Stretch Efficiency for Combustion Engines: Exploiting New Combustion Regimes

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U.S. Department of Energy

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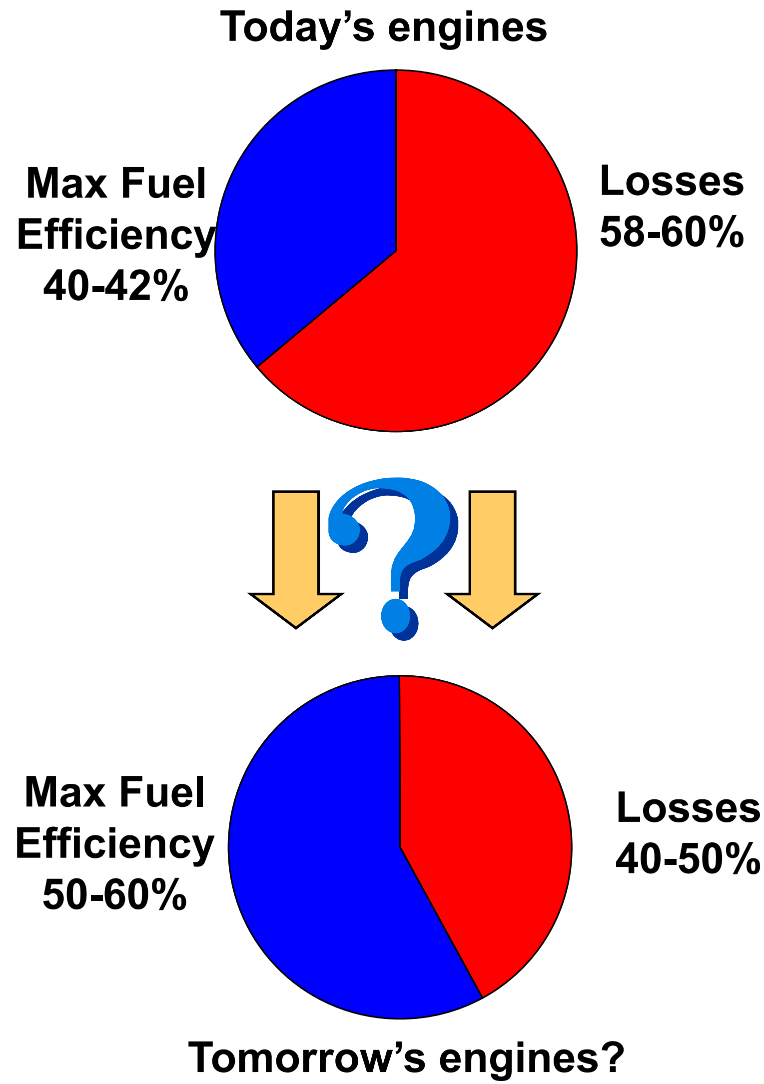
Overview

- **Timeline**
  - Start
    - FY05
  - Finish
    - Ongoing
- **Budget**
  - FY09 Funding
    - $250K
  - FY10 Funding
    - $250K

- **Barriers**
  - Max energy efficiencies of existing IC engines (including HECC and HCCI modes) are well below theoretical potential
  - Overcoming these limits involves complex optimization of materials, controls, and thermodynamics
- **Partners**
  - Gas Technology Institute
    - Partnered with catalyst supplier, engine OEM
  - Universities
    - Texas A&M University
    - University of Wisconsin
    - Illinois Institute of Technology
    - University of Alabama
    - University of Michigan, Dearborn

Objective: Reduce ICE petroleum consumption thru higher fuel efficiency

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



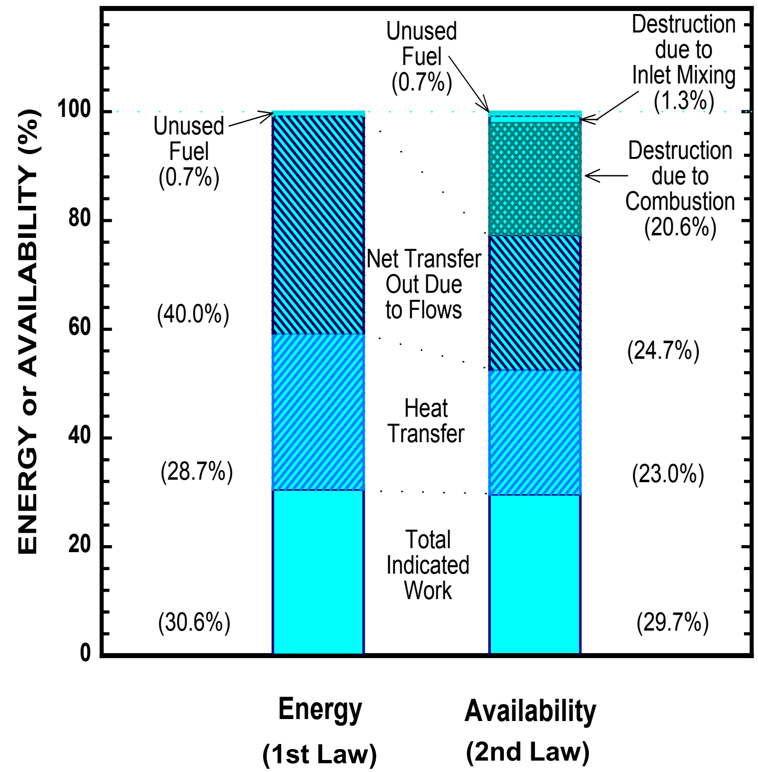
Milestones

- **FY09 Milestone (completed):**
  - Journal paper on preheating and thermochemical recuperation (CPER/TCR) as a means for increasing combustion engine efficiency (published in Energy and Fuels)
- **FY10 Milestone (on track for completion)**
  - Journal paper on chemical looping combustion (an alternative approach to chemical exhaust heat recuperation) as a means for increasing combustion engine efficiency (September 30, 2010)

General Approach: Combine thermodynamic analysis and experiments to identify potential paths for efficiency breakthrough

- **Collaborate with experts to clarify reasons for ICE efficiency limits**
  - Previous meetings at ORNL in past years
  - Colloquium at USCAR this past March
- **Implement supporting analytical and experimental studies**
  - Thermodynamics of leading concepts (both 1st and 2nd Law effects)
  - Flexible lab experiments for generating basic data, demonstrating proof-of-principle
  - Single-cylinder engine experiments
  - Multi-cylinder engine experiments and simulations

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



1st Law (energy) and 2nd Law (exergy) analysis

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The engine efficiency colloquium held at USCAR this March has been helpful in focusing our perspective

Participants were:

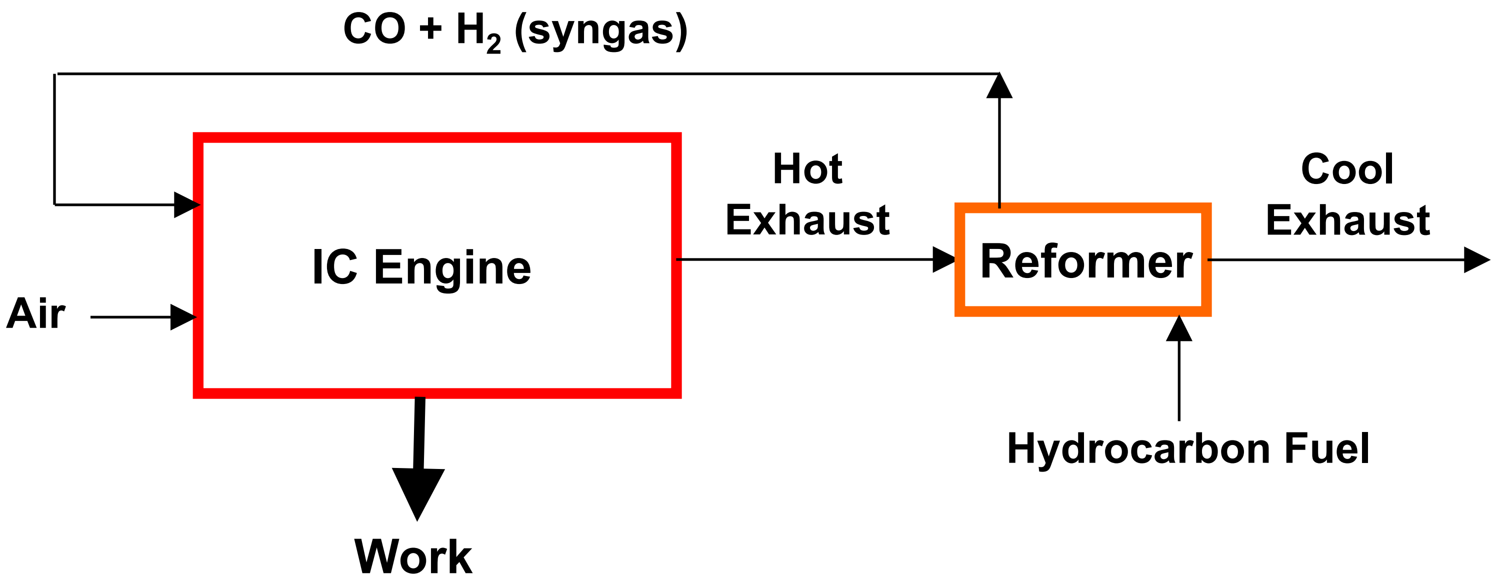
- Paul Najit (GM)
- Walt Weissman (Exxon)
- Eric Curtis (Ford)
- Gary Hunter (AVL)
- Jerry Caton (Texas A&M)
- Noam Lior (U Penn)
- Tony Greszler (Volvo)
- John Clarke (Cat® retired)
- Ron Graves (ORNL)
- Robert Wagner (ORNL)
- Bengt Johansson (Lund)
- Dan Flowers (LLNL)
- Kellen Schefter (DOE)
- Terry Alger (SwRI®)
- Ron Reese (Chrysler)
- Don Stanton (Cummins)
- George Muntean (Cummins)
- Gurpreet Singh (DOE)
- Chris Edwards (Stanford)
- James Yi (Ford)
- Dave Foster (U Wisconsin)
- Steve Ciatti (ANL)
- Harry Husted (Delphi)
- Stuart Daw (ORNL)
- Pete Schihl (U.S. Army)
- Paul Miles (SNL)
- Roy Primus (GE)
- John Kirwan (Delphi)
- Tim Coatesworth (Chrysler)

The colloquium participants recommended near and longer-term potential approaches for stretching fuel efficiency including:

- High EGR and boosting *
- Higher peak cylinder pressures *
- Extended lean combustion (both conventional and HECC) *
- Variable valve and cylinder geometries *
- Waste heat recovery and cycle compounding *
- Dual fuels and fuel-adaptive combustion *
- Alternative slider-crank architectures as well as more novel engine configurations beyond slider-crank *

* Directly related to this project

One promising longer-term approach we have been pursuing is thermochemical recuperation (TCR)

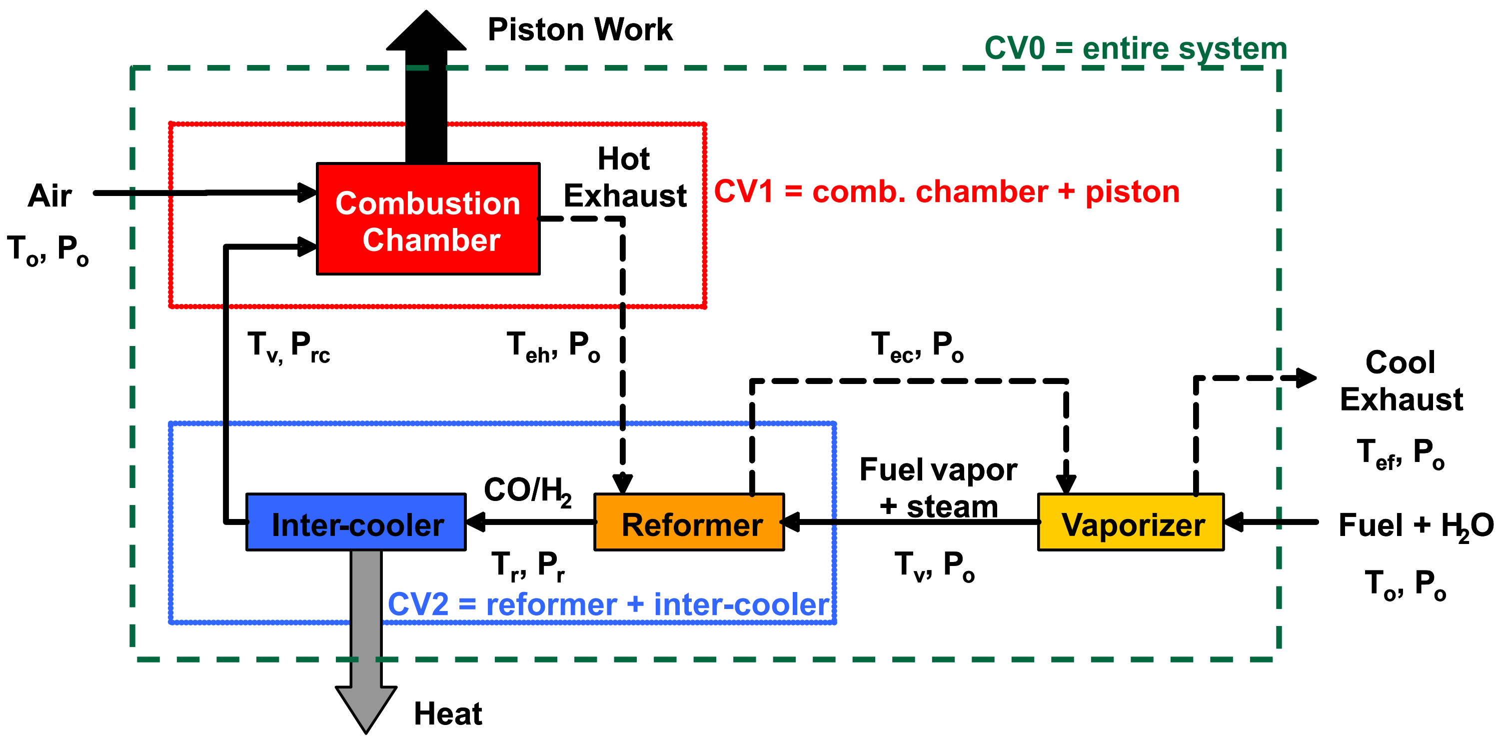


- Exhaust heat drives endothermic reforming reactions that convert hydrocarbon fuels to a mixture of CO and H_2 (syngas).
- Engine fueling is supplemented with syngas (in place of some or all original HC).
- Fuel heating value increases, recuperating exhaust energy.
- Molar gas expansion from reforming creates pressure boost.
- H_2 enrichment extends lean limit, improves C_p/C_v ratio, lowers cylinder heat loss, assists cold start, lowers combustion irreversibility.

Results (TCR 1): This year we completed a basic analysis of a highly simplified version of TCR

- Objective to clarify the thermodynamic potential of TCR for simplest possible case.
- Included both 1st and 2nd Law (energy and exergy) effects.

