Efficient Micro-Combustors for Thermoelectric Devices

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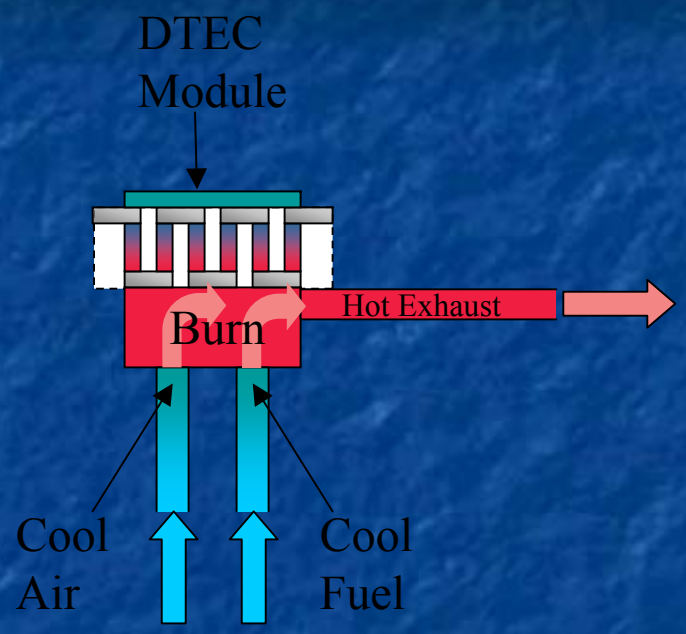
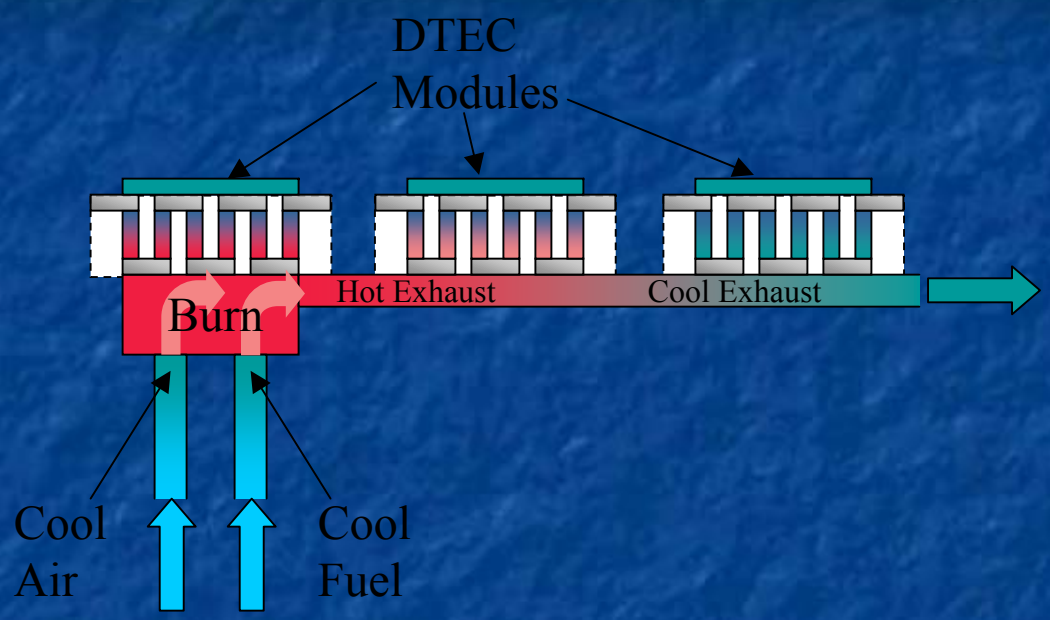
Ideal Combustor

- Deliver Heat Efficiently
  - Little or no heat in exhaust (this also reduces thermal signature)
- Throttlable
  - Ideally – Delivery efficiency and conversion efficiency do not suffer.
- Deliver Heat at Highest Temperature Possible
  - Designed to maximum operating temperature of material for highest Carnot efficiency.
- High Watts/cm^2 and High Watts/gram
- Low Cost Technology
  - For development - Versatile technology
  - For production – Established manufacturing base

