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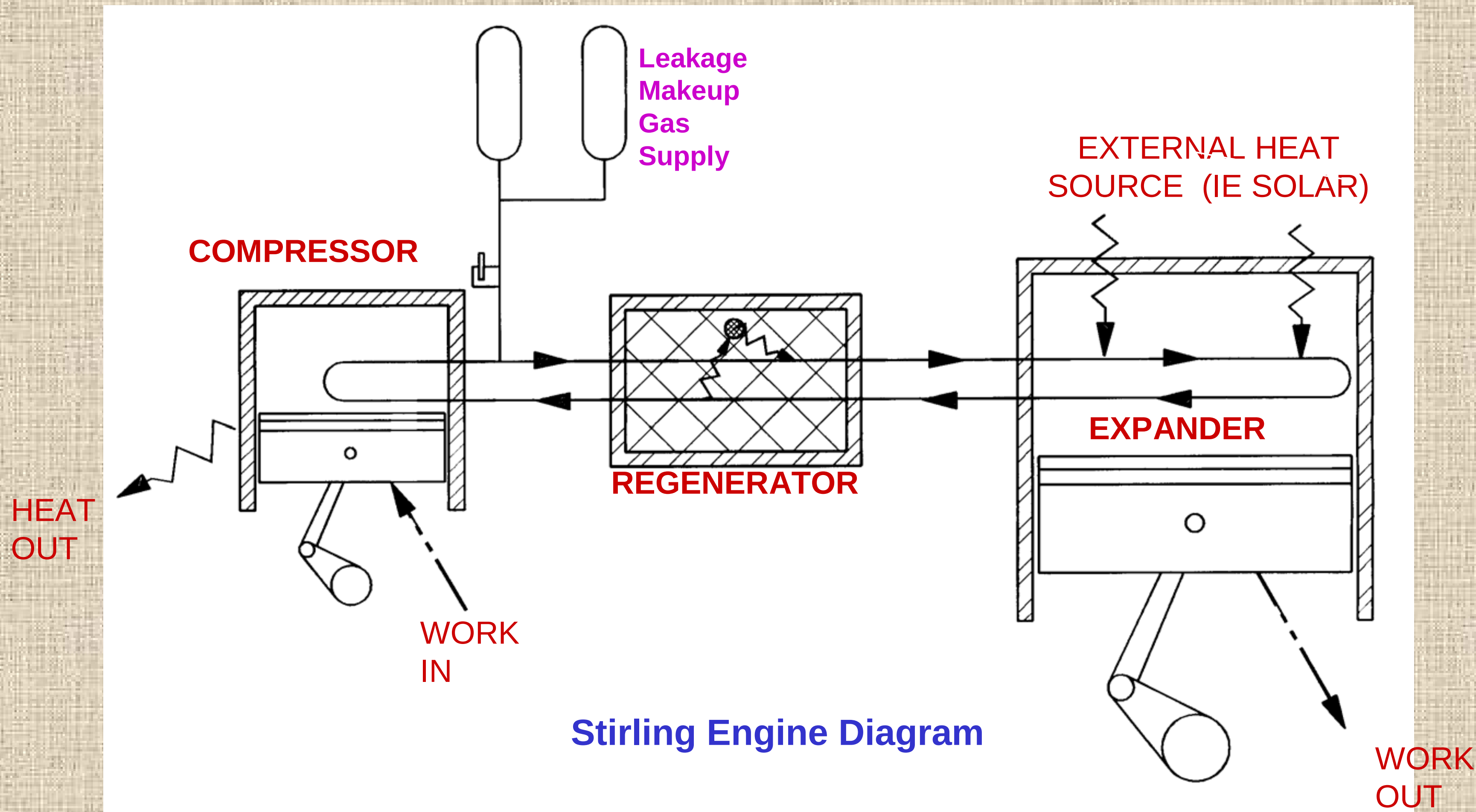
Proe Afterburning™ Cycle for 21st Century Power

Stirling Engine Cycle Comparison



Stirling Engine Diagram

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raproe@proepowersystems.com

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Engines Convert Energy To Make it Useable

Input Energy:

- Non Combustion
  - Solar
  - Nuclear
  - Geothermal
  - …

Engine

Useable Energy:

- Rotating Shaft
- Electrical Generation
- …

- Combustion
  - Dedicated Combustion
  - Waste Heat from Industrial Combustion
  - Waste Heat from other Engine Exhaust

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Efficiency Determines the Cost of Conversion

$$\textit{Efficiency} = \frac{\text{Useable Energy}}{\text{Input Energy}}$$

The Higher the Efficiency, the “better” the engine

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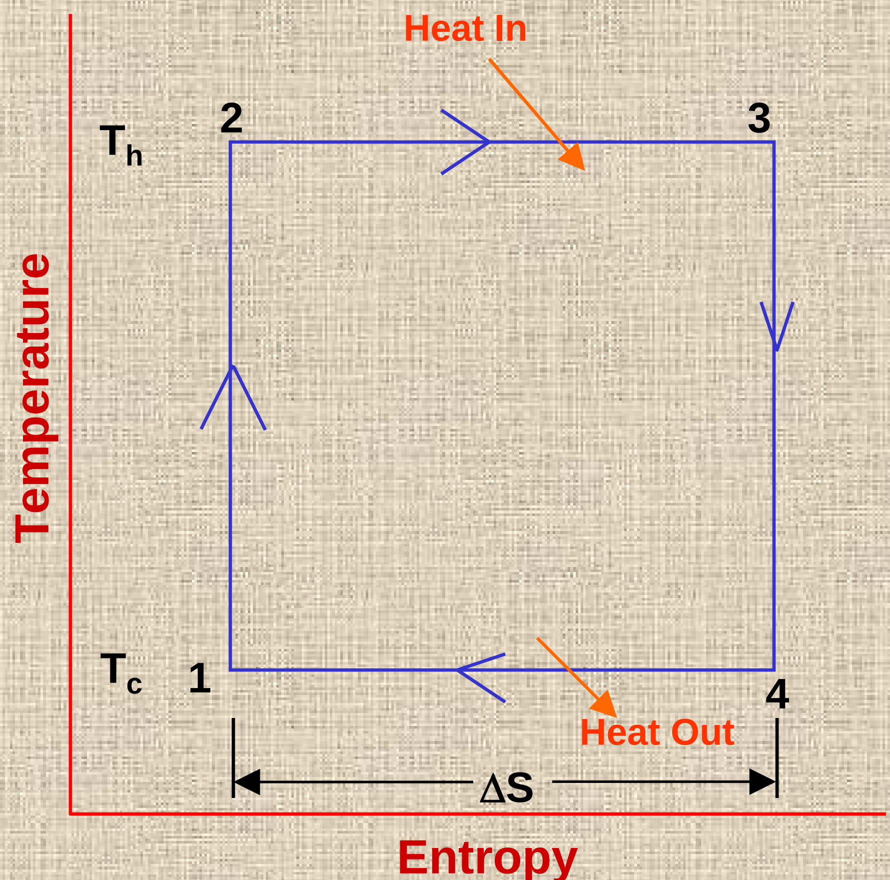
Time Out for Some Thermodynamics

"Carnot Efficiency":

The maximum possible for an engine operating between two temperature reservoirs



The Carnot Cycle: The 'Perfect Engine'