Energy & Fuels, 2010, 24 (3), pp 1529-1537



For no reforming, fuel and exhaust pass CV2 unchanged

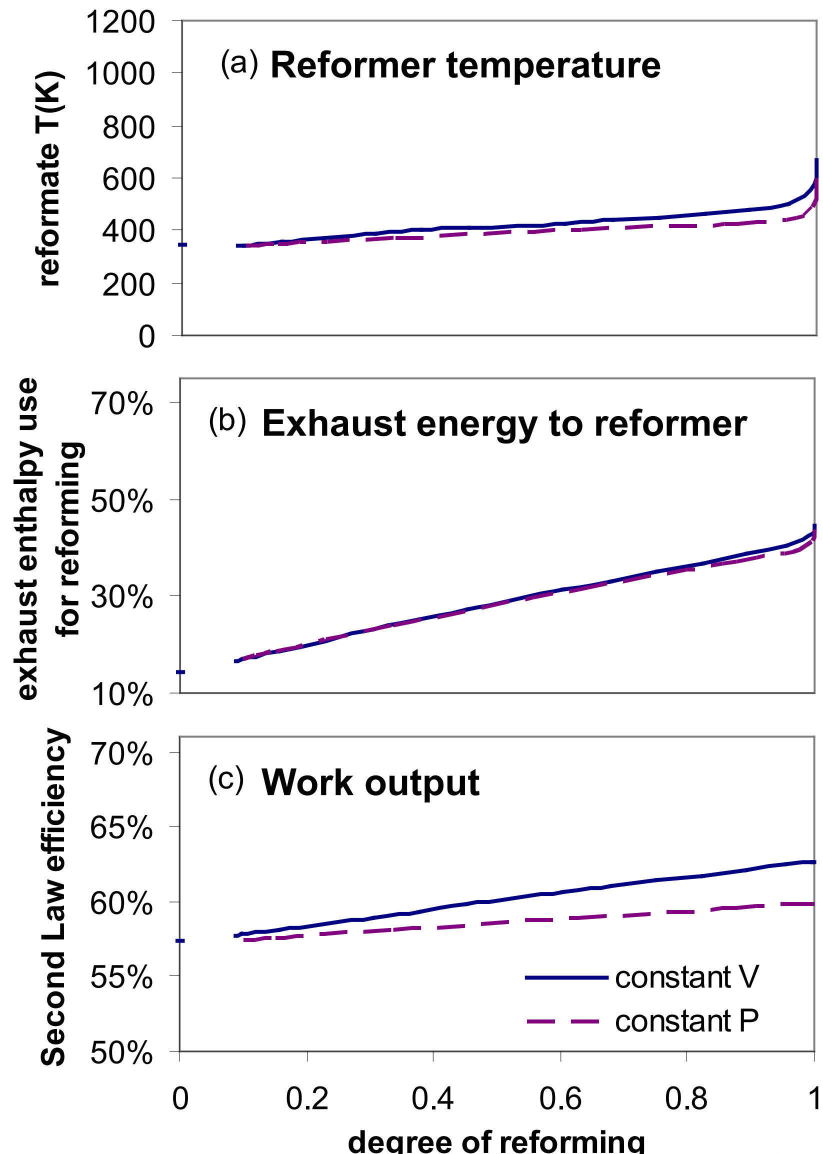
Results (TCR 2): Our initial TCR analysis focused on ideal thermodynamic steps instead of mechanical and transient details

Key assumptions:

- **Ideal catalytic reformer**
  - Batch mode to interface with engine
  - Water injected with fuel (enough to completely reform fuel to CO and H_2)
    Ex: $C_8H_{18} + 8\ H_2O \rightarrow 8\ CO + 17\ H_2$;
  - Water, liquid fuel vaporized at P_{atm} with exhaust heat prior to reformer
  - Reforming reactions at equilibrium at specified T and constant P or constant V
  - 3 fuels: methanol, ethanol, iso-octane
    - Methanol requires no added water
    - Wet ethanol of special interest from production standpoint
- **Frictionless, 1-stage piston engine operating over ideal Otto cycle**
  - Air and fuel mixed in cylinder at constant P or V;
  - Isentropic compression of fuel + air mixture;
  - Adiabatic constant volume combustion at max compression;
  - Isentropic expansion of combustion gases to P_{atm};
  - All work from single stage piston expansion;
  - Steady-state operation (engine state repeats precisely at each point in the cycle)

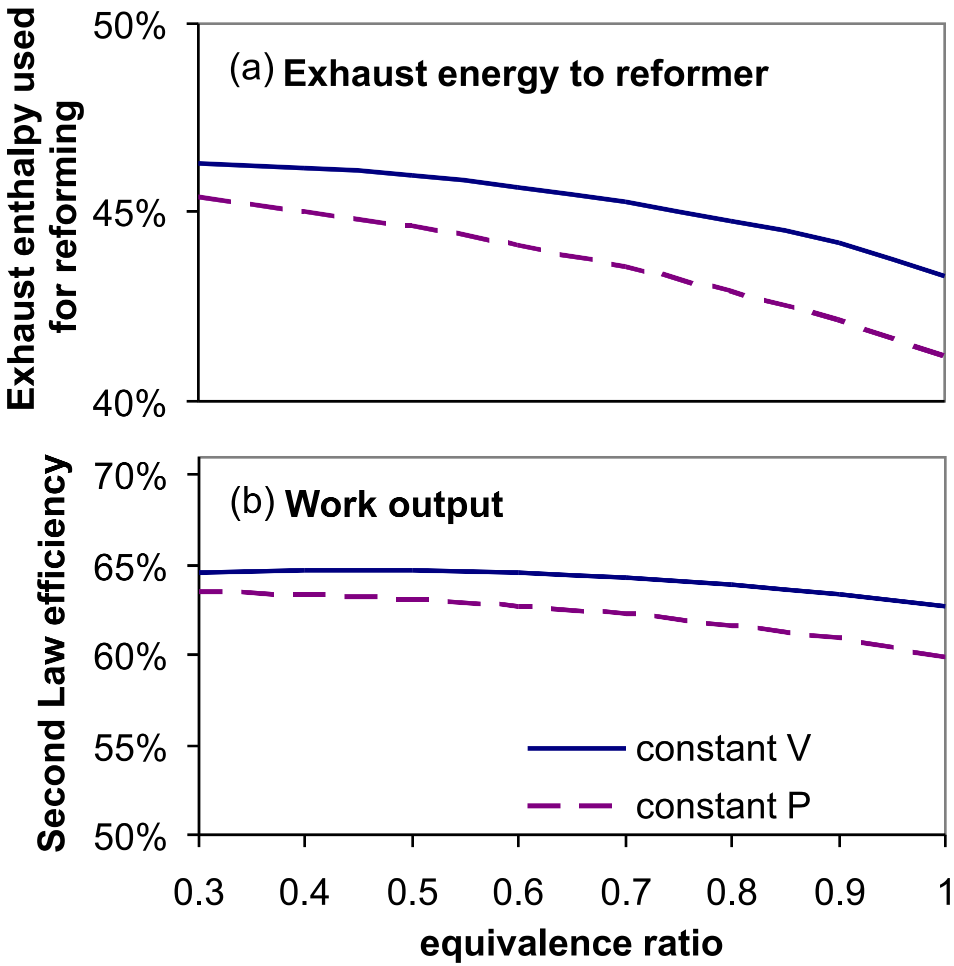
Results (TCR 3): One important observation is that reforming mode has large efficiency impact

- **Methanol fuel**
- **Variation with reforming level**
  - 0 = no reforming
  - 1 = 100% reforming
- **Reforming temperature and exhaust energy required are almost unchanged by constant P or V**
- **Pressure boost from constant V reforming increases work output by several percent**



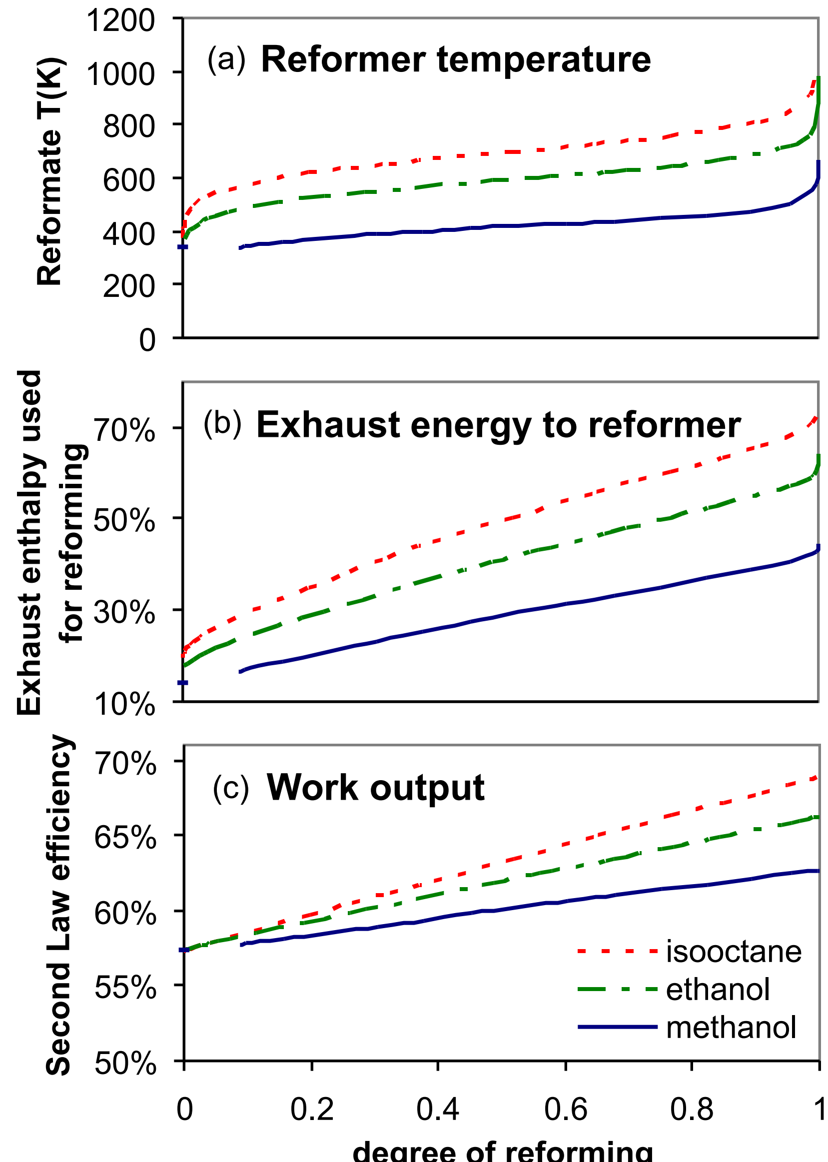
Results (TCR 4): Leaner combustion with H_2 from TCR also significantly boosts efficiency

