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Hydrogen Engine Center, Inc.

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Hybrid Power Generation: Combined ICE – Steam System with Double the Fuel-to-Wire Efficiency

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Objectives for Hybrid Power System

- Recover waste heat and convert it to electricity at a minimum of 60% fuel-to-wire efficiency;
- Be cost competitive with bulk power plants;
- Reduce emissions & increase efficiency:
  - ½ the fuel for a given power level means ½ the emissions.
- Produce an ICE-Steam hybrid system that will operate on any known fuel (liquid, gaseous or alcohol-particulate mix).

First Hybrid System Building Block: ICE

- An internal combustion engine (ICE) is the basic building block.
- Coupled to a generator, the ICE provides 50% of the electrical power for the combined/hybrid cycle system.
- ICE efficiency for NH_3 is between 36% - 38%.
- Generator is 92%-94% efficient.
- Overall fuel-to-wire electric production efficiency for ICE component is between 33.1% -35.7% and is proven technology.

Second Hybrid Building Block: Steam

- Typical engine energy lost is between 62% - 64%.
- Using 63% as the average loss :
  - Radiated losses = 4%
  - Coolant losses = 18%
  - Exhaust losses = 41%
- The steam building block takes the 18% coolant loss and 41% exhaust loss to make high-temperature steam which is then converted to electrical power.

Second Hybrid Building Block – Steam 2

- 70% - 80% of waste ICE heat produces steam.
- Steam is converted to electricity by a micro-steam turbine or reciprocating steam engine.
- Steam conversion to electricity is about 80% efficient using a micro-turbine.
- 10% losses in the steam delivery system allows conversion at approximately 70% efficiency.

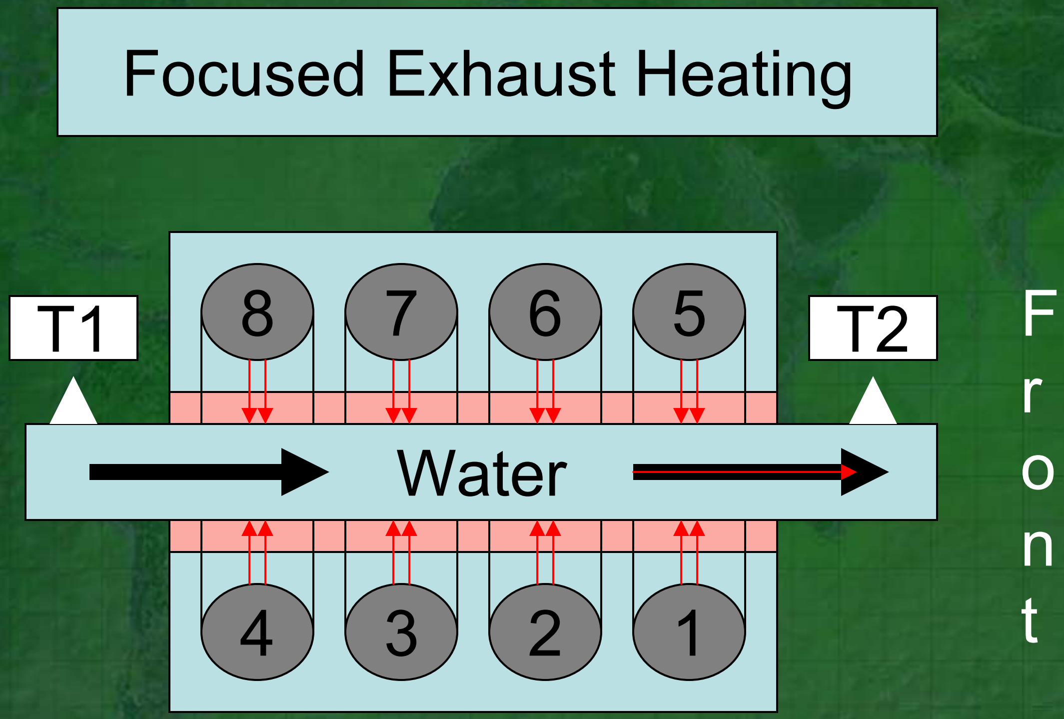
Second Hybrid Building Block – Steam 3

- 70% heat recovery + 70% steam-driven generator efficiency allows 49% recovery of heat losses as electricity:
  - 49% times 59% = 28.9%.
- Combining steam-powered electrical generation (28.9%) with ICE generation (33.1% to 35.7%) results in ***combined/hybrid system fuel-to-wire efficiency of 62% to 64.6%.***