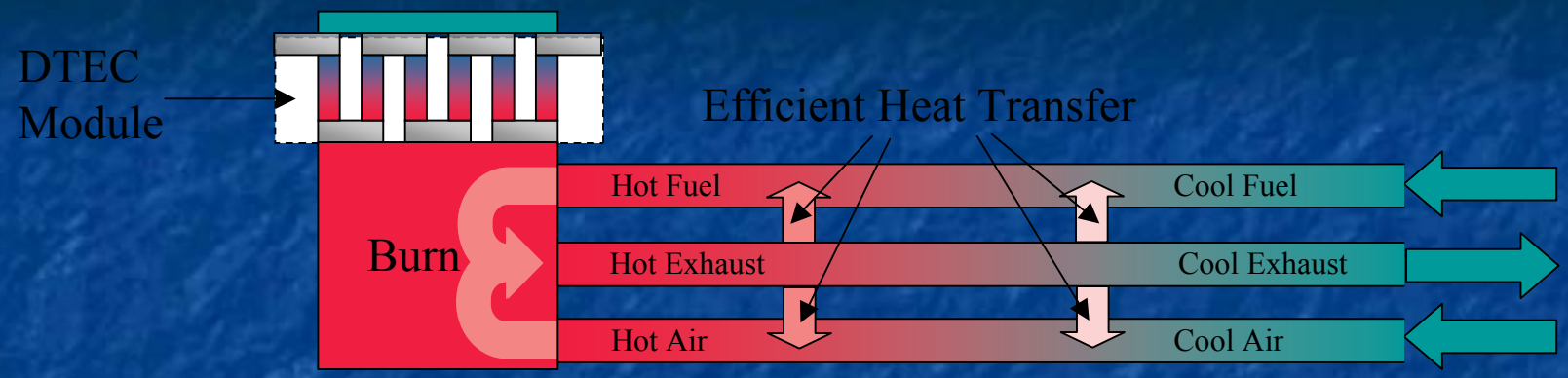
Possible Designs





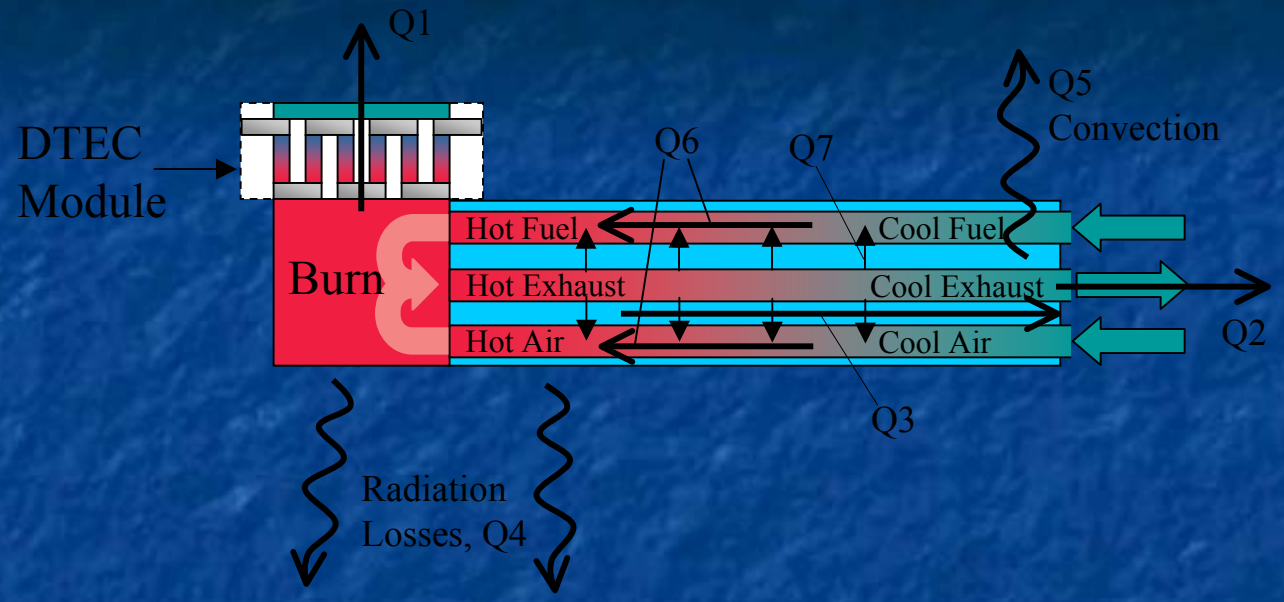
- Simple Burner
  - Exhaust temp. is very high
    - Wastes heat
    - High thermal signature
- Simple burner with TE gauntlet
  - More efficient overall
  - Low exhaust temp.
  - Each successive module converts less heat-flow into electricity at lower conversion efficiency.