- **Methanol fuel, reformed at 600 K**
- **Variation with fuel/air equivalence ratio**
- **Lean fueling improves piston work because of higher exhaust C_p/C_v**
- **Constant V reforming + lean burn increases efficiency by about 7%**



Results (TCR 5): TCR efficiency benefits increase with higher MW fuels

- Methanol vs. ethanol vs. isooctane
- Variation with constant V reforming level
  - 0 = no reforming
  - 1 = 100% reforming
- Isooctane and ethanol require higher reformer temperature
- Isooctane and ethanol generate larger pressure boost (larger mole ratio)



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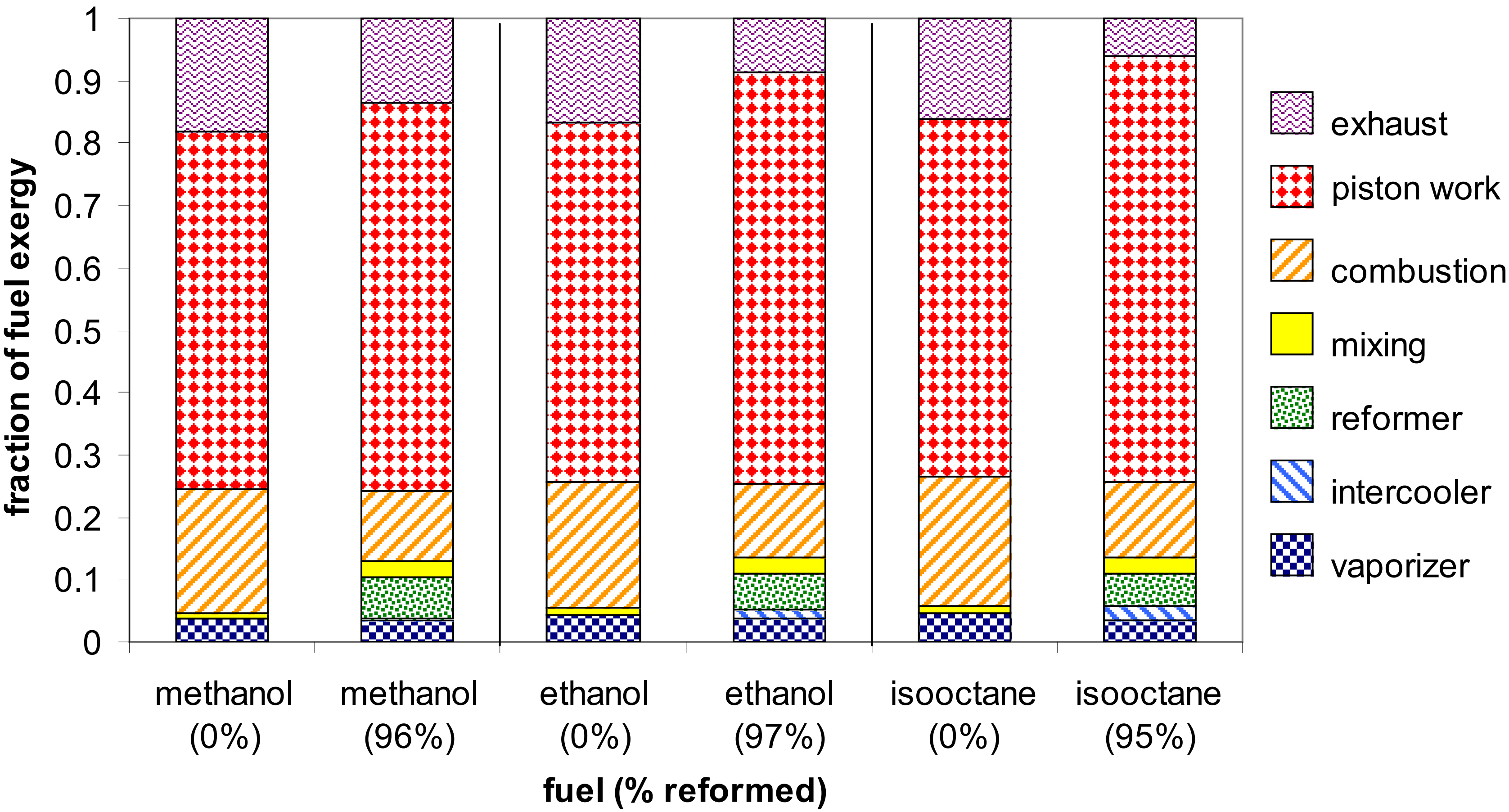
Results (TCR 6): Overall exergy balances reveal more about impact and possibilities



- **Combustion irreversibility is significantly reduced for reformed fuel**
- **Reformer and intercooler exergy destruction could be reduced**
- **Any additional conserved exergy will have to be converted to work downstream from the piston (bottoming cycle)**

Results (TCR 7): Initial Analysis Summary

Key Observations about TCR:

- Potential to substantially boost piston work for a range of fuels.
- Constant V reforming better because of the pressure boost.
- H_2 can extend lean limit, improve exhaust C_p/C_v.
- Benefits greater for higher MW fuels, but reforming conditions more severe.
- Benefits for ethanol attractive because of:
  - Reduced need for water removal during production
  - Effective boost in volumetric fuel energy