New HEC Technology Engine

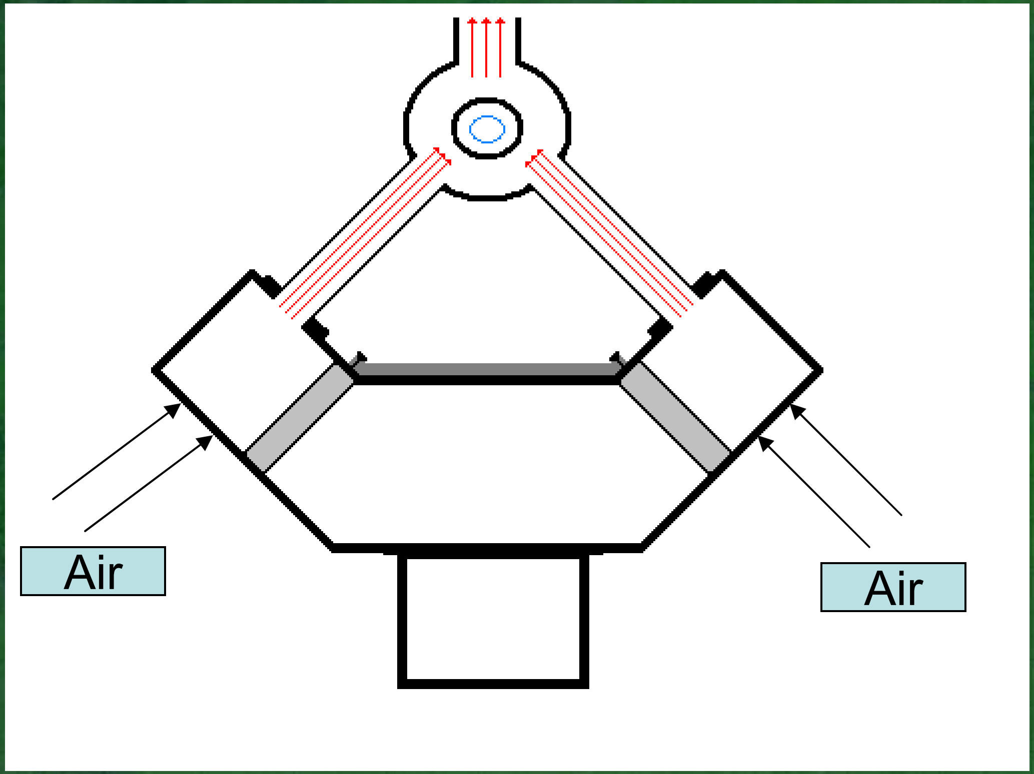
- A new ***reverse flow engine (RFE)*** has been built and tested successfully.
- ***RFE*** focuses the exhaust for maximum heating and best combined heat and power efficiency.
- The ***RFE*** technology is applicable to all V-shaped engines, spark-ignited or combustion-ignited (diesel)
- **Patent Filed 5/29/13**