A Better Concept



- In steady state (w/ identical C_p), the system sets up a constant temperature difference everywhere, between the exhaust and the air & fuel.
  - Longer exchanger, lower velocities, higher thermal K ceramic = less ΔT
- This system is not limited by the traditional burn temperature.
  - Care must be taken to prevent coking in fuel line.
- More efficient use of catalyst than fuel cells (small amount of platinum gives large power).
  - Fantastic kinetics in burn head
- Heat delivery efficiency changes little with variation in fuel flow/head temp. – however, DTEC efficiency decreases with lower head temp.

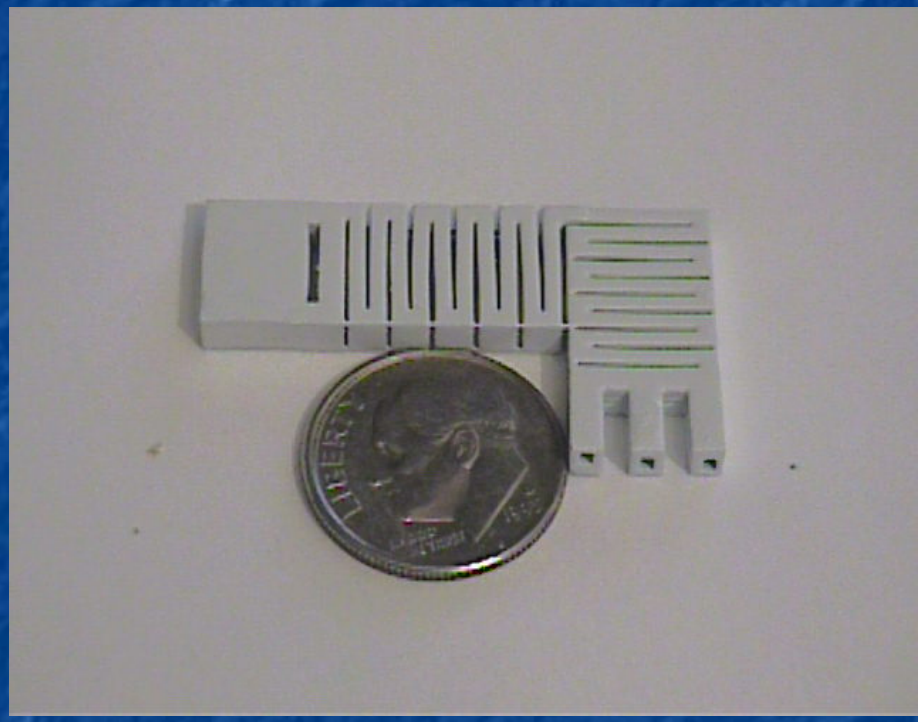
Heat Flows



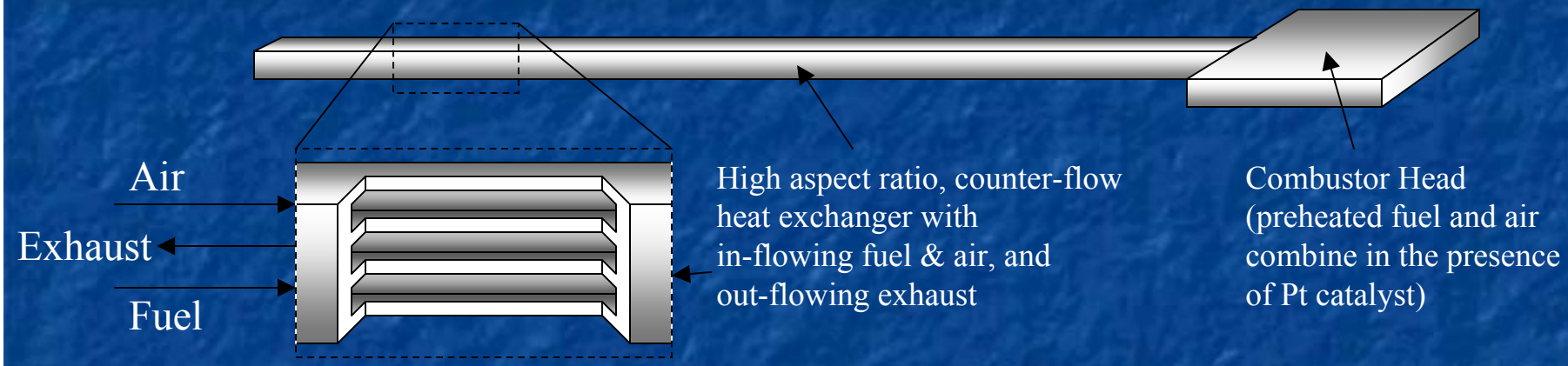
- We want to maximize Q1 by maximizing Qs 6 & 7, and minimizing Qs 2-5
  - High aspect ratio exchanger minimizes Q3
  - Long exchanger maximizes Qs 6 & 7 while minimizing Q2
  - Vacuum insulation minimizes Q5
  - Radiation shielding minimizes Q4.

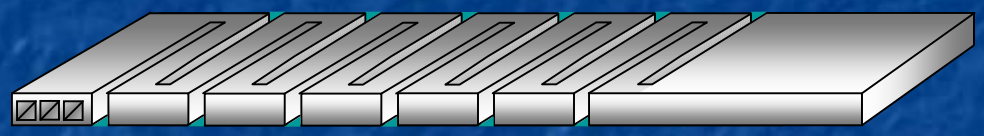
Current Combustor

- 95% Ultimate heat delivery efficiency
- Operates on H_2, Butane, and H_2/Kerosene mix… so far.
- 20W output at temps up to 650C (w/ liquid H_2O exhaust)
- Throttlable (while maintaining efficiency)
- Only 3 grams
- Less than 10μg Pt @ $835/oz.= $.000013/Watt



