Pragmatic Thermodynamic Efficiency Limits for IC engines

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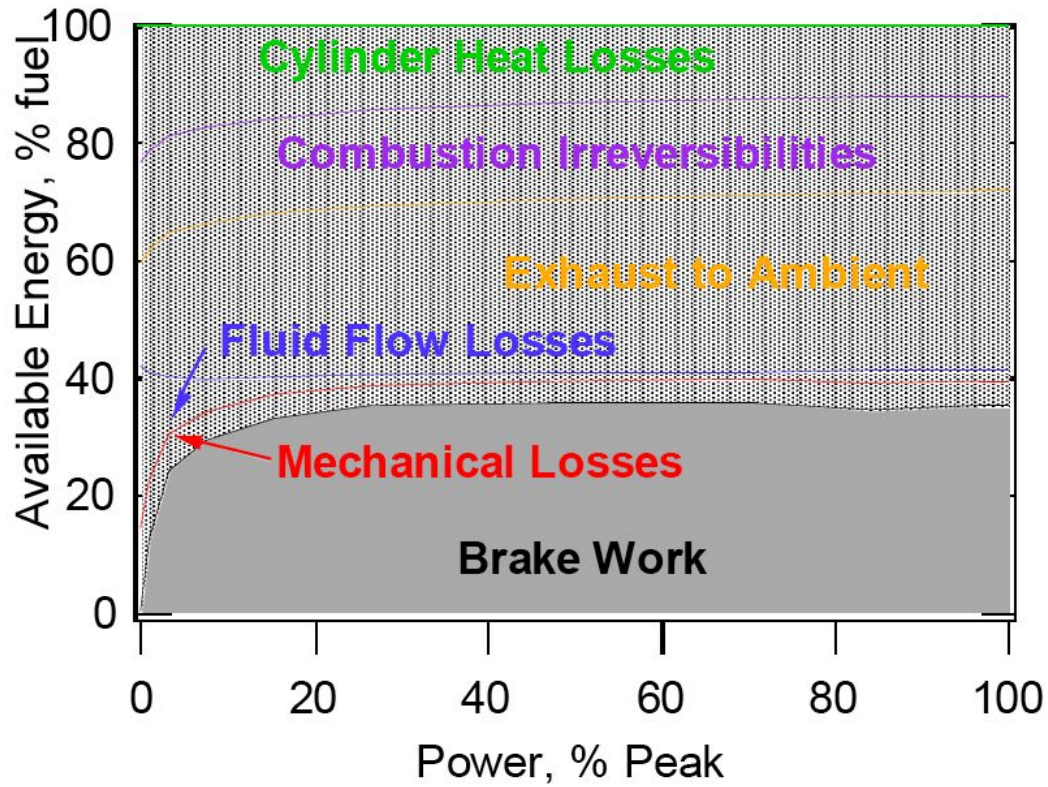
Partitioning of the Fuel Energy

$$W_{max,useful} = -\Delta G$$

$$W_{max,useful} = -\left(H_{prod} - H_{react}\right) + T_o\left(S_{prod} - S_{react}\right)$$