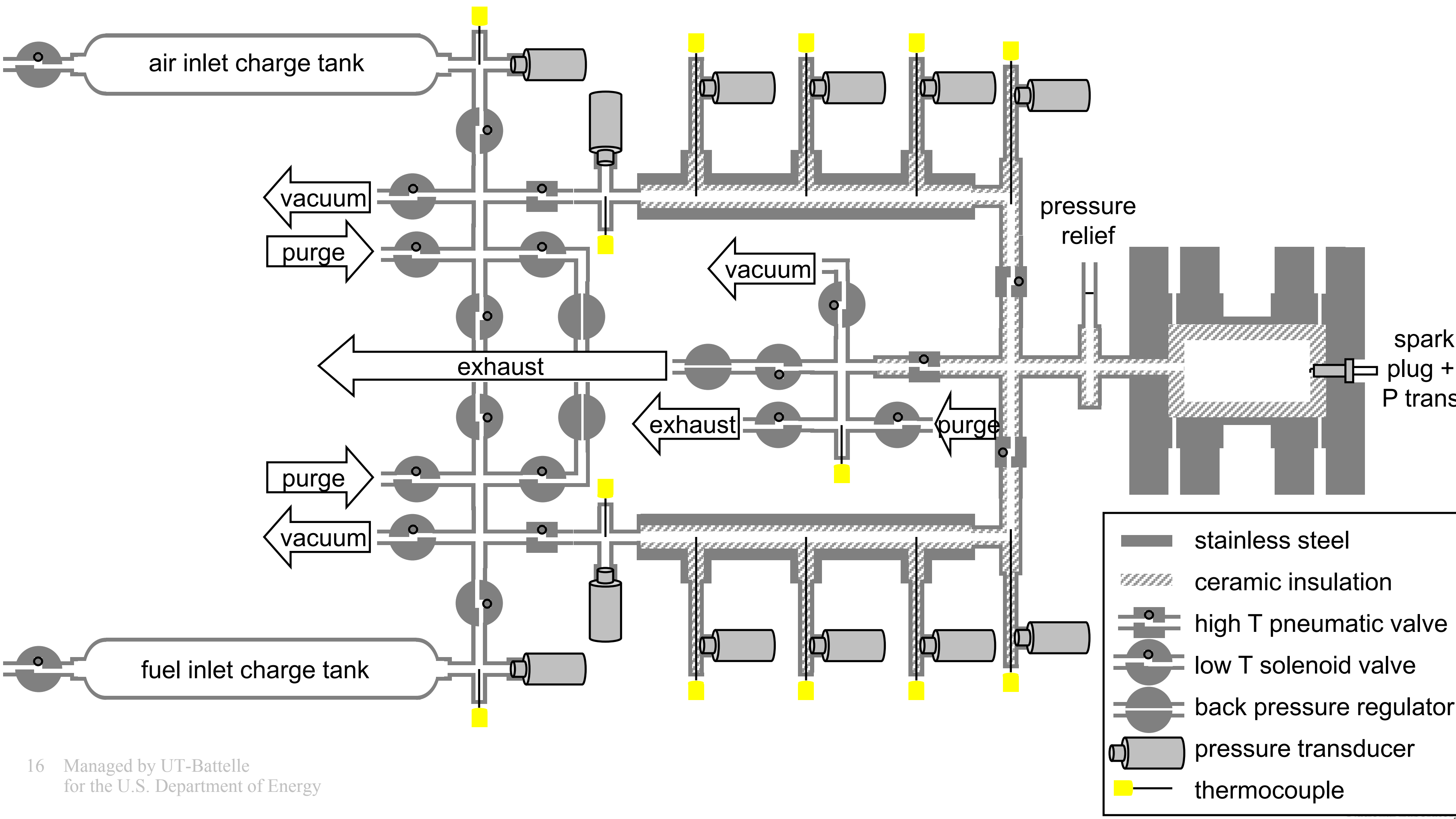
Additional Questions:

- Do the basic results change when non-idealities are included?
- How can TCR be implemented in real engines? (Multiple approaches including external and in-cylinder)
- How fast are reforming reactions and heat transfer? (Catalytic vs. non-catalytic, fuel effects)
- How much can irreversibility of reforming and inter-cooling be reduced?
- Does it make sense to include bottoming cycle on engines utilizing TCR?
- Are there other viable approaches to chemical heat recuperation (e.g., chemical looping)?

Above are being addressed with additional experiments and modeling

Results (RAPTR 1): The RAPTR experiment provides a way to study constant volume TCR

- **RAPTR stands for Regenerative Air Preheating and Thermochemical Recuperation**



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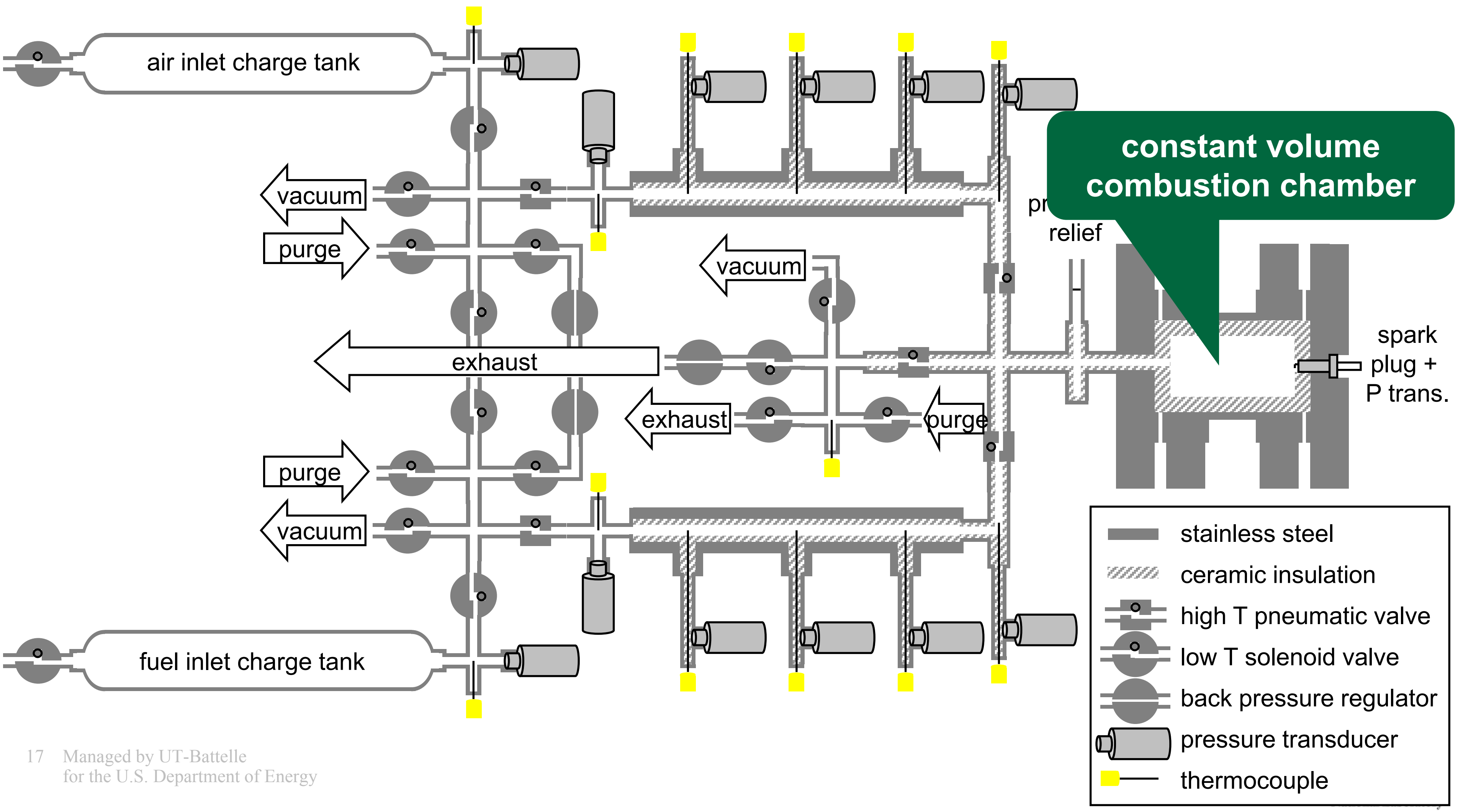