1-2 Compression without heating (dS=0)
2-3 Constant Temperature Expansion (dT=0)
3-4 Expansion without heating (dS=0)
4-1 Constant Temperature Compression (dT=0)

Heat In = $Q_{in} = T_h \Delta S$
Heat Out = $Q_{out} = T_c \Delta S$

Work = $Q_{in} - Q_{out} = (T_h - T_c)\Delta S$

Efficiency = η = Work/Heat In
$= (T_h - T_c)\Delta S / Th\Delta S$

$$\eta = 1 - T_c/T_h$$

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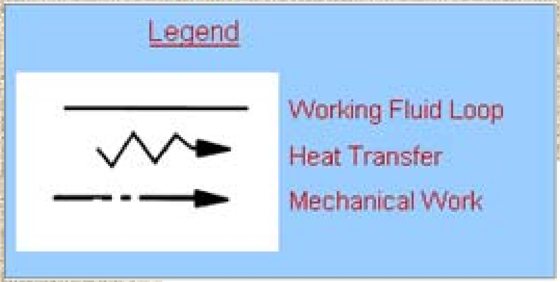
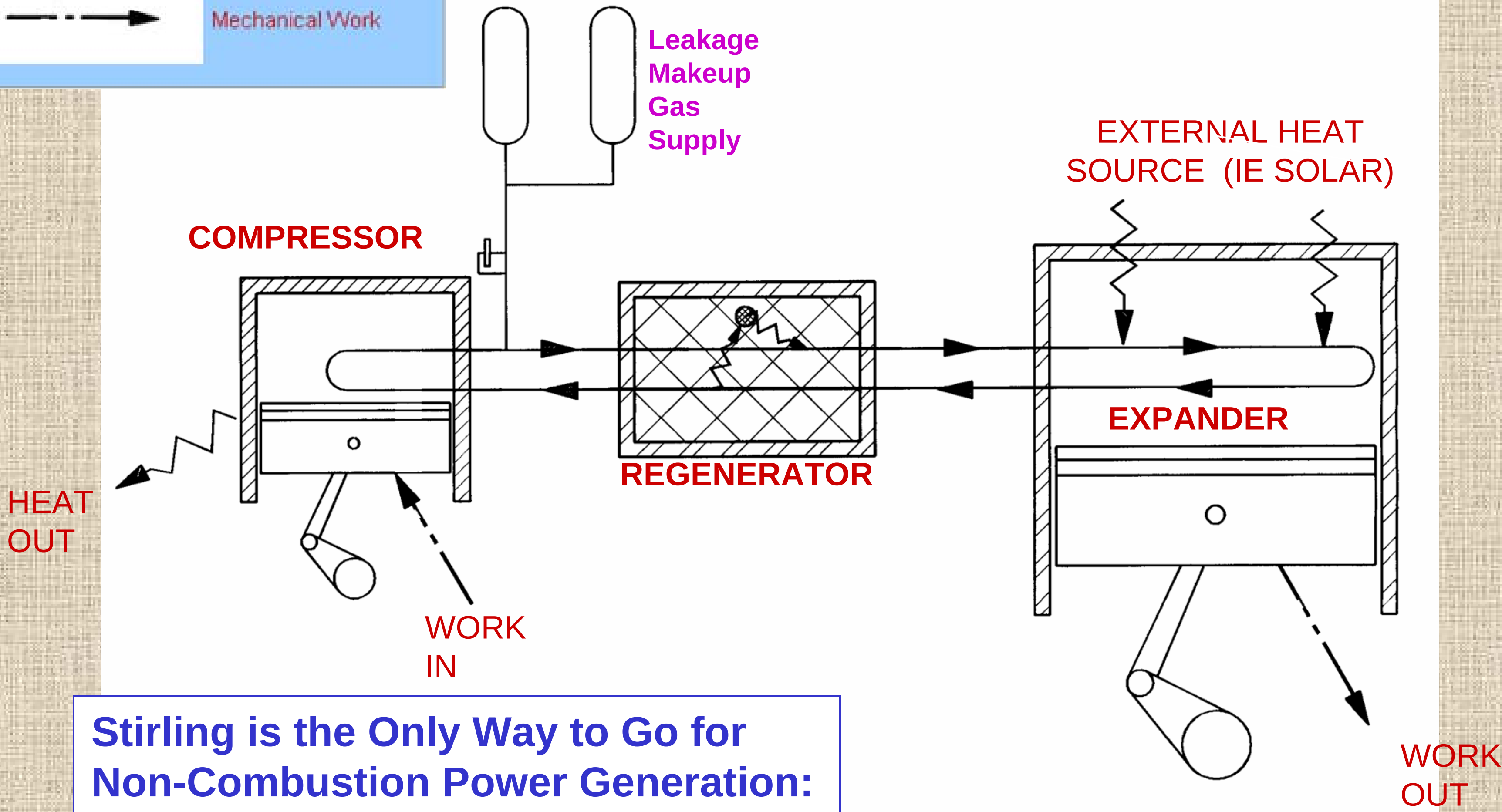
A Practical Approach to Carnot Efficiency: the Non Combustion Stirling Cycle





Stirling is the Only Way to Go for Non-Combustion Power Generation: – Simple and Efficient

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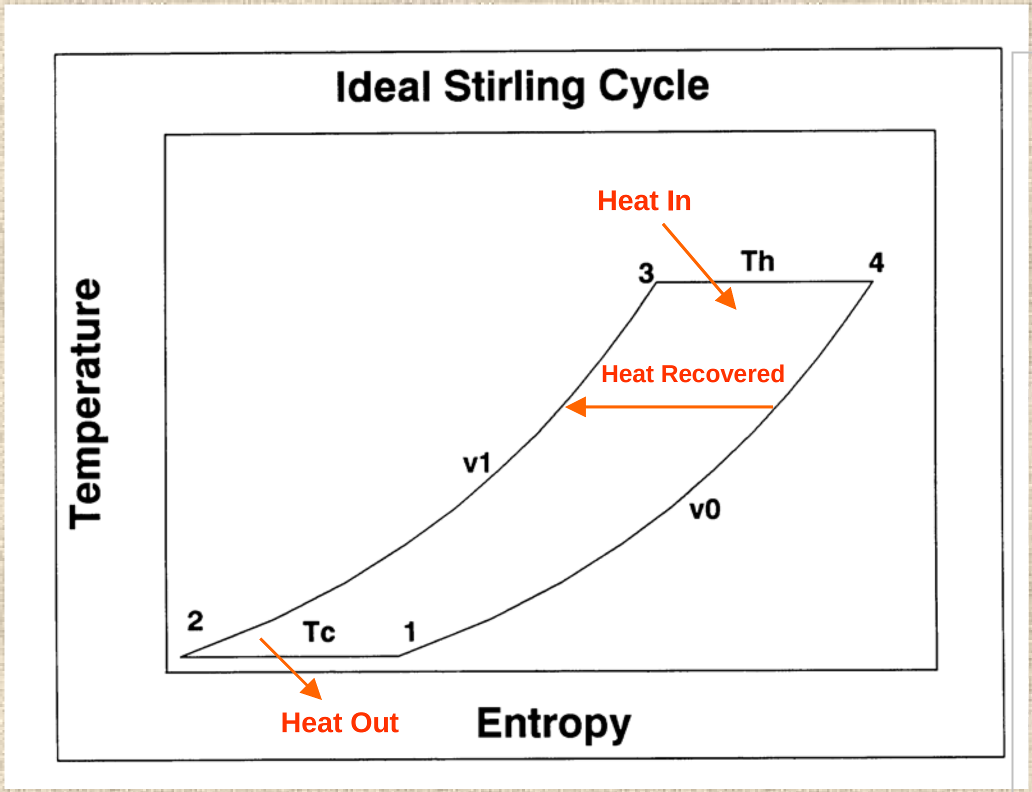
In a Perfect World, The Stirling Engine Has "Carnot Efficiency"