$$W_{max,useful} = Q_{HV} + T_o\left(S_{prod} - S_{react}\right)$$

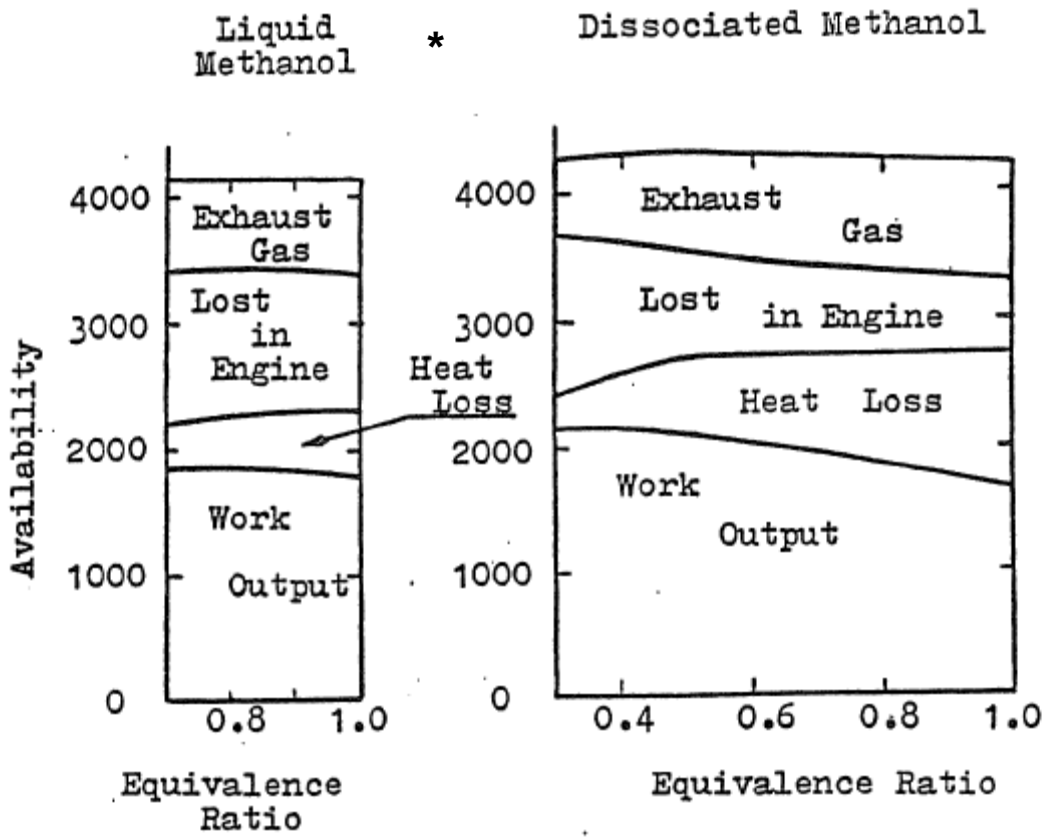


Weissman, Walt, ExxonMobil, presented at UW-ERC, 9 June 2005

- **HC energy carriers are precious**
  - **Theoretical efficiency is 100%**
- **Availability partitioning diagrams show were the losses are**

Availability Considerations in Combustion

- **Engine Responds to a Fuels Availability**
  - **Minimum availability destruction occurs at stoichiometric combustion**
- **Maximum work per unit mass of fuel, maximum efficiency, occurs for lean combustion**
  - **No attempt to recover availability in the exhaust**



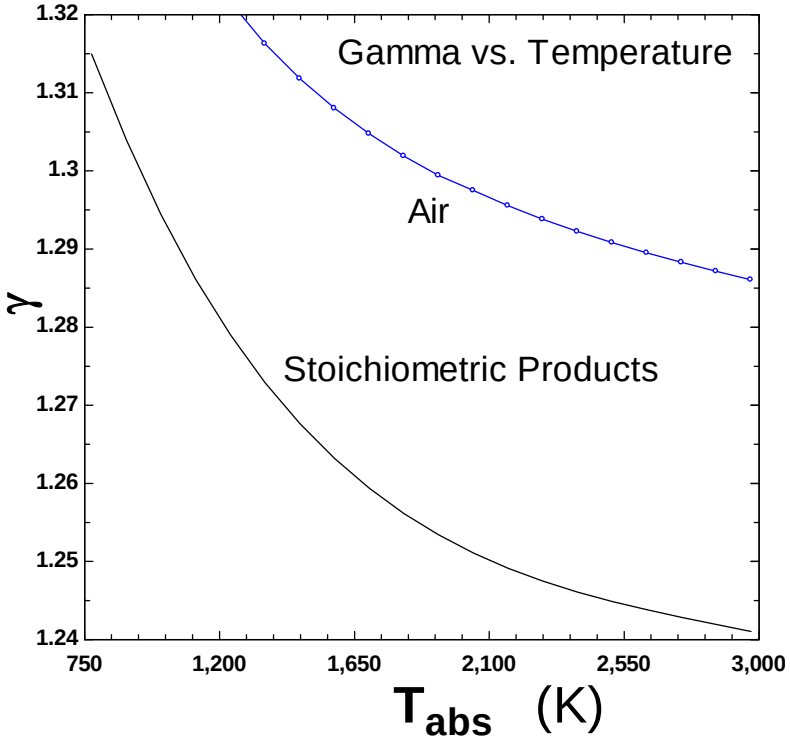
*Edo and Foster, Vi International Symposium on Alcohol Fuels Technology, Ottawa Canada, 1984