Focused Exhaust Diagram for Combined Heat and Power



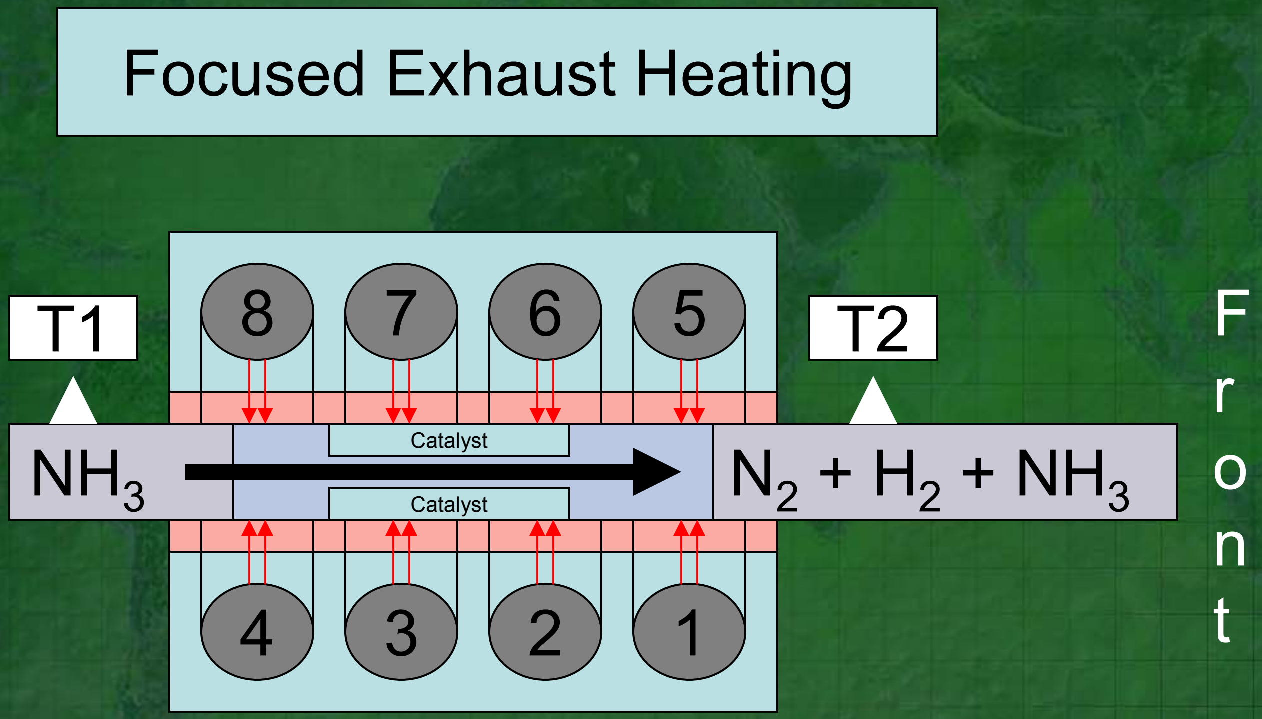
Output temperature controlled by flow rate