1-2 Constant Temperature Compression from v0 to v1with Heat Removal
2-3 Constant Volume Heat Addition (Regenerator)
3-4 Constant Temperature Expansion from v1 to v0 with Heat Addition
4-1 Constant Volume Heat Removal (Regenerator)

Heat In = $Q_{in} = T_h \Delta S$
Heat Out = $Q_{out} = T_c \Delta S$

Work = $Q_{in} - Q_{out} = (T_h - T_c)\Delta S$

Efficiency = η = Work/Heat In = $(T_h - T_c)\Delta S / T_h\Delta S$

$\eta = 1 - T_c/T_h$

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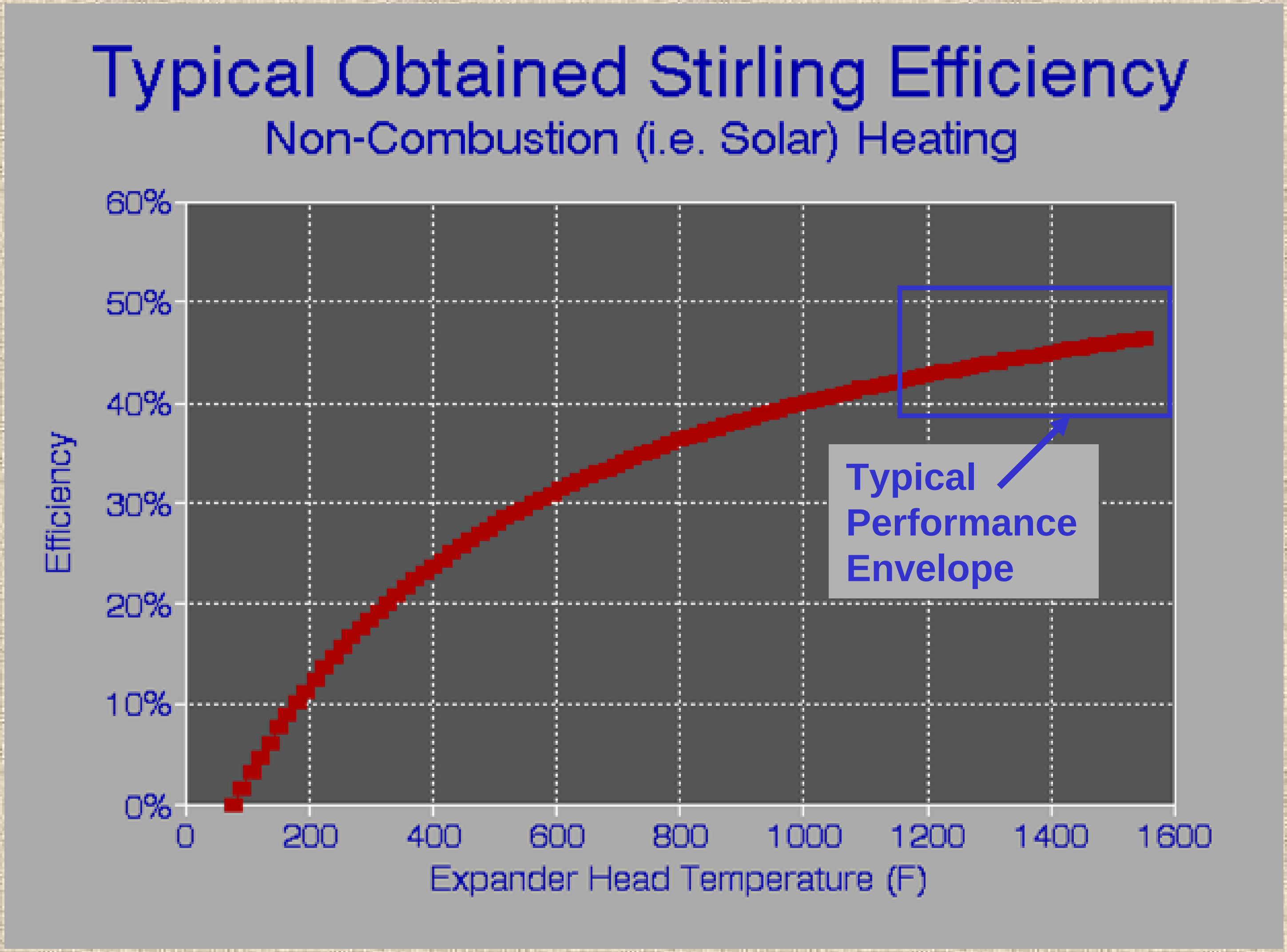
And, In the Real World, Non-Combustion (i.e. Solar) Stirling Engines Can Achieve Excellent Efficiency