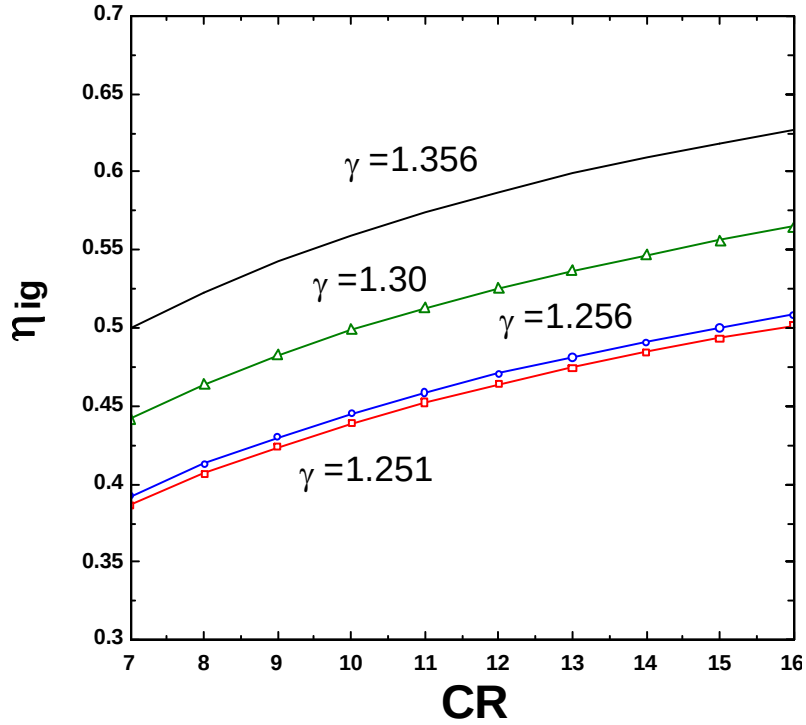
Discussion and a Question

- **Why is efficiency higher for lean combustion while combustion irreversibilities are higher?**
  - **Lower relative combustion temperatures results in larger work extraction per unit of volume expansion (ratio of specific heats = f(T))**
  - **This results in lower exhaust energy remaining at EVO**
  - **Also, lower temperatures result in lower heat transfer at the most critical point in the cycle, near TDC.**

- **Can combustion irreversibilities be reduced?**
  - **More discussion to follow**