Focused Exhaust Diagram for Combined Heat and Power



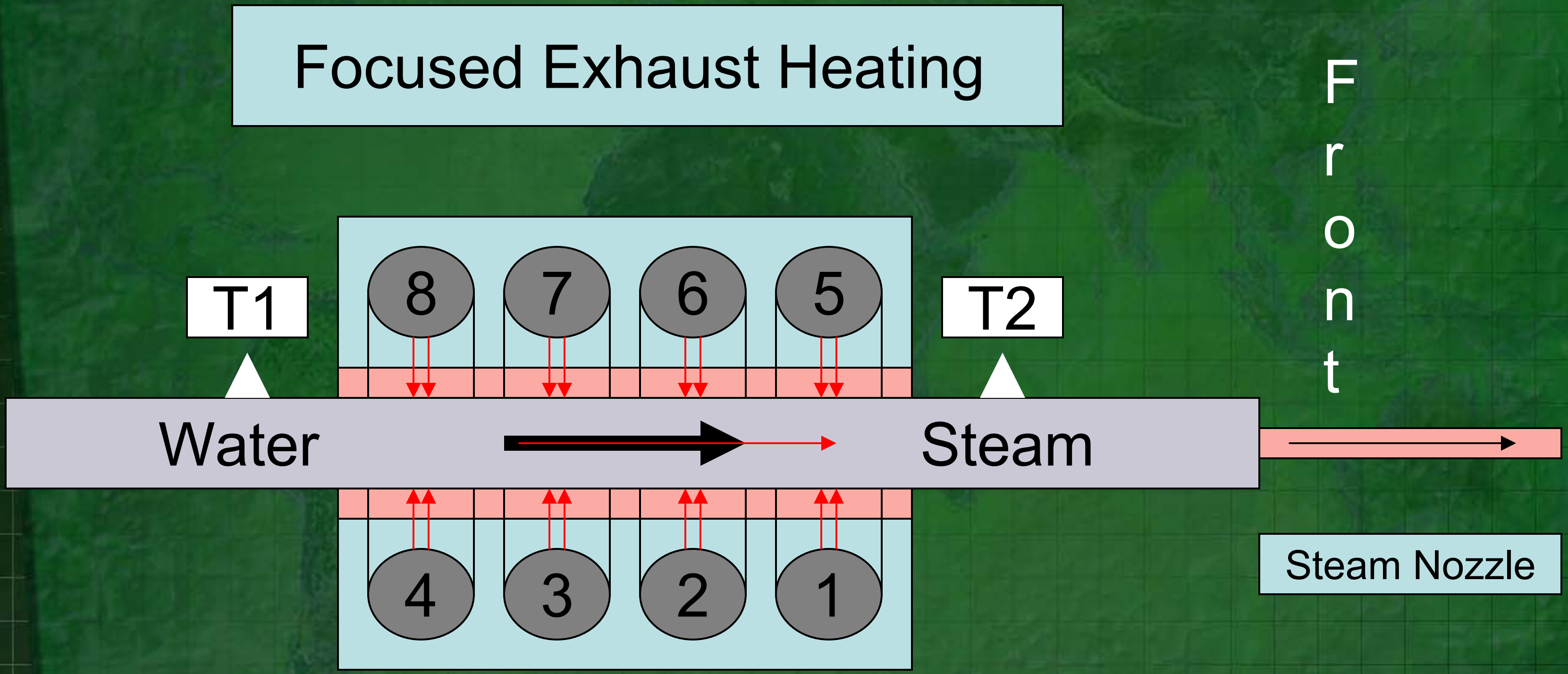
End view showing exhaust heat flow

Focused Exhaust Diagram for Ammonia Cracking



NH_3 % is controlled by flow rate & temperature.
A special catalyst is used in the process.