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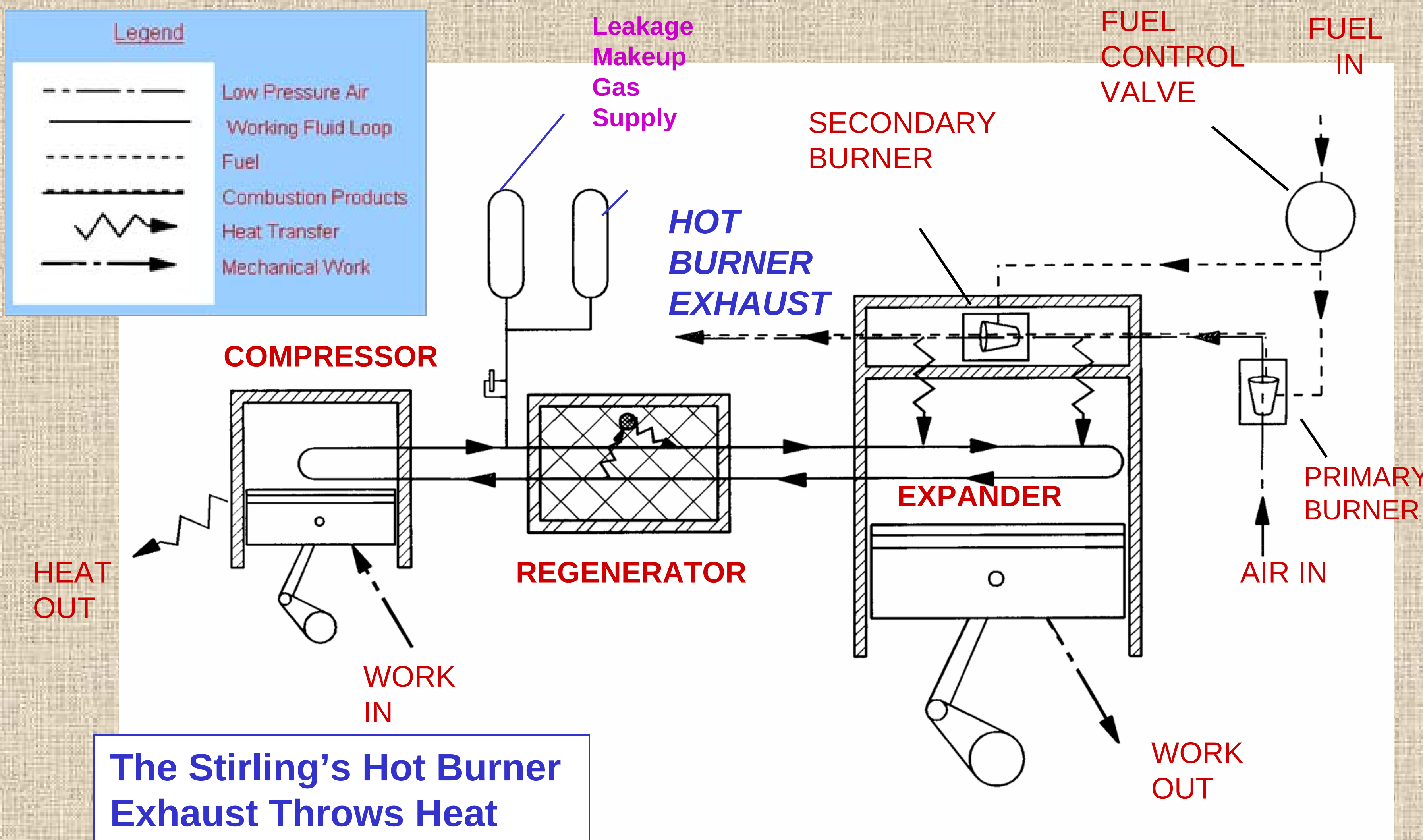
BUT….The Combustion Stirling Cycle Faces A "Burner Barrier" To High Efficiency



The Stirling's Hot Burner Exhaust Throws Heat Energy Away

Afterburning Ericsson Cycle Engine, Proe 90™ Recuperator, and Proe Afterburning™ Cycle Engine are protected by US Patents Number: 5,894,729; 6,390,185 and 7,028,476

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The Stirling Cycle with a Burner Cannot Approach Carnot Efficiency

Closed cycle engines are constrained by burner efficiency

$$\eta_b = \frac{\text{Heat Transferred to Engine}}{\text{Heat of Combustion}}$$

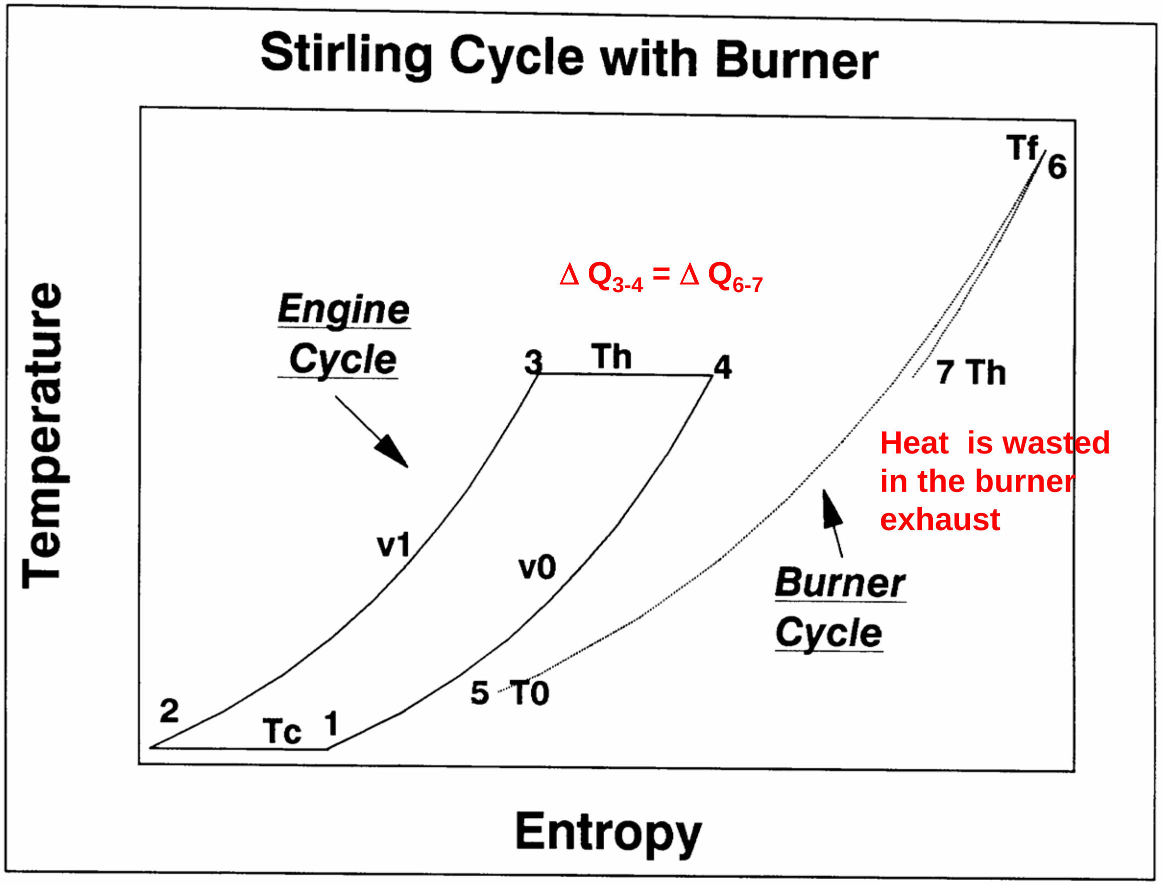
$$\eta_b = (H_f - H_{exit})/(H_f - H_{amb})$$

Where H_f = flame enthalpy
H_{exit} = exhaust exit enthalpy
H_{amb} = Burner entrance enthalpy

Overall Cycle Efficiency is:

$$\eta = \eta_b \eta_{Carnot}$$

$$\eta = \eta_b (1 - T_c/T_h)$$



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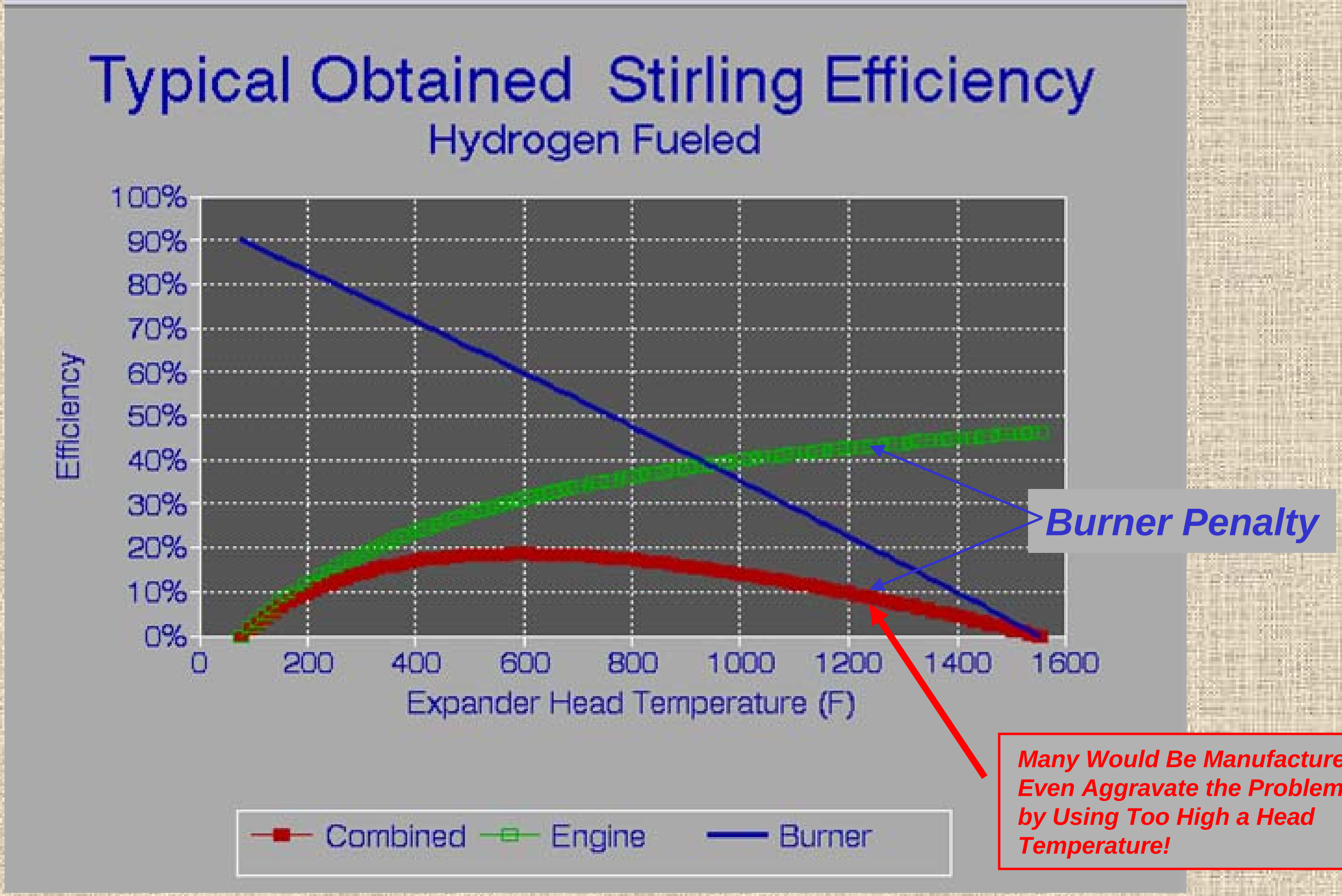
Actual Combustion Fired Stirling Cycle Engines are Greatly Disappointing



Many Would Be Manufacturers Even Aggravate the Problem by Using Too High a Head Temperature!

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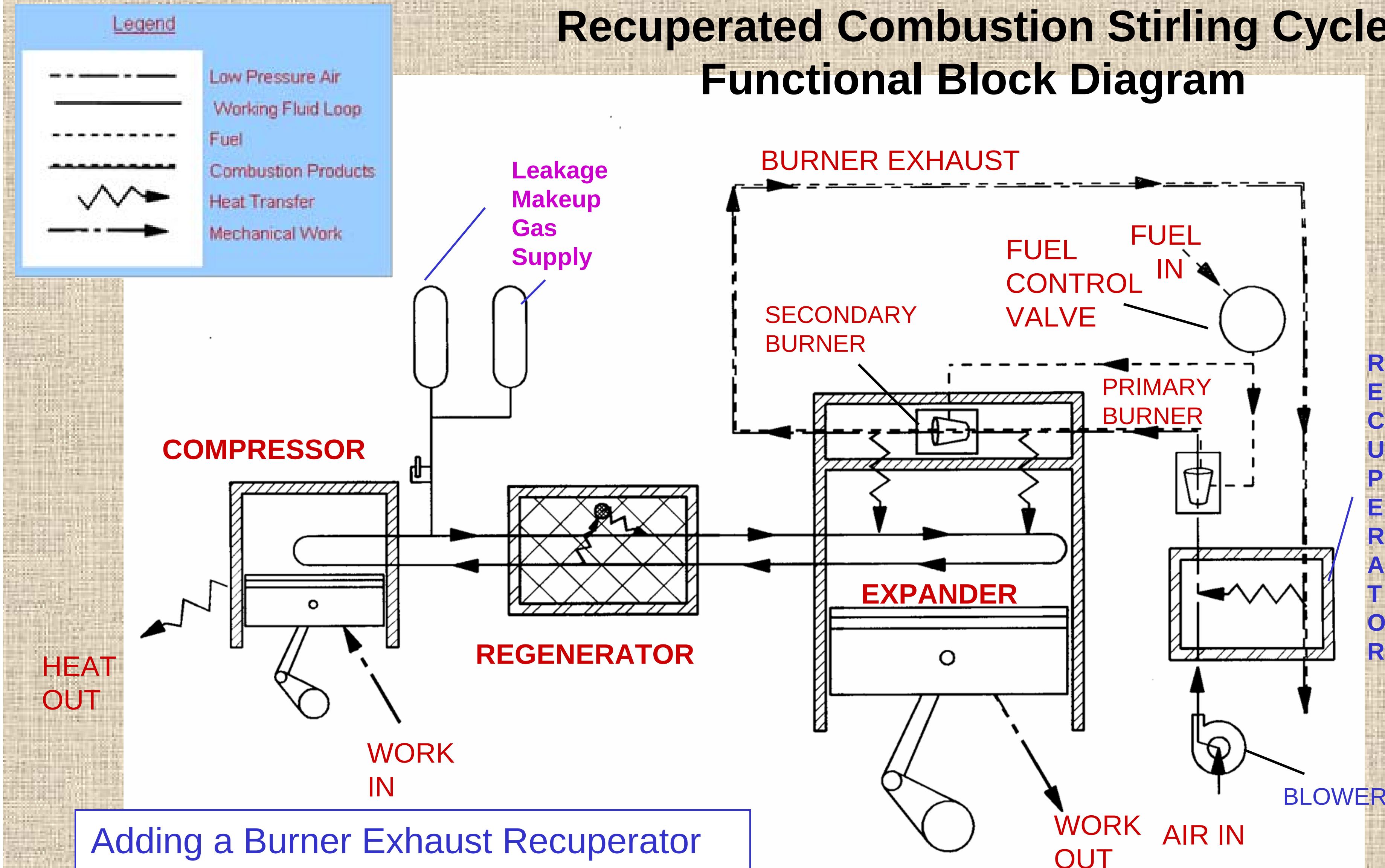
Recuperated Combustion Stirling Cycle Functional Block Diagram



Adding a Burner Exhaust Recuperator & Blower Can Recover Wasted Heat But Add Cost & Complexity