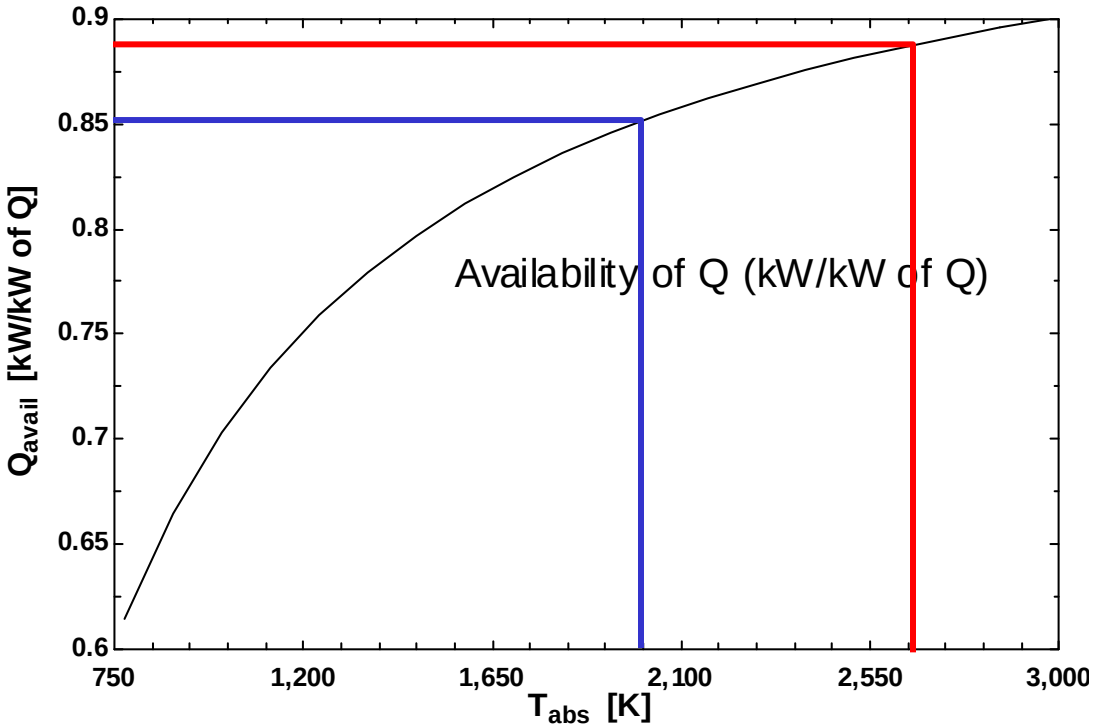
γ vs η





- γ decreases with conversion of A/F to products
- γ decreases as temperature increases
- η decreases as γ decreases