Focused Exhaust Diagram for Steam Generation

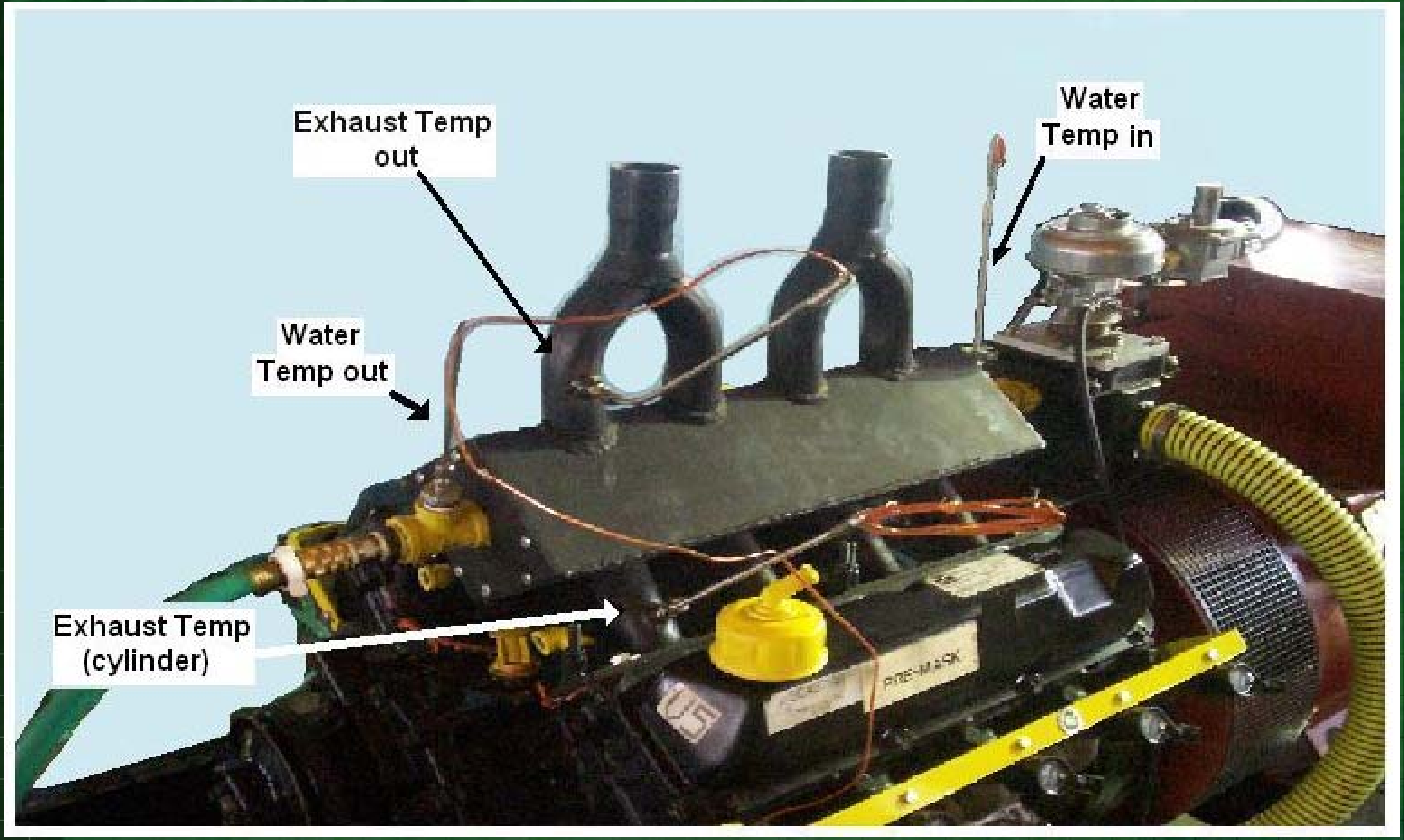


Steam created from (recirculating) water and exhaust heat

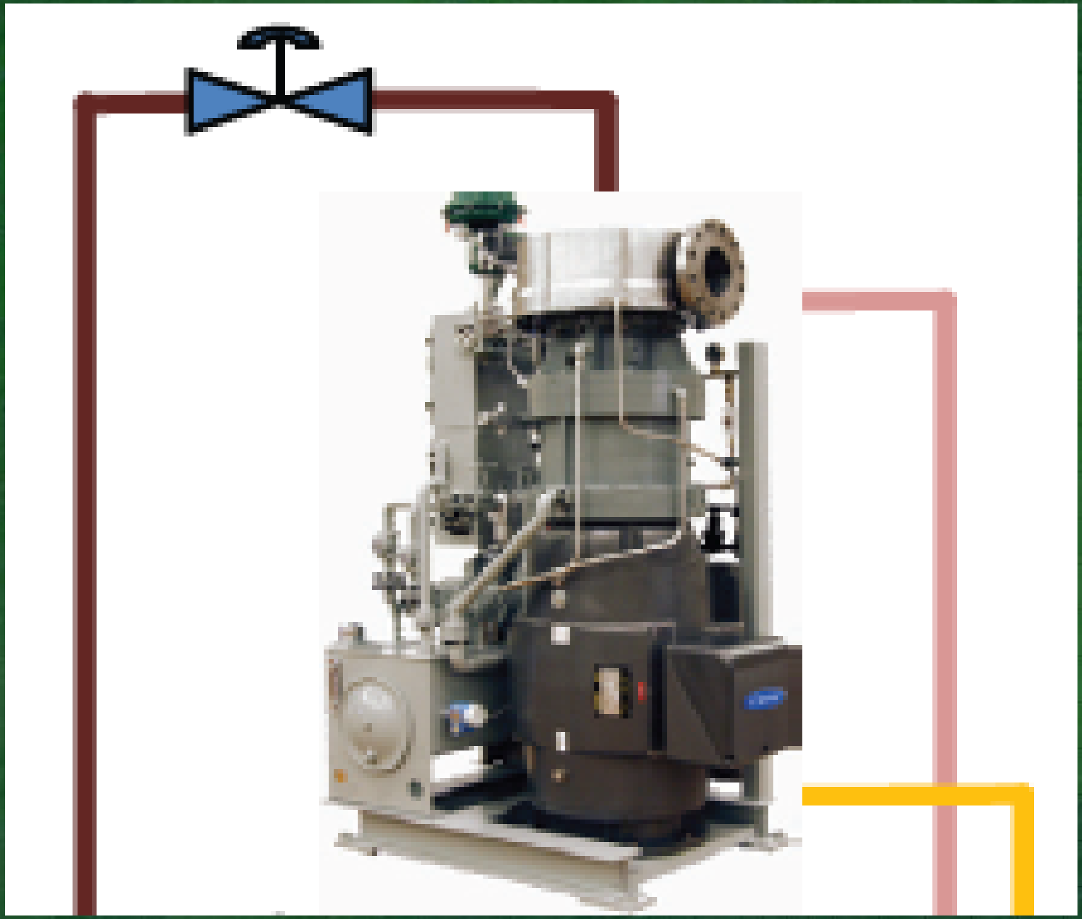
Patent Description of Focused-exhaust Engine

- “A focused-exhaust engine … where the plane of the exhaust gases from one head intersect the plane of the exhaust gases from the other head and a maximum heat (temperature) is obtained at that intersection.”

Picture of 1st Reverse Flow Engine



Carrier Microsteam Turbine 78% efficient



Heat Recovery

- The British thermal unit (**BTU** or **Btu**) is a traditional unit of **energy** equal to about 1,055 joules.
- It is the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit.
- Water flow rate (gallons/min.) * 8.34 pounds/gallon * (Output temperature [F] – Input temperature [F]) = ***Recovered BTUs***

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Heat Recovery Table for 460 (7.5L)

Rec. %	Air in FT^3/min	Exhaust F	Exhaust BTUS	Exhaust KW	Tons AC	Exhaust Tout
100	479	1200	620784	182	51.7	0
90	479	1200	558706	163	46.6	120
80	479	1200	496627	145	41.4	240
70	479	1200	434549	127	36.2	360
60	479	1200	372470	109	31.0	480
50	479	1200	310392	91	25.9	600
40	479	1200	248314	73	20.7	720
30	479	1200	186235	54	15.5	780
25	479	1200	155196	45	12.9	840
20	479	1200	124157	36	10.3	960
10	479	1200	62078	18	5.2	1080