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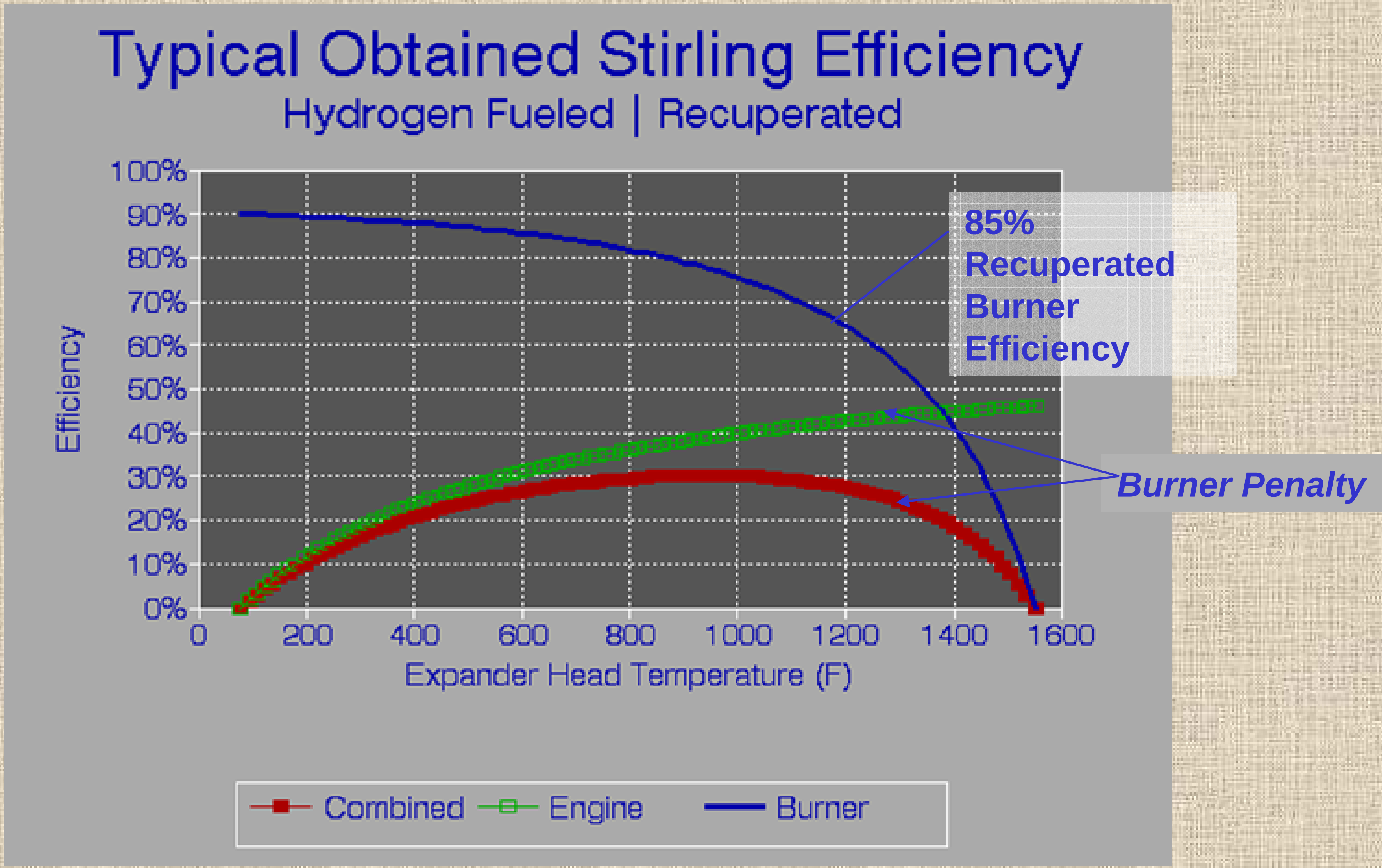
The Stirling Cycle with a Recuperated Burner Still Faces an Efficiency Barrier



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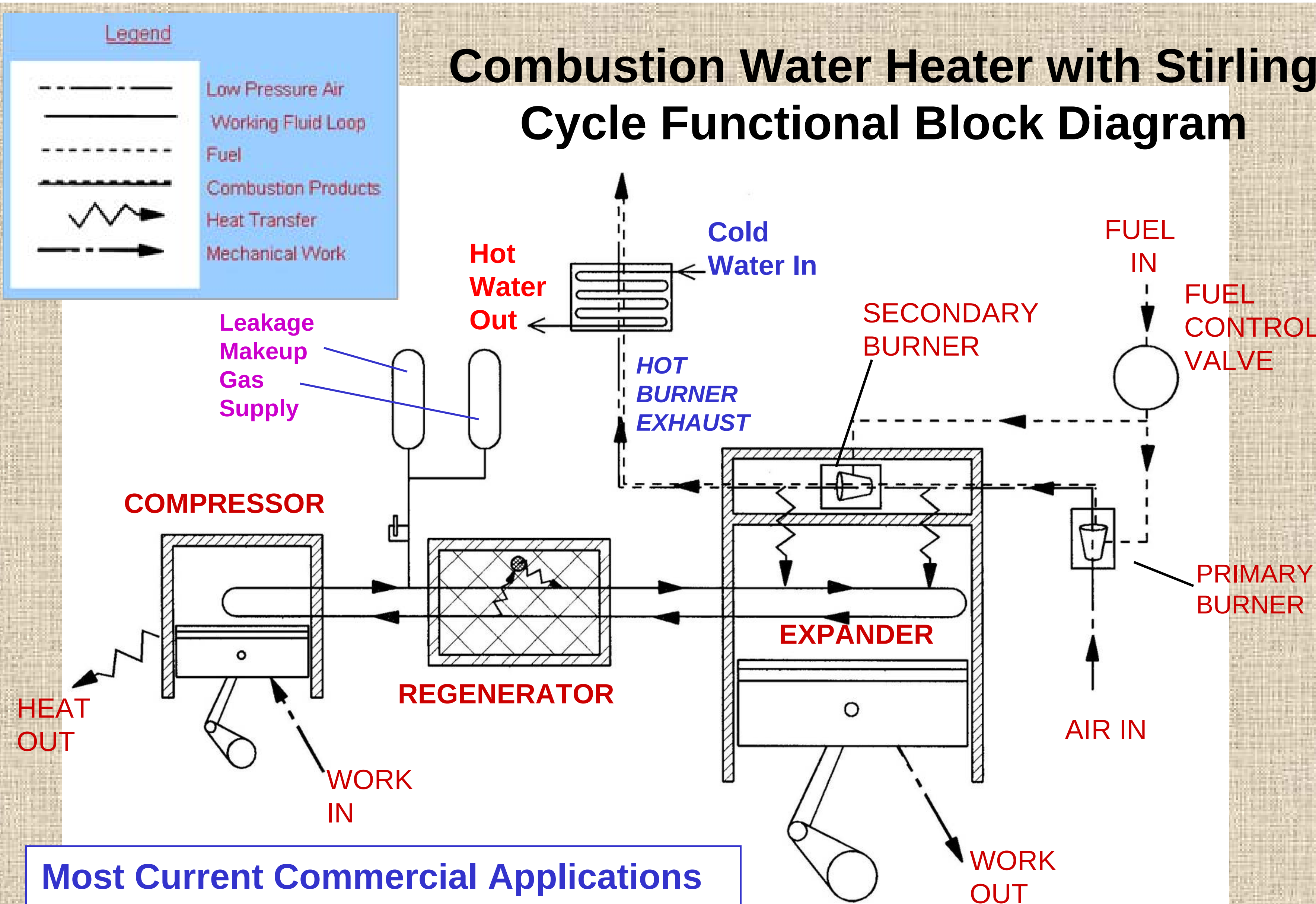
Combustion Water Heater with Stirling Cycle Functional Block Diagram