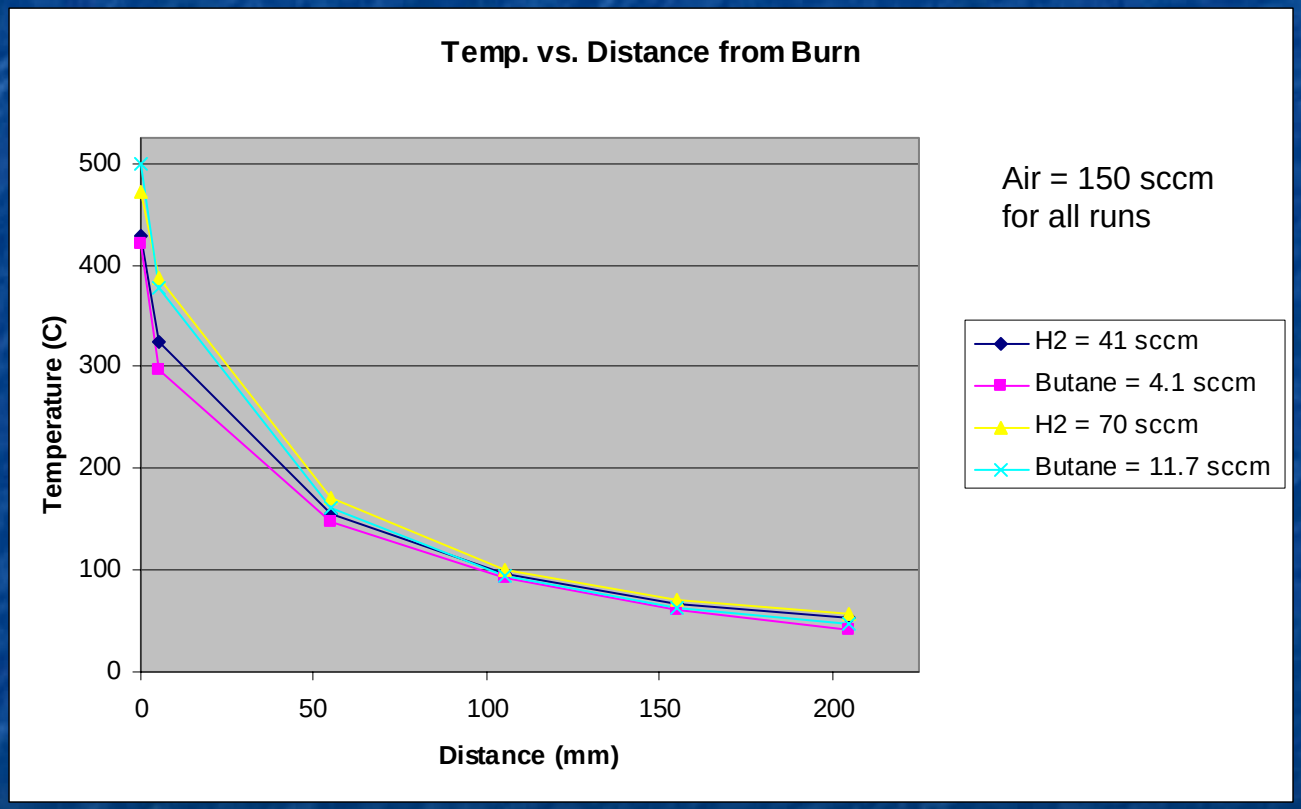
Design Features





Combustor with more compact serpentine heat exchanger

Real Data


Temp. vs. Distance from Burn
Temperature (C)
500
400
300
200
100
0
0
50
100
150
200
Distance (mm)
Air = 150 sccm
for all runs
H2 = 41 sccm
Butane = 4.1 sccm
H2 = 70 sccm
Butane = 11.7 sccm

Design Considerations

Using octane as a representative fuel:

$C_8H_{18} + 12.5\ O_2 + 50\ N_2 == 8\ CO_2 + 9\ H_2O + 50\ N_2$ Enthalpy = 5470.1 kJ/Mole (high heat value)

<u>Heat capacities (Cp in J/Mole K, analytically for T in K):</u>

N2 = 39.96 – 8135/T + 2.1e6/T^2 †

O2 = 48.59 – 540/√T + 3587/T †

CO2 = 68.36 – 15,309/T + 1.836e6/T^2 †

Octane (gas) = 60.77 + .405T (for T>175C) †

Octane (liq.) ≈ 254.6 J/mole K *

H2O (gas) = 83.81 – 1878/√T + 17,583/T †

H2O (liq.) = 75.2 J/mole K *

<u>Heats of vaporization (H_{vap}):</u>

Octane = 41,600 J/mole (at 175C)*

H2O = 40,657 J/mole (at 100C)*

† Marks' Standard Handbook for Mechanical Engineers, 8th Edition, McGraw Hill.

* CRC Handbook of Chemistry and Physics, 80th Edition, CRC Press

Maximum Efficiency

Using Octane and operating at 700K:

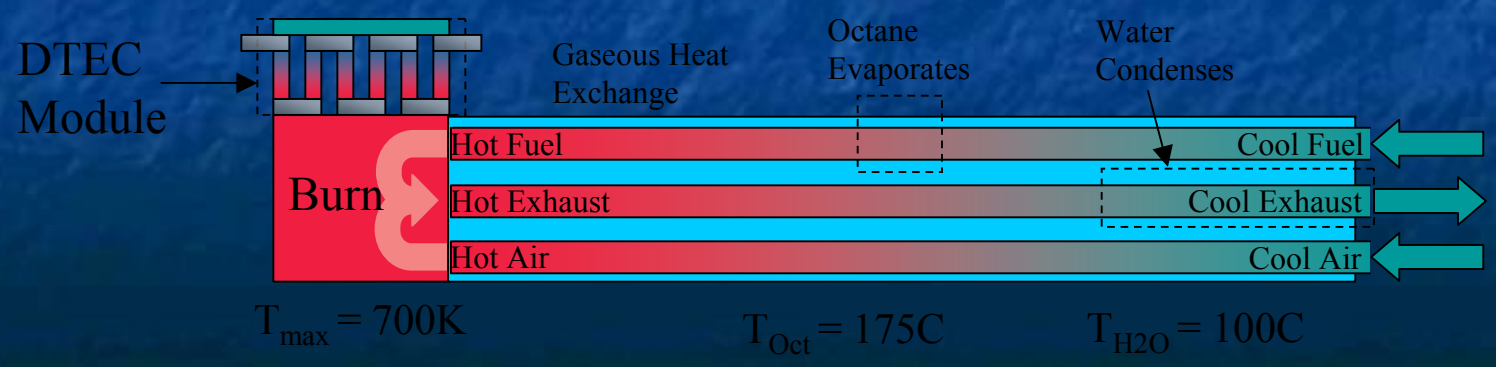
-The integral of the heat capacities over T of the products less that of the reactants yields the total excess heat in the exhaust stream (this can result in an excess or deficiency).

-Integrating between 450K (vaporization temp. of octane) and 700K, we get:
1195 J/Mole excess heat in exhaust gasses.

-This excess is easily absorbed by the vaporization of octane (**41,600 J/Mole**) so some inefficiency in the heat exchanger (a bypass exhaust stream) will need to be incorporated to vaporize the fuel. Between 100C and 175C, the heat capacitance of the inlet and exhaust materials is nearly equal.

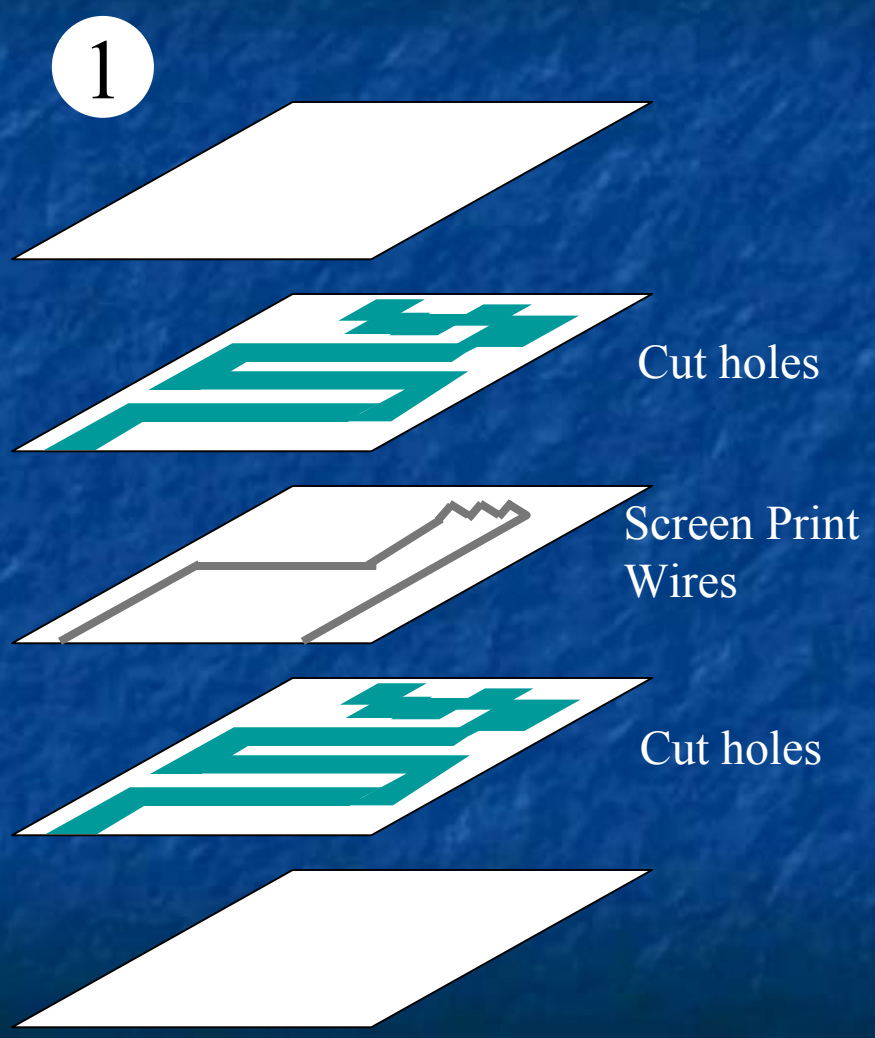
-The limit on the thermal efficiency for this system is the ability of air and fuel to condense only **45%** of the water in the exhaust as its temperature is raised from 25C to 100C.