Heat Recovery Table for 572 (9.4L)

Rec. %	Air in Ft³	Exhaust F	Exhaust BTUS	Exhaust KW	Tons AC	Exhaust Tout
100	696	1200	902016	264	75.2	0
90	696	1200	811814	237	67.7	120
80	696	1200	721613	211	60.1	240
70	696	1200	631411	185	52.6	360
60	696	1200	541210	158	45.1	480
50	696	1200	451008	132	37.6	600
40	696	1200	360806	105	30.1	720
30	696	1200	270605	79	22.6	780
25	696	1200	225504	66	18.8	840
20	696	1200	180403	53	15.0	960
10	696	1200	90202	26	7.5	1080

Heat Recovery

- Exhaust flow rate is determined by engine speed and engine load:
  - It can be derived from the engine controller data.
- Cylinder exhaust temperature x exhaust flow can be used to determine the maximum energy that can be recovered.
- Exhaust temperature out x exhaust flow can be used to determine the lost energy that was not recovered.

Heat Recovery

- (Maximum Energy – Lost Energy) / Maximum Energy = Maximum Efficiency as a percentage.
- (Maximum Energy – Lost Energy – Recovered Energy) = heat lost in the manifold.

Testing Objective Summary

- Using a 1-inch black iron pipe, HEC intends to establish a base line for all heat recovery systems.
- This is the simplest and least effective of all recovery systems.
- It will be used to determine the effectiveness of all other systems by being the baseline to which all other systems will be compared.

Testing Expected Results

- Using a 460 cubic inch engine at 3,600 rpm, we can expect an intake air flow rate of:
  - 57.5 in^3/cylinder * 8 cylinders * 1 intake per 2 revolutions * revolutions/minute = intake volume
  - 57.5 x 8 x .5 x 3,600 cu. inches per minute = 828k cu. inches = 479 ft^3 /minute

Exhaust Gas Flow Calculation

- Exhaust flow rate may be calculated using the following formulae:
  - [Exhaust Temperature (ºF) + 460] / 540] x Intake Airflow (CFM) = Exhaust Flow (CFM)
  - (1,200 F +460) / 540 x 479 = 1,660 / 540 x 479 = 3.07 x 479 = 1,472 cubic feet per minute

Exhaust Energy Calculation

- BTUH / 1.08 * ΔT = CFM
  - 4,791.08 * 1200 = 620,784 BTU
  - 620k BTU = 180 kW = 51.7 tons of AC
  - At 20% recovery = 10.3 tons of AC
  - Gives 960^{o}F Exhaust Out Temperature
  - At 25% recovery = 12.9 tons of AC
  - Gives 84 ^{o}F Exhaust Out Temperature

Air Conditioning Definitions

Cooling Load in - *kW/ton*

- The term ***kW/ton*** is commonly used for larger commercial and industrial air-conditioning, heat pump and refrigeration systems.
- The term is defined as the ratio of energy consumption in *kW* to the rate of heat removal in *tons* at the rated condition. The lower the *kW/ton* the more efficient the system.
- ***kW/ton* = Pc / Er** where:
  - Pc = energy consumption (kW)
  - Er = heat removed (ton)

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Air Conditioning Definitions

Coefficient of Performance - *COP*

- Coefficient of Performance (***COP***) is the basic parameter used to report efficiency of refrigerant-based systems.
- ***COP*** is the ratio between useful energy acquired and energy applied and can be expressed as

  COP = Eu / Ea *where:*

  - COP = coefficient of performance
  - Eu = useful energy acquired (btu in imperial units)
  - Ea = energy applied (btu in imperial units)

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Typical Air Conditioning Specifications

- Coefficient of Performance or COP = 3.5
- COP of 3.5 means that for 1 ton of air conditioning, one needs 3.5 tons equivalent of electrical power.
- COP of 3.5 would give an efficiency of 28.6%
- Therefore, it would take 3.5 * 3,517 watts to produce 1 ton of AC = 12.3 kW.

