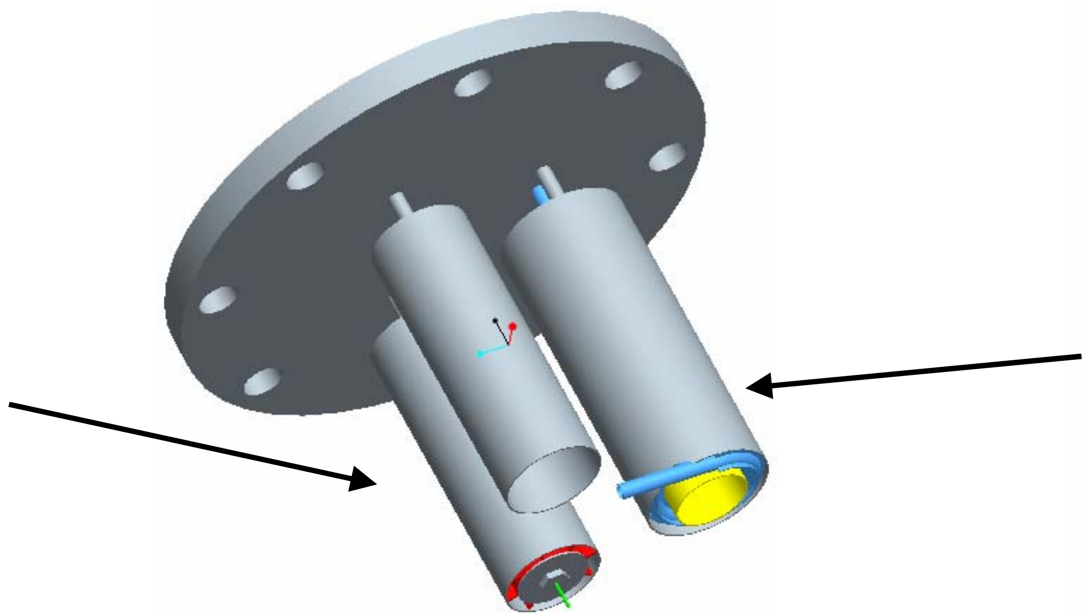
Design for demonstration of reduced combustion irreversibility with CPER-TCR

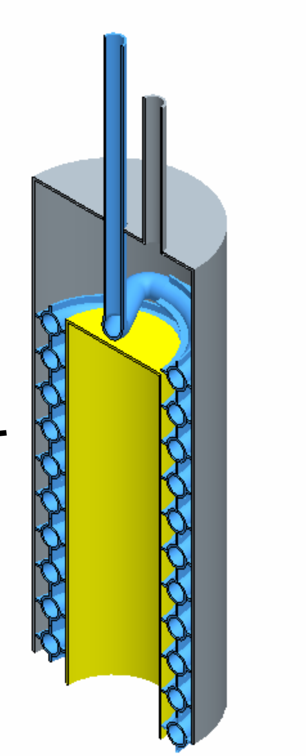
- **Exhaust exits top of burner chamber via three separate vents**
- **Valves on vent lines allow control of flow rates through exhaust manifold components**
- **Incoming fuel and air preheated by exhaust in counterflow heat exchangers**
- **Fuel can be mixed with water vapor and steam reformed in catalyst chamber**
- **Instrumented with thermocouples and gas flow meters to measure exhaust energy flows**
- **Two quartz windows provide optical access to burner**



Combustor incorporates counterflow preheaters for air and fuel and reformer catalyst on fuel inlet





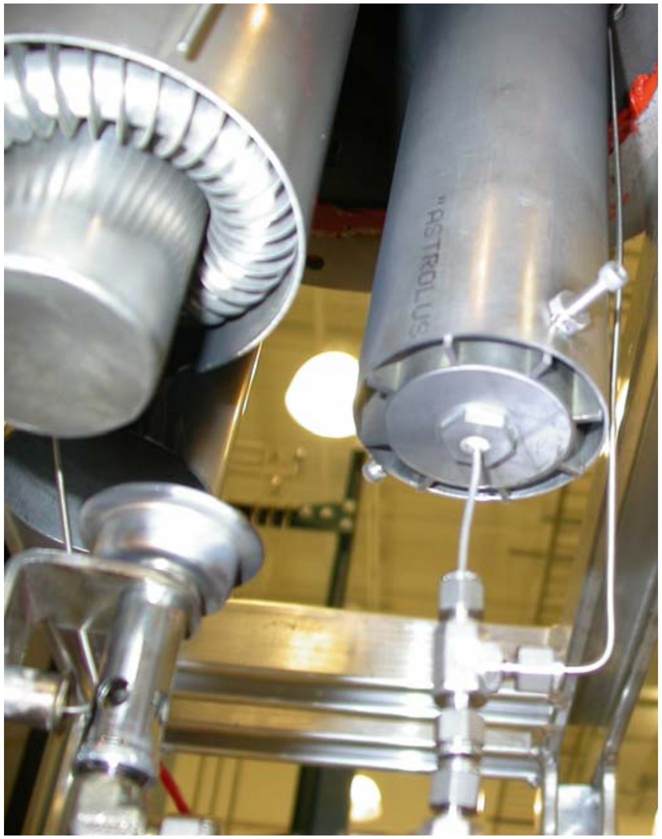


fuel preheater/reformer

air preheater

Construction of combustor has been completed

Shake-down experiments are underway



burner assembly with preheaters

fully assembled combustor

Technology transfer achieved through industrial collaborations, presentations, publications

- **Consulted with industry representatives during Phase I analyses.**
- **Published and presented Phase I conclusions.**
- **Identified catalyst supplier interested in TCR application and willing to provide catalyst samples.**
- **Negotiating NDA with industrial partner interested in collaborating on, and possibly commercializing, CPER-TCR.**
- **Will publish/present Phase II results.**

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Future work focused on CPER-TCR demonstration and application in ICEs

- **Remainder of FY08**
  - **Complete combustor shakedown**
  - **Conduct experiments & analyses to quantify availability in CPER-TCR combustor**
    - **with varying degrees of fuel and air preheating**
    - **with and without reforming**
- **FY09 and beyond**
  - **Refine CPER/TCR for application in ICEs**
  - **Analyze preheating and reforming pre/post compression**
  - **Consider approaches for converting recovered chemical energy to pressure versus heat**
  - **Design, construct, and control preheater/reactors to minimize thermal gradients and maximize conversion**
  - **Define theoretical impacts of compounding with other work extraction cycles (e.g., topping and bottoming cycles, integration with turbo-charging, thermo-electrics)**

Summary

- **Relevance to DOE Objectives**
  - **Identifying pathways to reduced petroleum consumption through improved combustion engine efficiency**
  - **Supporting DOE-OVT needs for improved fundamental knowledge of engine combustion and efficiency related to thermodynamic losses**
- **Approach**
  - **Conduct proof-of-principle demonstration of staged/restrained combustion techniques that reduce availability losses due to combustion irreversibility**
- **Technical Accomplishments**
  - **Completed construction of constant pressure bench-top CPER-TCR combustor**
- **Technology Transfer**
  - **Publishing and presenting results in relevant forums**
  - **Pursuing collaboration with industrial partner**
- **Future Plans**
  - **Conduct experiments with CPER-TCR combustor to demonstrate reduced availability losses**
  - **Refine CPER/TCR strategies for use in ICEs**