Most Current Commercial Applications are to Augment a Water Heater by Providing a Small Power Output

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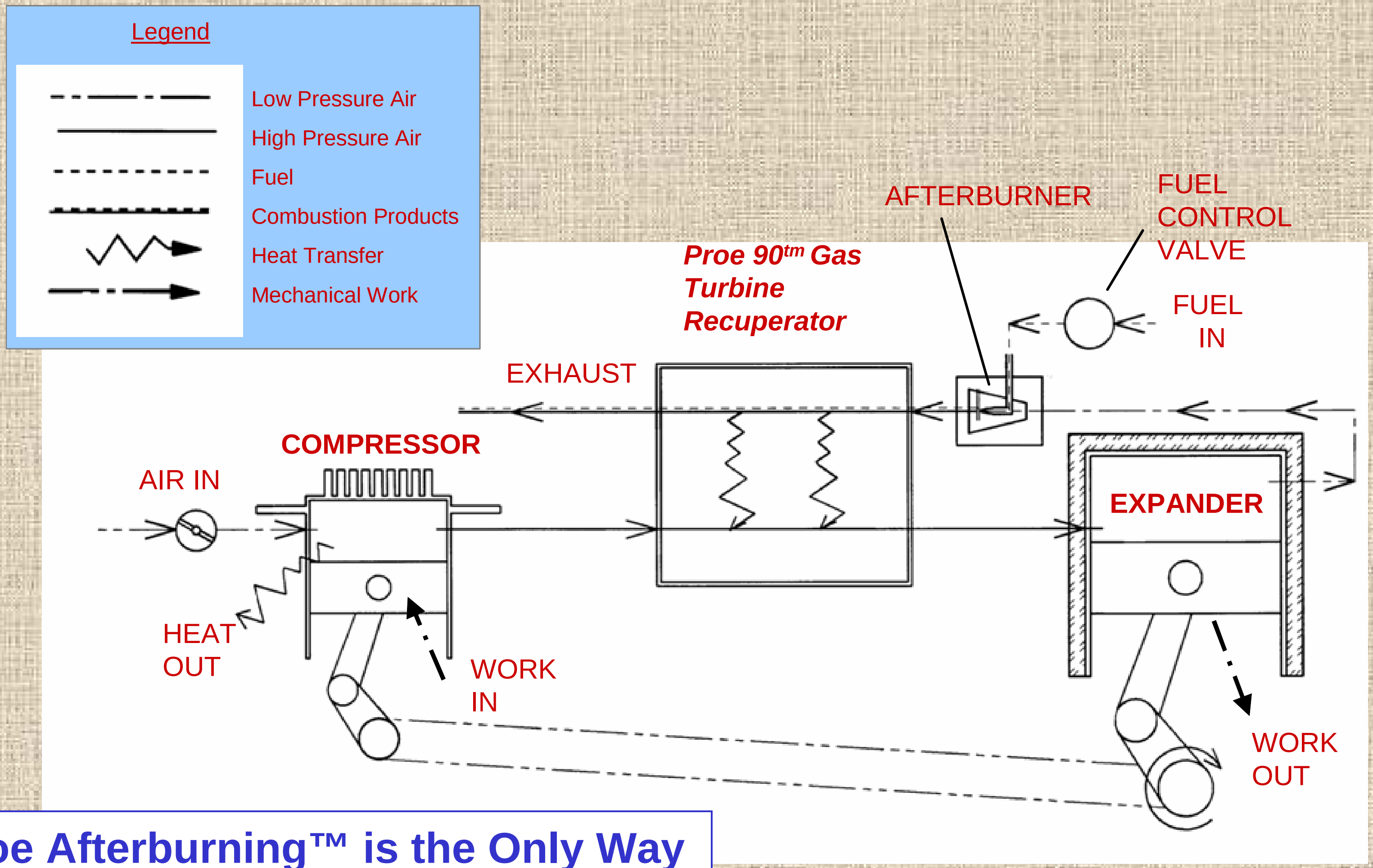
A Practical Approach to Carnot Efficiency with a Combustion Engine: the Proe Afterburning™ Engine Cycle



Proe Afterburning™ is the Only Way to Go for Combustion Power Generation: – Simple and Efficient

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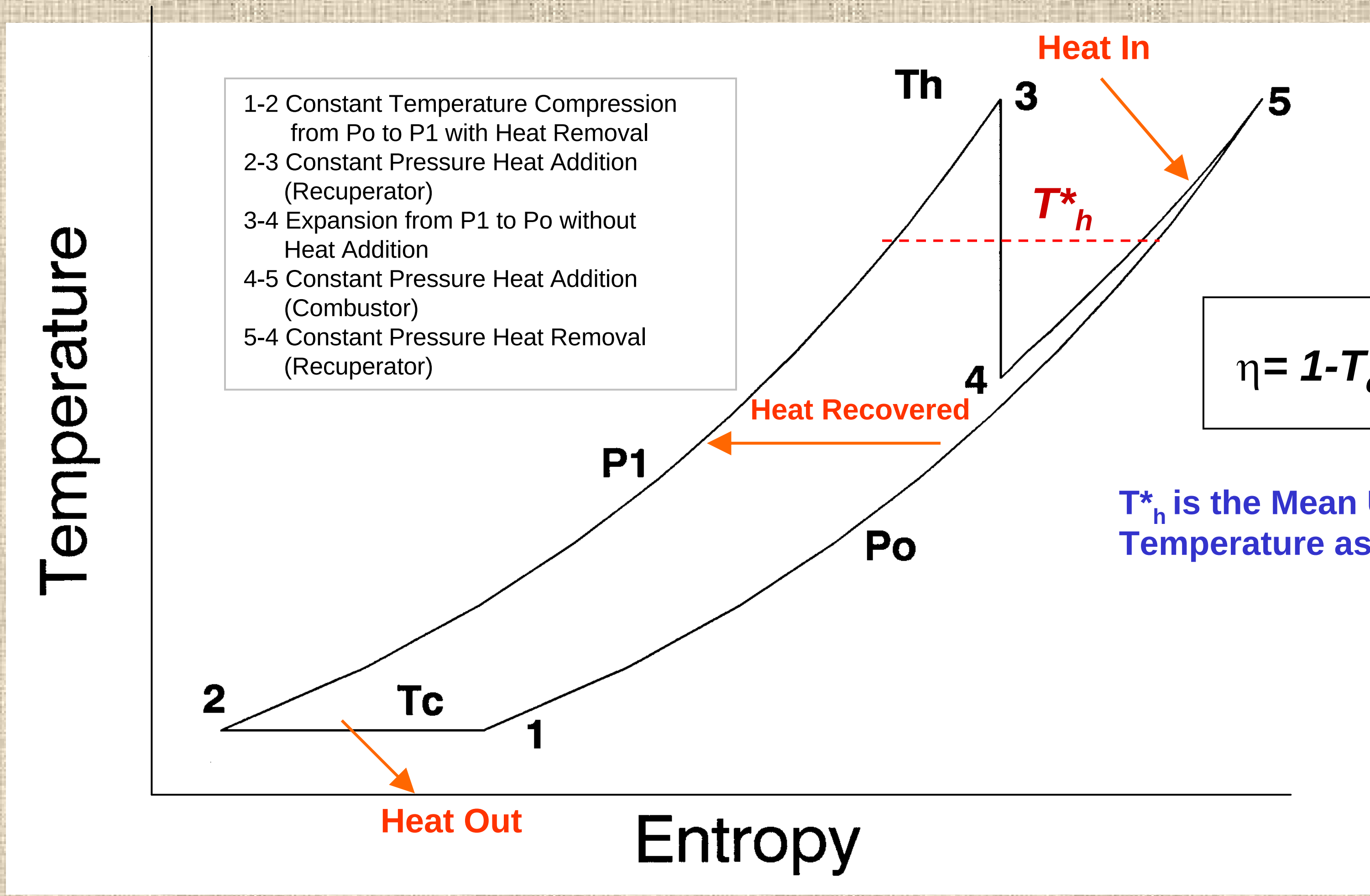
The Proe Afterburning™ Engine can Approach "Carnot Efficiency" with a Combustion Engine