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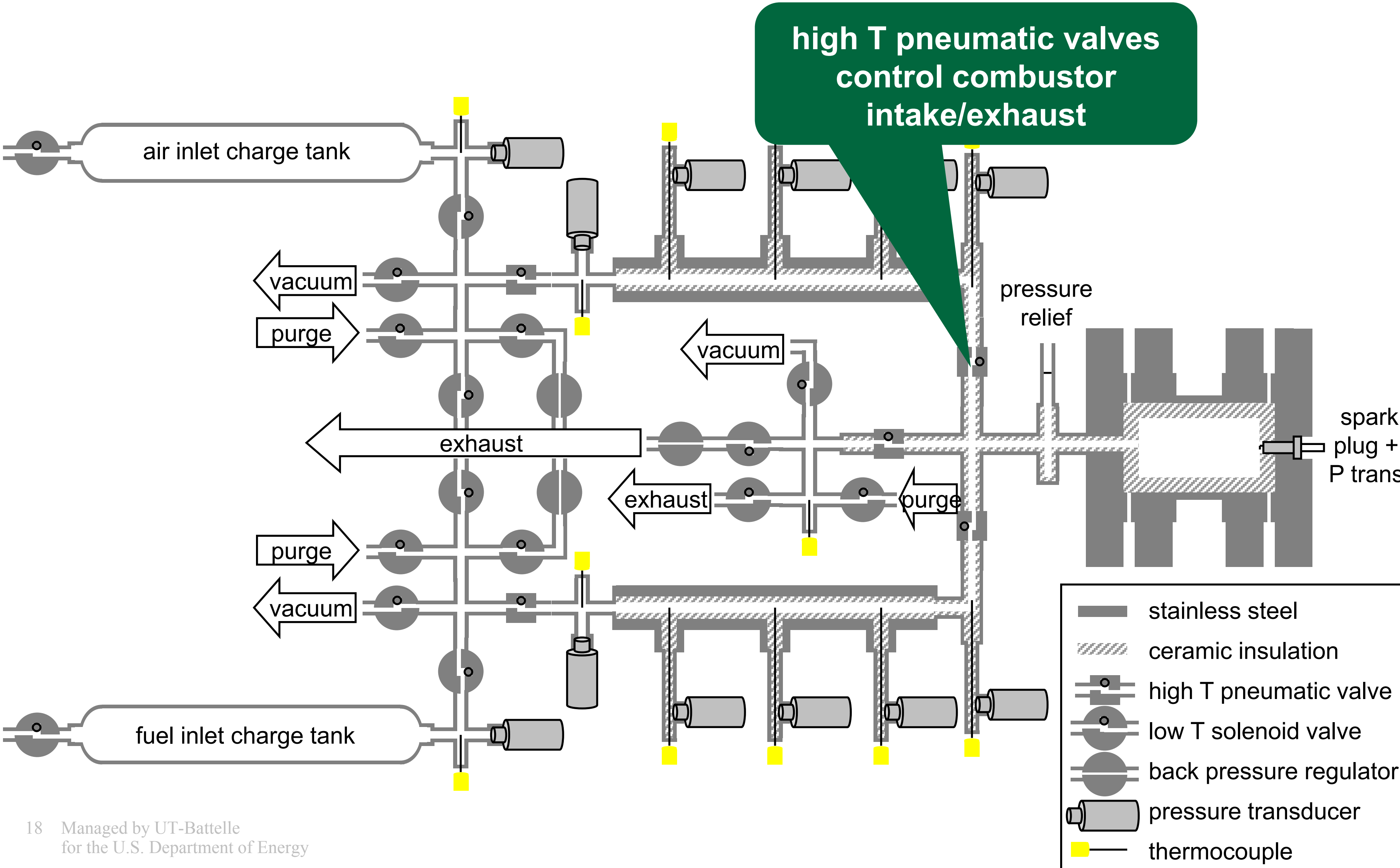

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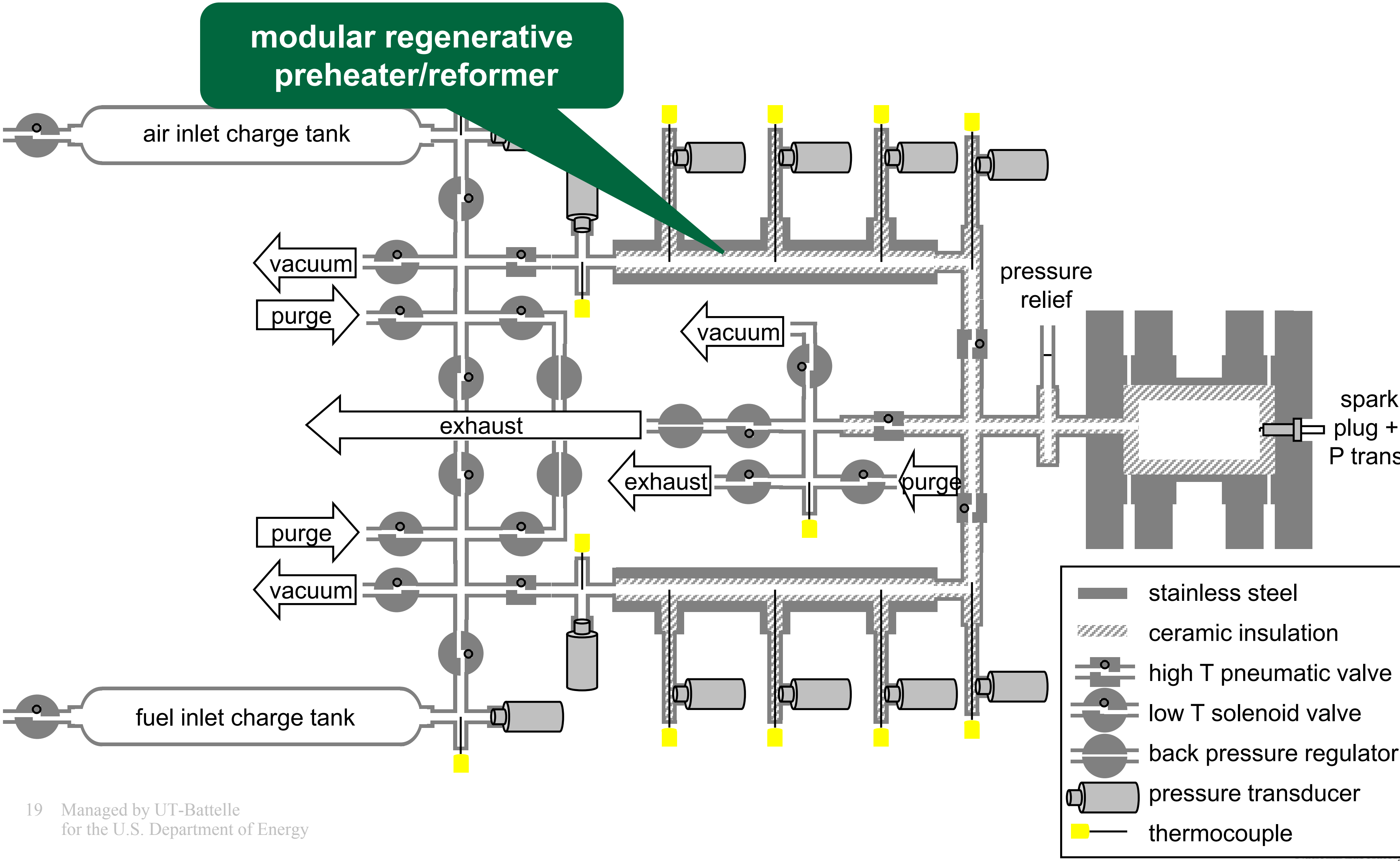

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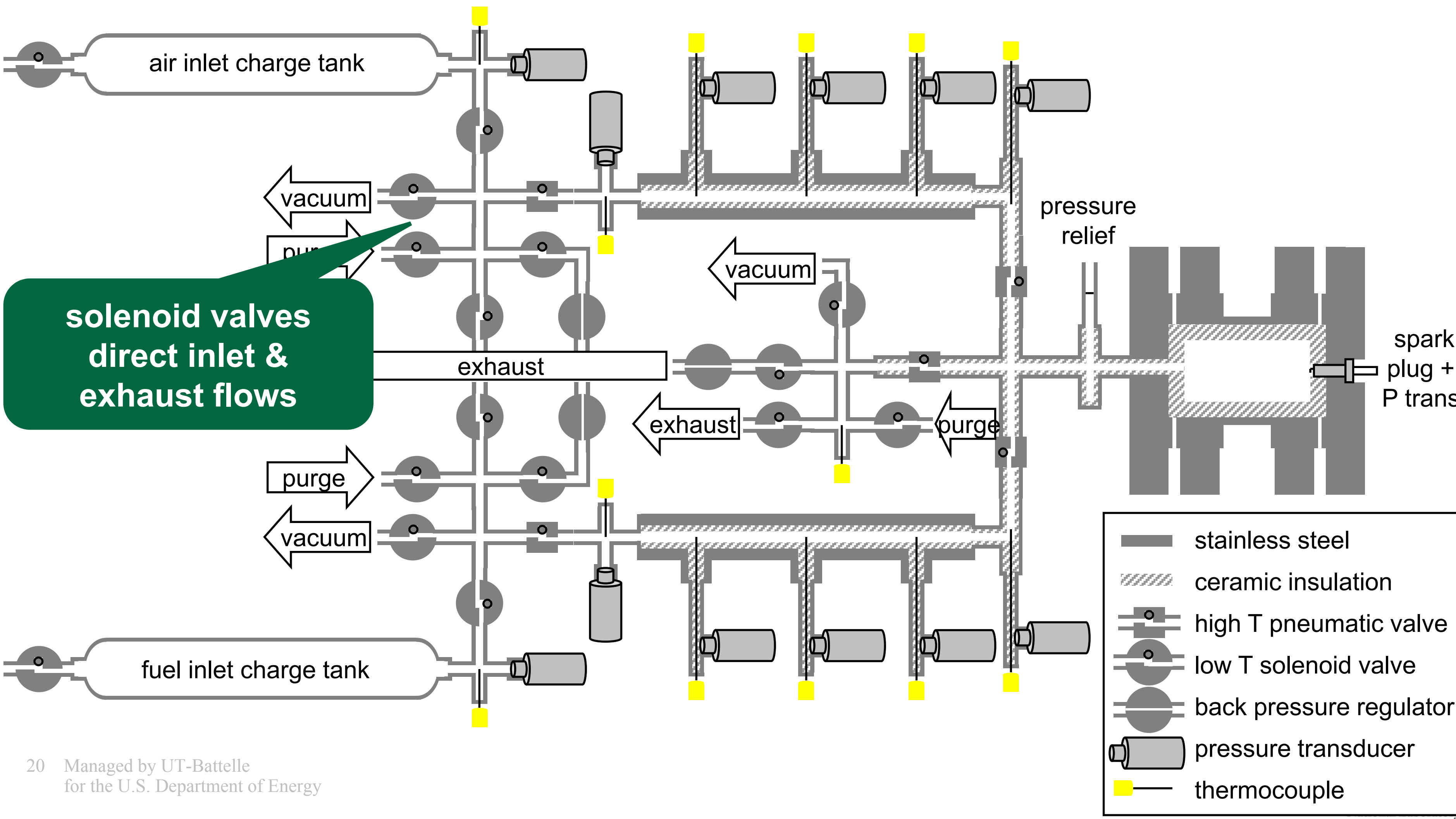