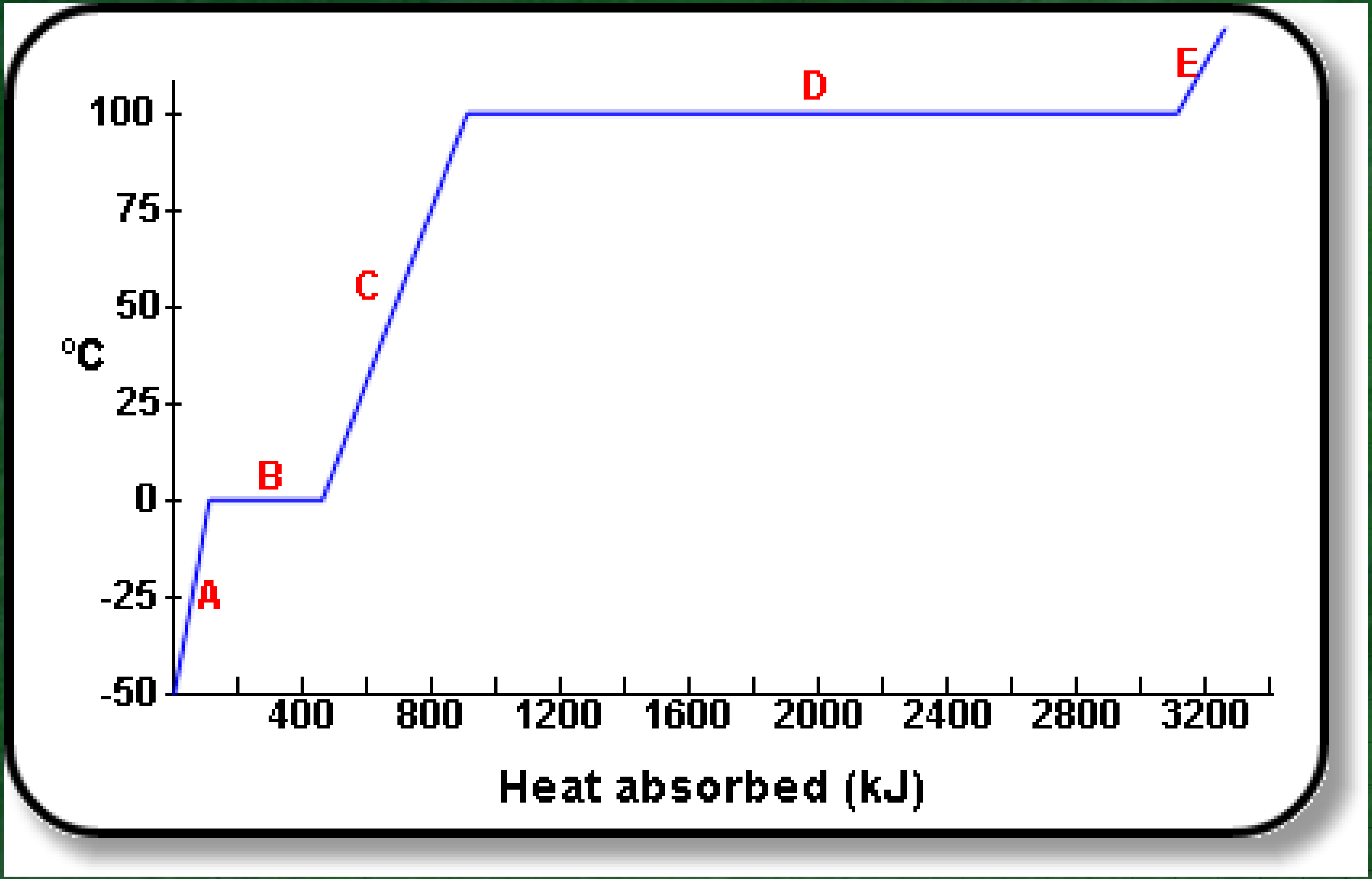
Typical Air Conditioning Specifications

- At 12.3 kW/ton, a 9.4L engine should produce 37.6 tons of AC and reduce the electrical requirement by 463 kW.
- This means that a 9.4L engine operating on either natural gas or propane can produce 250 kW of electrical power and reduce the incoming power requirement by an additional 463 kW for a total of 713 kW.