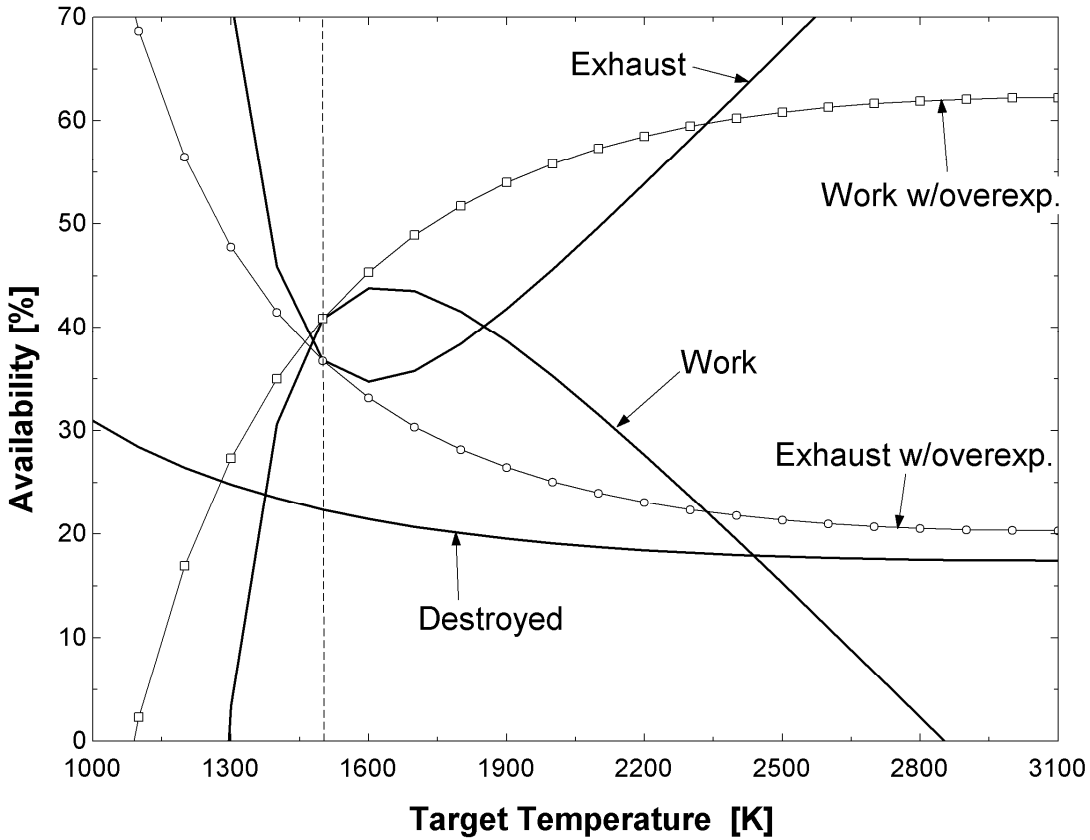
Availability of Q_{loss} vs Temperature



- **Not only is Q reduced but the availability lost with Q is also reduced**
  - **~4.6 percent for lines shown**

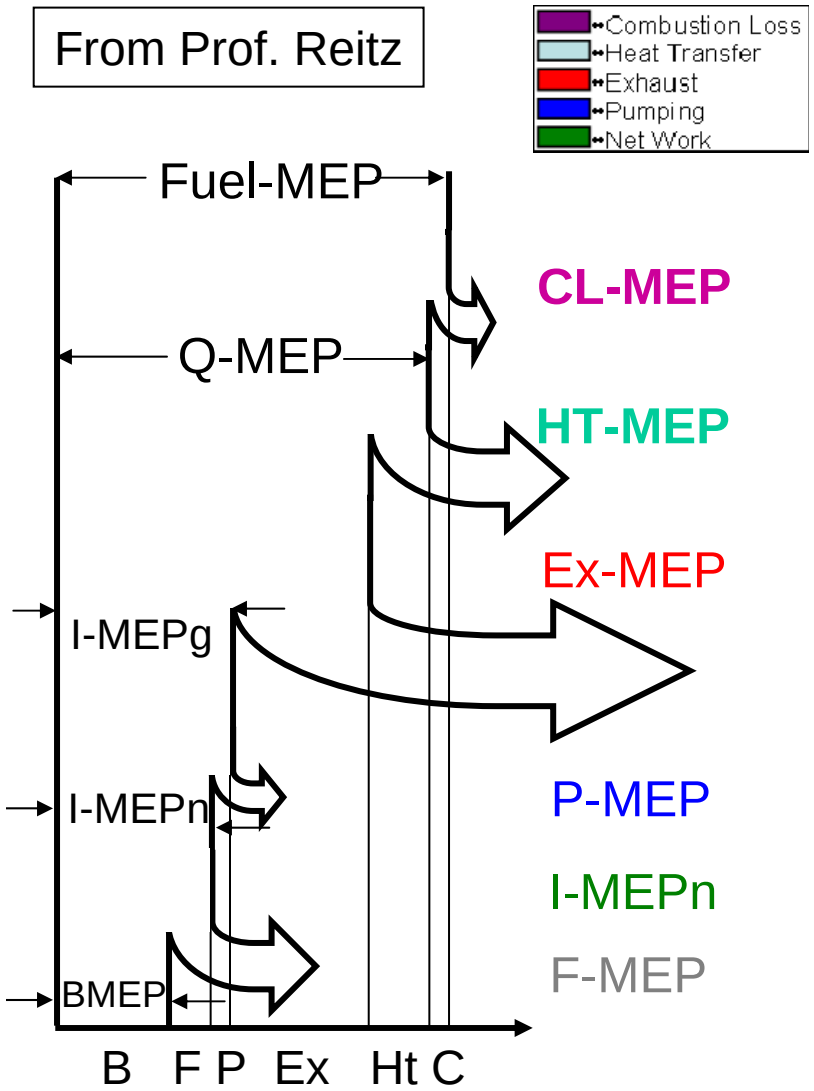
Trying to Reduce Combustion Irreversibilities