$$\eta = 1 - T_c / T^*_h$$

T^*_h is the Mean Upper Temperature as Shown

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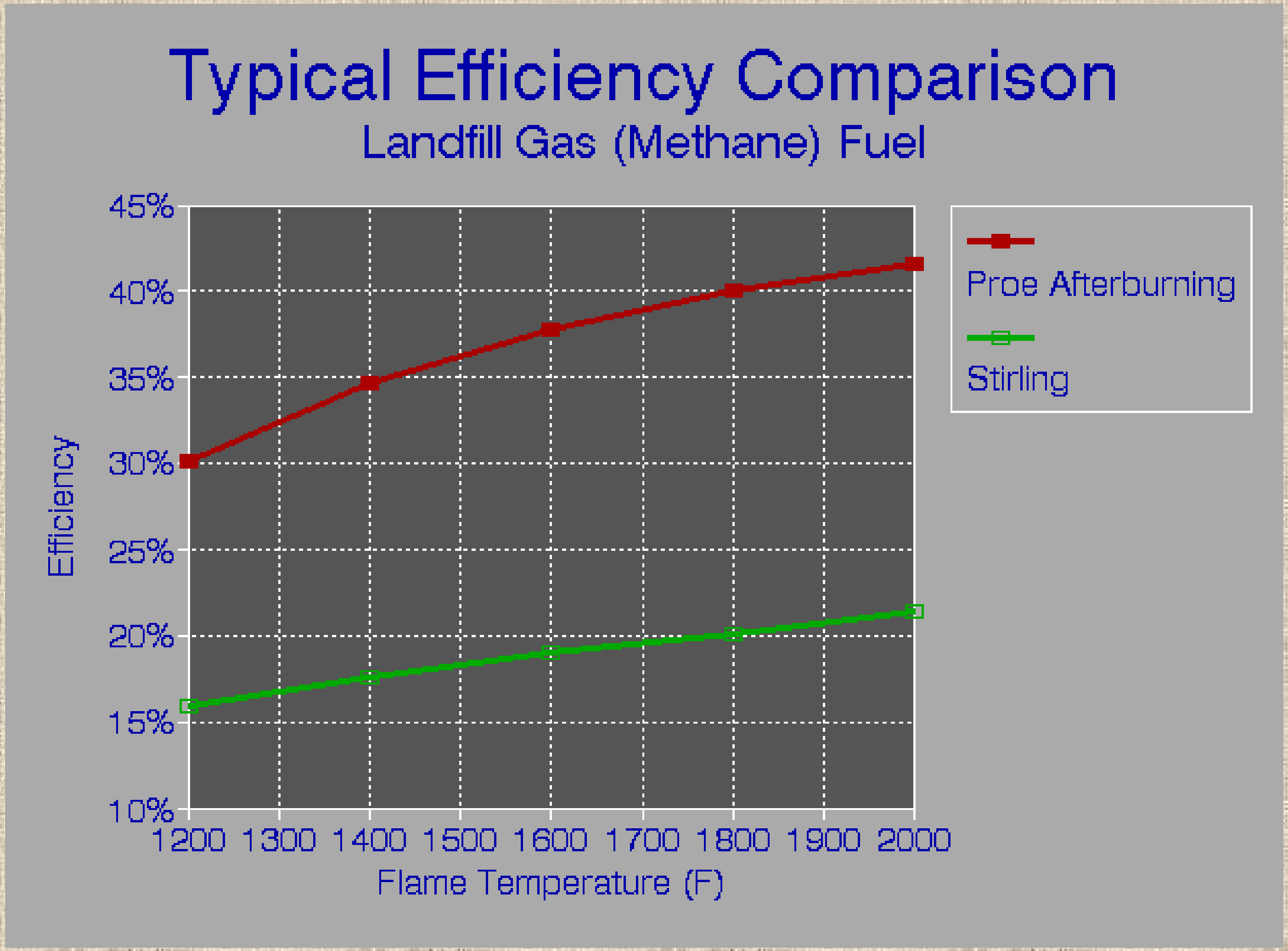
There is No Contest in the Combustion Engine Efficiency Race



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So Why Not A Stirling Engine Instead?

- ***Stirling Cycle is Outstanding for Non-Combustion Heat Source***
  - **- Very simple closed cycle**
  - **- In Theory, Can approach Carnot Cycle Efficiency limit**
  - **- Has been very successful in solar and nuclear applications**
    (Also extremely successful when run backwards as a refrigerator cycle)

- ***But the Stirling Cycle Consistently Fails as a Combustion Engine***
  - **- <u>Cannot integrate the combustion and engine processes</u>**
  - **- The burner is always a separate, <u>counter-productive</u>, process**
    - **- Burner air must be heated from room temperature to flame temperature**
    - **- Hot Burner air only can give heat to the engine as it is cooled from flame temperature to expander temperature**
    - **- Energy is wasted as the burner exhaust cools from expander to room temperature**
  - **- *Or*: Burner heat can be recovered but only with additional complexity**
    - **- Requires a burner recuperator and blower**
      (A leading Stirling developer has approached Proe Power Systems to use our Proe 90™ Ericsson Recuperator for their Stirling Engines)
    - **- The Stirling engine then incurs the cost and heat and flow losses of two heat exchangers, <u>both a regenerator and a recuperator</u>**

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Conclusion:

The Heat Source Determines the Engine

Heat Source	Best Engine Match
Non-Combustive Heat Sources:	***Closed Cycle (Stirling)***

Solar
Nuclear - Radioisotope
Geothermal …

Air Combustion Heat Sources:	***Open Cycle (Proe Afterburning™ Engine)***

Combustion of Fossil Fuel Gases, Liquids or Solids
Combustion of Biowaste Gas (methane etc.)
Combustion of Biowaste Liquid (corn oil, waste cooking oil etc.)
Combustion of Biowaste Solids (wood chips, corn etc.)
Combustion of Village Power Fuels (solid waste, dung etc.)
Waste Heat from Industrial Combustion Processes
Waste Engine Exhaust Heat (Proe HRPG® Heat Recovery Power Generator)

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