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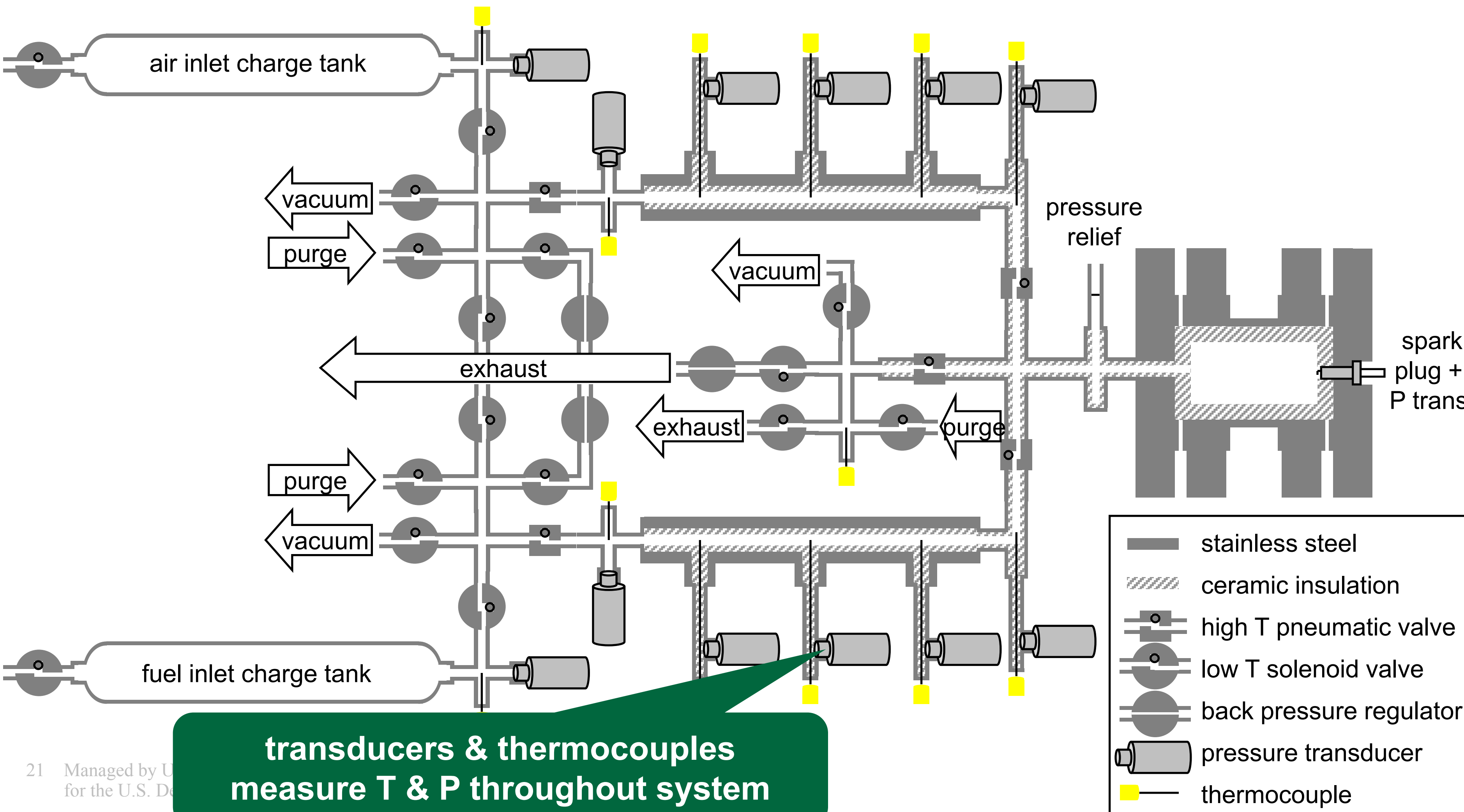
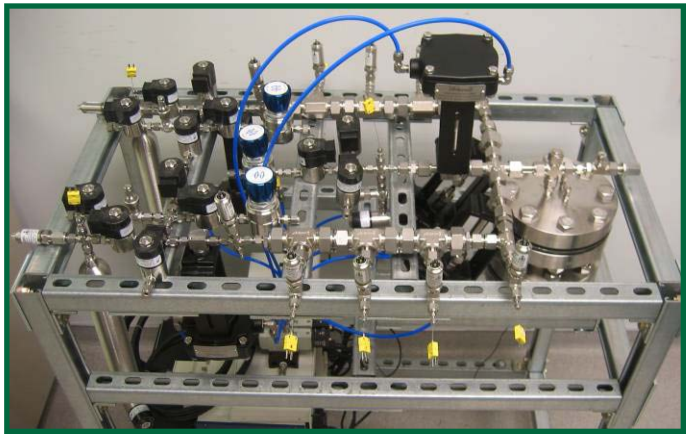


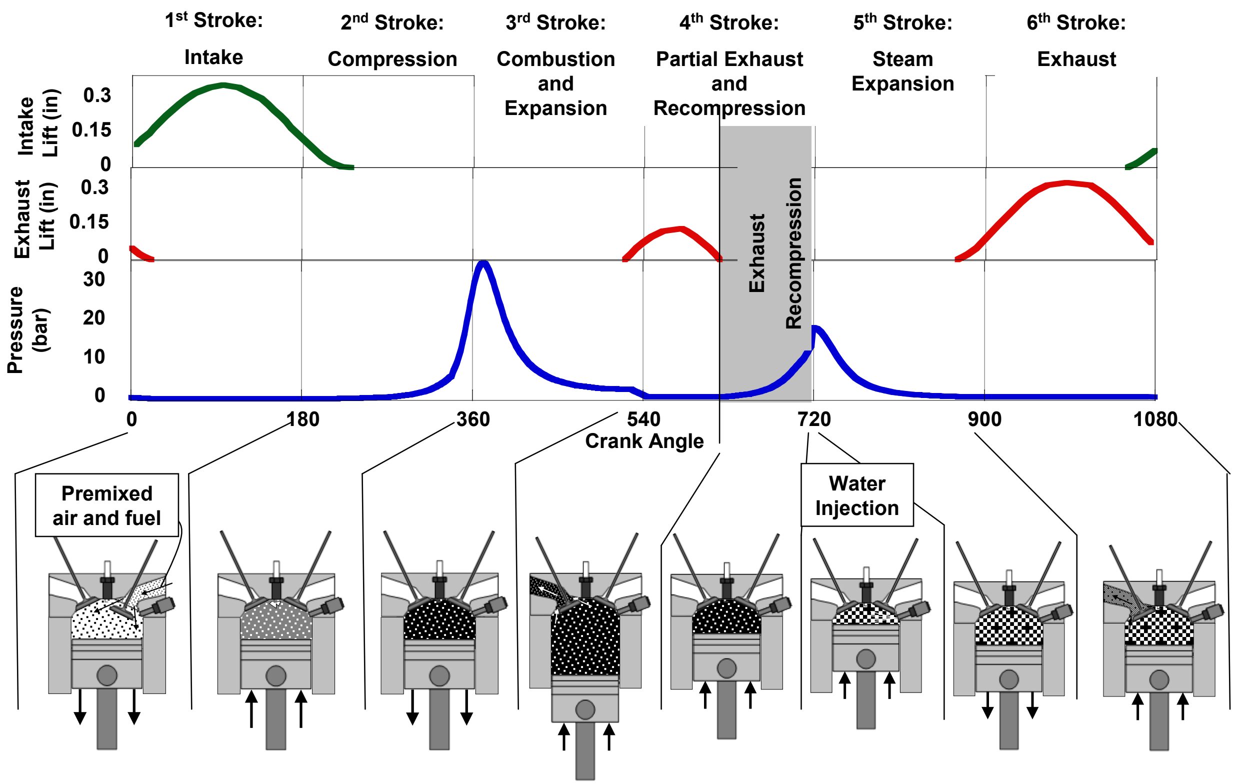
transducers & thermocouples measure T & P throughout system