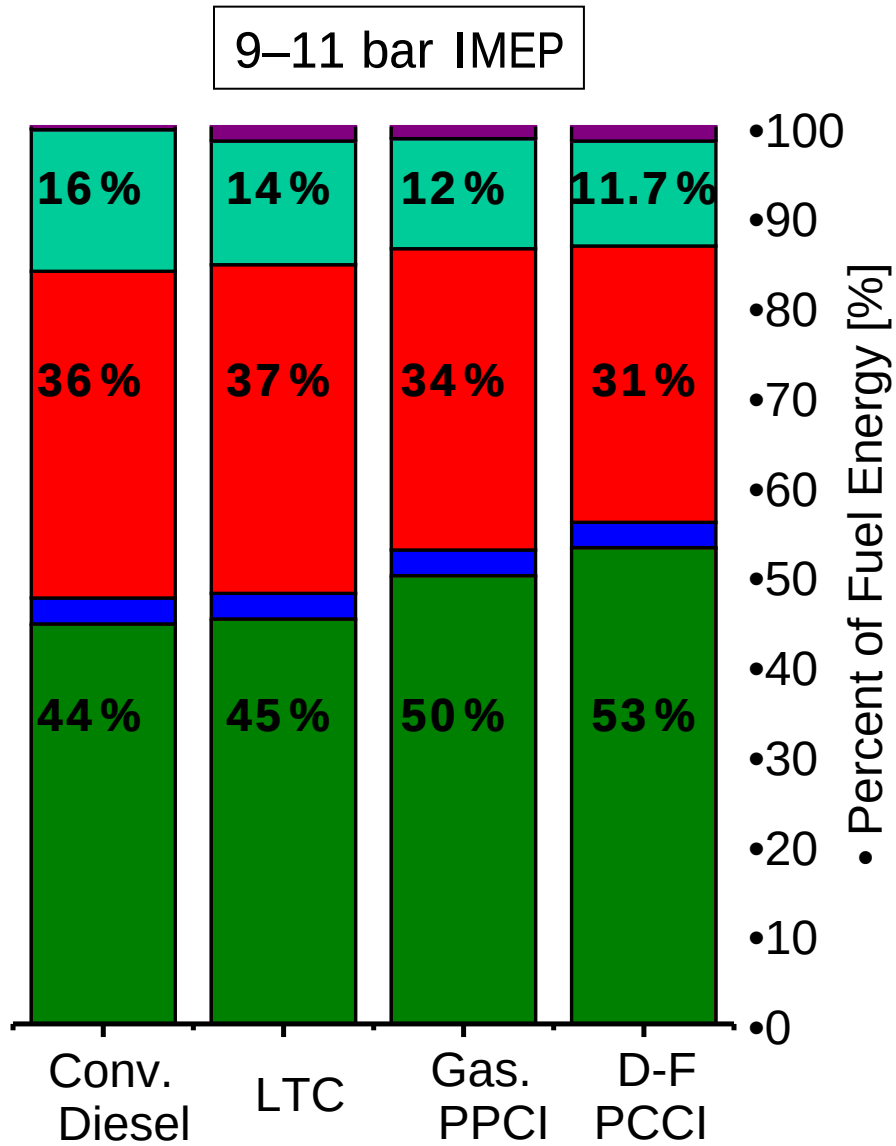
- **Simulated Constant Temp. Combustion**
  - **Work extraction rate matched combustion rate (fuel introduction) or, combustion rate matched work extraction rate**
  - **Base case – expansion stops when combustion stops**
    - **Vertical line is condition where P=1 atm at EOC**
  - **Overexpanded – expansion/compression continues until the gases in the cylinder are at atmospheric pressure**
- **Constant temp. combustion does not reduce comb. irrev.**