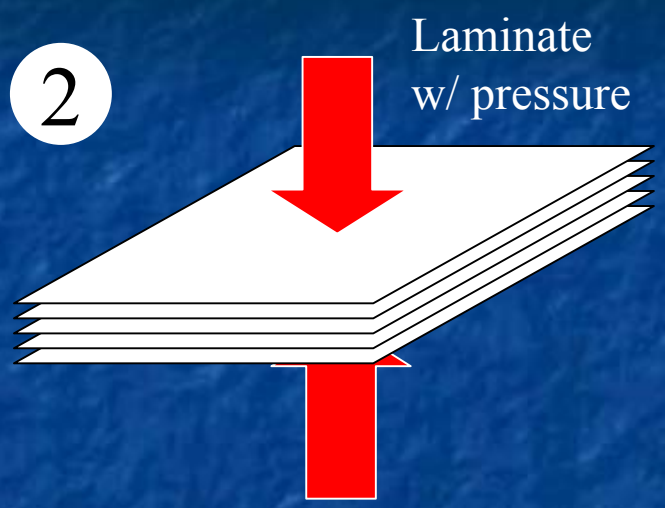
-Using this fact, the total wasted heat in this system is only 7%, making it ideally **93% efficient** at delivering heat to the burn head.

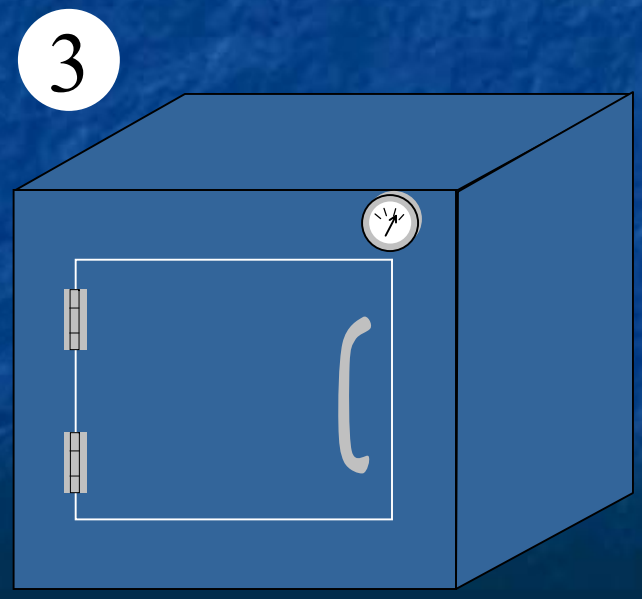


LTCC Technology

(Low Temperature Co-fired Ceramic)







Fire in Oven

Limitations of Current Design

- Requires H2 start
  - Hydrocarbons will not catalytically react at room temperature.
- Excessive backpressure
- LTCC ceramic limited to 600-650C
- Cannot operate on pure Kerosene
- Coking of fuel line when operated at max temps
- No thermal insulation

Next Steps

- Integrate electronic igniter
- Open channels and optimize channel lengths for backpressure reduction
- Create in High Temp Co-fired Ceramic (HTCC) for increased temperature capability
- Integrate vaporization section for liquid fuels
- Modify fuel delivery to eliminate coking for customers wanting >500C
- Develop vacuum envelope and shielding scheme