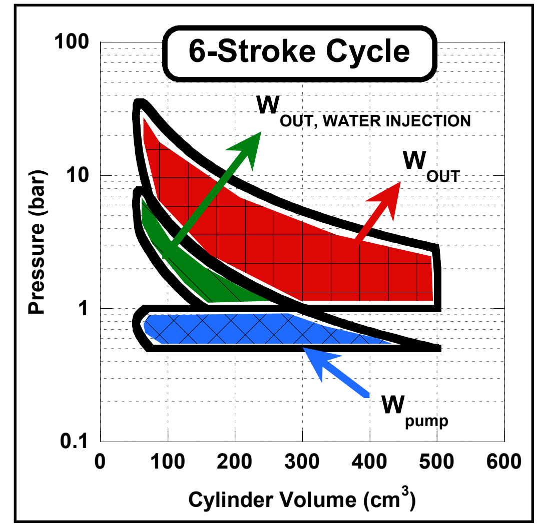
Results (RAPTR 2): RAPTR will be operational by end of fiscal year

- Construction nearing completion
  - wiring, insulation, and programming remain
- Experiments will evaluate feasibility of TCR for IC engines
  - quantify post-combustion availability with and without TCR
  - measure rates of gas/solid heat transfer
  - measure rates of catalytic and non-catalytic steam reforming reactions
  - screen potential heat transfer materials and catalysts
  - evaluate heat exchanger & catalyst configurations (packed bed, monolith, wire mesh, etc.)



We have also begun investigating a new 6-stroke cycle as a way to implement in-cylinder exhaust heat recuperation and TCR



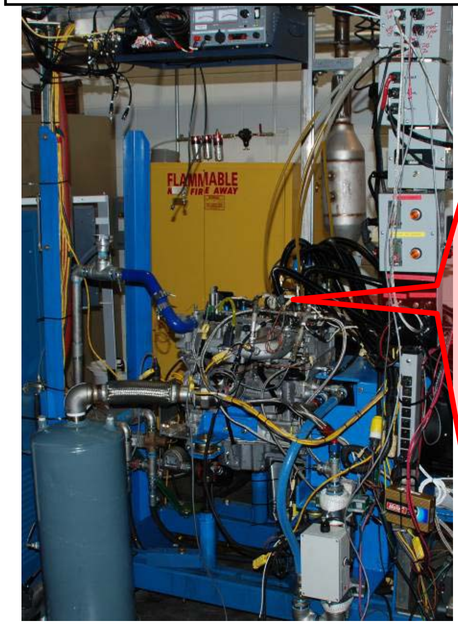


– Water version conceived and modeled under ORNL LDRD
  - Patent application
  - Journal Article (Conklin and Szybist. *Energy*, 2010, v35:4, pp1658-1664)
– Experimental demonstration planned for 3rd quarter FY10
– Now investigating fuel injection with water + in-cylinder reforming

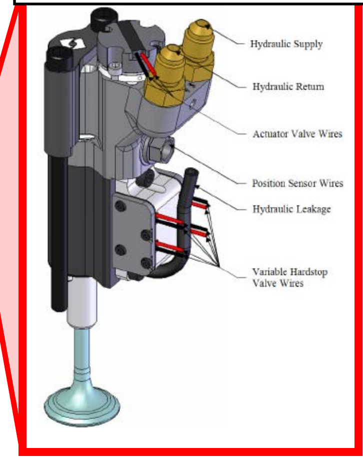
A new research engine with fully variable hydraulic valve actuation is being used to demonstrate 6-stroke cycle

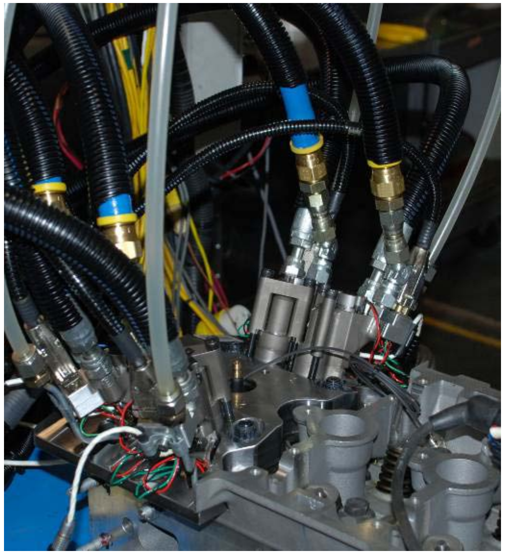
- Engine functional at ORNL in March 09
  - Internal ORNL funds used to establish capability (LDRD and other)
- Infinitely variable HVA is capable of unconventional combustion strategies
  - NVO and exhaust re-breathing HCCI combustion strategies, over-expanded cycles, and others

Engine Installation



Sturman Hydraulically Actuated Valve





- Platform is being used for a number of additional DOE HCCI projects (SA-HCCI, gasoline FACE, NPBF, Delphi HCCI CRADA)
- First experimental study performed with engine was ethanol optimization, Delphi CRADA
  - Presented at 2010 SAE Congress
  - Additional details in Merit Review presentation FT-008
- Ideal for 6-stroke cycle demonstrations because valve events are not controlled by cams

Collaborations

As described earlier, we have technical interactions with the following groups regarding various aspects of this work:

- Gas Technology Institute
  - Partnered with catalyst supplier, engine OEM
- Texas A&M University
- University of Wisconsin
- Illinois Institute of Technology
- University of Alabama
- University of Michigan, Dearborn

This project is intended to address longer range, high risk concepts for increasing engine efficiency, thus near-term commercial application is expected to be limited. However, we have attempted to promote as much information transfer as possible through the following mechanisms:

- State-of-technology dialogue with academic and industry experts (e.g., the USCAR colloquium).
- Publication of articles on TCR and 6-stroke cycle thermodynamic analyses.
- Utilization of HVA Sturman engine (potential links to ongoing CRADAs involving this engine and current industry work- e.g., SAE 2010-01-0621).
- Technical discussions with GTI regarding application to stationary heavy-duty engines.

Planned Activities

- **Near term**
  - 0-D thermodynamic modeling of TCR in 6-stroke cycle
  - Complete RAPTR construction and shakedown
  - Continued lab characterization of reformer catalysts
  - Initial experimental studies of exhaust heat recuperation in RAPTR and Sturman engine
  - Initial thermodynamic evaluation of chemical looping as an alternative heat recuperation method for engines
- **Longer term**
  - Extended RAPTR and Sturman experiments
  - More detailed cycle simulations with non-ideal engine components
  - Theoretical analysis of possible major changes to engine architecture (along lines proposed in USCAR colloquium)

Summary

- Thermochemical exhaust heat recuperation (TCR) has the theoretical potential for increasing peak IC engine efficiency by more than 10%.
- A large part of this potential TCR benefit is associated with the pressure boost generated by reforming.
- A highly flexible constant volume bench-top combustor and HVA engine are being set up to experimentally evaluate this potential.
- Further analytical studies are underway to explore how direct exhaust heat recuperation and TCR might be exploited in both current and future engine architectures.

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