Druecke,et al., Central States Combustion Institute, Chicago, IL, March 2006

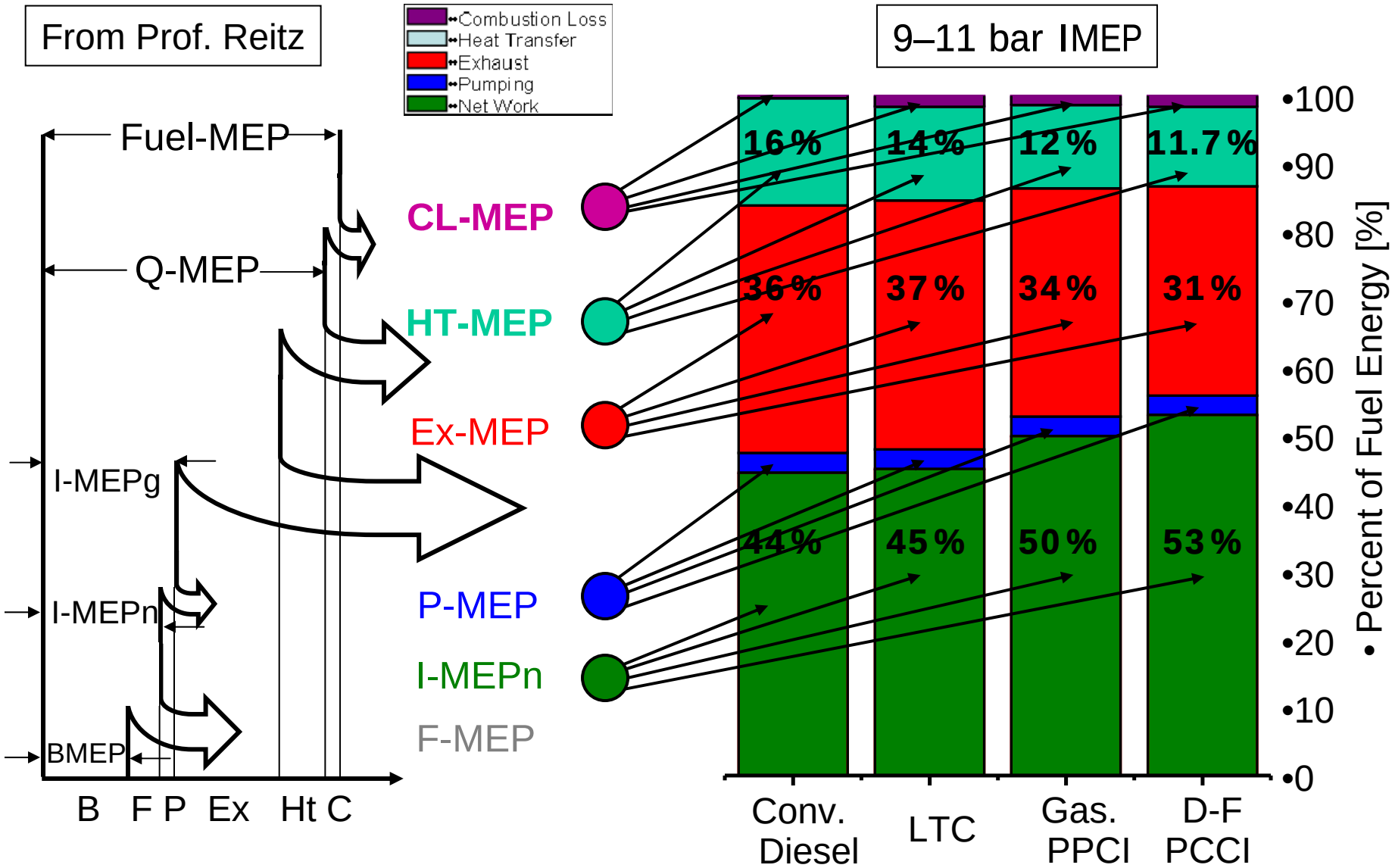
Reconciling with the 1st Law (Thermal Efficiency)





Conv. Diesel: Staples; LTC: Hardy; Gas PPCI: Hanson; D-F PCCI: Hanson

Thermal Efficiency Improvement (1st Law)



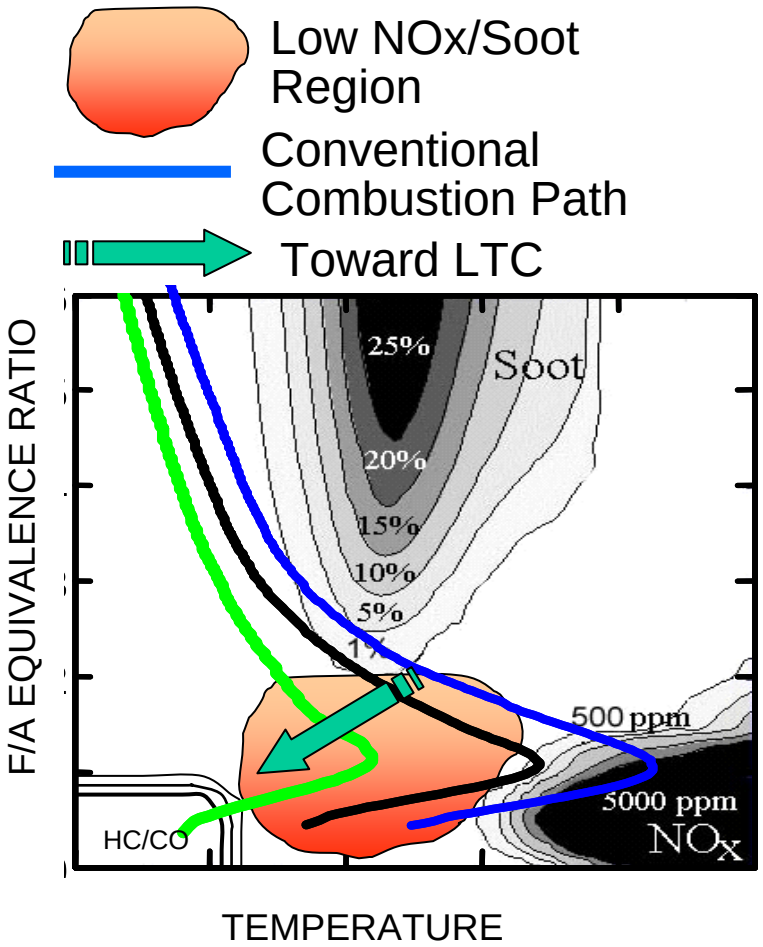
Conv. Diesel: Staples; LTC: Hardy; Gas PPCI: Hanson; D-F PCCI: Hanson

Pragmatic Limits to Engine Efficiency

- With current combustion systems (including LTC) combustion irreversibilities will be unavoidable
- Maximum in-cylinder efficiency will be obtained by keeping temperatures low
  - Maximizes work per unit expansion
  - Reduces in-cylinder heat transfer
  - Reduces available energy in the exhaust

Low-Temperature Combustion (LTC)

- **Critical Issues:**
  - **Practical "windows" can be identified:**
    - **T<2100 K to keep NOx from forming**
    - **T>1500 K to generate sufficient OH to complete oxidation of CO and HC**
  - **Exhaust temperature are low with LTC**
    - **Catalytic clean up of the exhaust may be difficult**
  - **The soot and NOx islands were determined by static calculations of, T = 1.0 ms, P = 6 MPa and EGR = 0% - In reality they move!**



Concept was originally proposed by Kamimoto, SAE 880423