Exhaust Energy Calculation

- BTUH / 1.08 x ΔT = CFM
  - ➢ 479 * 1.08 * 1200 = 620,784 BTU
  - ➢ 620k BTU = 180 kW = 51.7 tons of AC
  - ➢ At 40% recovery = 20.6 tons of AC
  - ➢ Gives 720 F Exhaust out temperature
  - ➢ At 50% recovery = 25.8 tons of AC
  - Gives 600º F Exhaust Out temperature

Heat of Evaporation of Water



Uptake of heat by 1 kg of water, as it passes from ice at -50 ºC to steam at temperatures above 100 ºC

Heat of Evaporation of Water

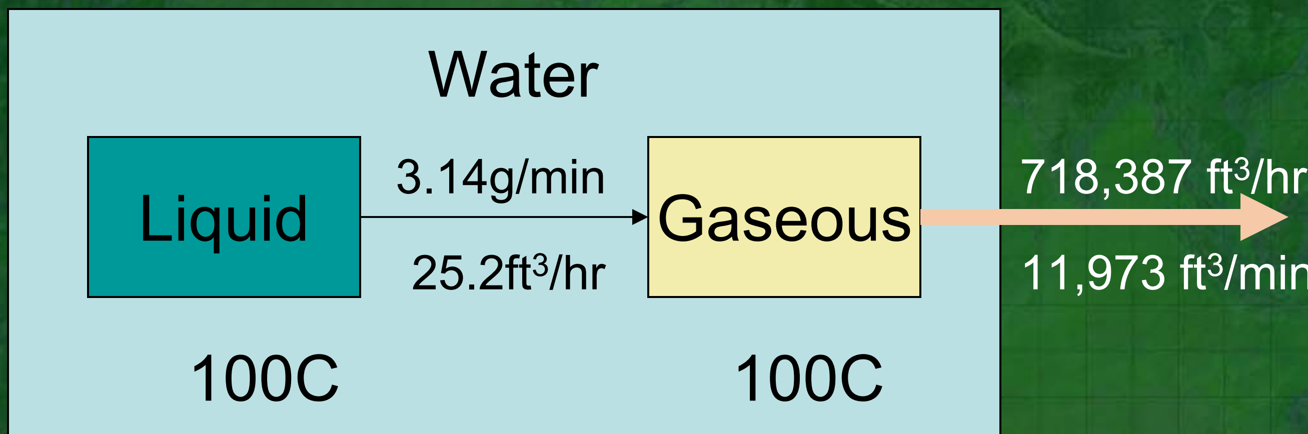
- The diagram on the previous slide shows the uptake of heat by 1 kg of water, as it passes from ice at -50 ºC to steam at temperatures above 100 ºC, affecting the temperature of the sample.

- **A**: Rise in temperature as ice absorbs heat.
- **B**: Absorption of latent heat of fusion.
- **C**: Rise in temperature as liquid water absorbs heat.
- **D**: Water boils and absorbs latent heat of vaporization.
- **E**: Steam absorbs heat and increases its temperature.

Zone D: Liquid to Gaseous Water (Steam)

Liquid to Gaseous Conversion (evaporation)

At 212°F, 14.7 psia, liquid water has a specific volume of 0.016716 ft3/lbm and steam has a specific volume of 26.80 3/lbm, which is a volume ratio of ~1603 : 1 of steam : water.



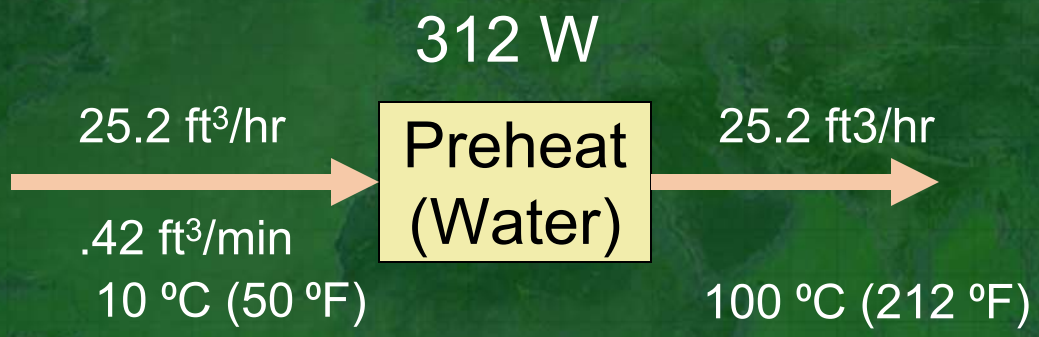
188 gal/hr ∗ 8.35 lb/gal ∗ 972 btu/lb ∗ kW hr/3412 btu = 448kW

188 gal/hr ∗ 231 in^3/gal x ft^3/1728 in^3 = 25.2 ft^3/hr

25.2 ft^3/hr ∗ 1603 = 718,387 ft^3/hr = 11,973 ft^3/min

Zone C: Water Heating

Heating of 3.14 gallons of water per minute:

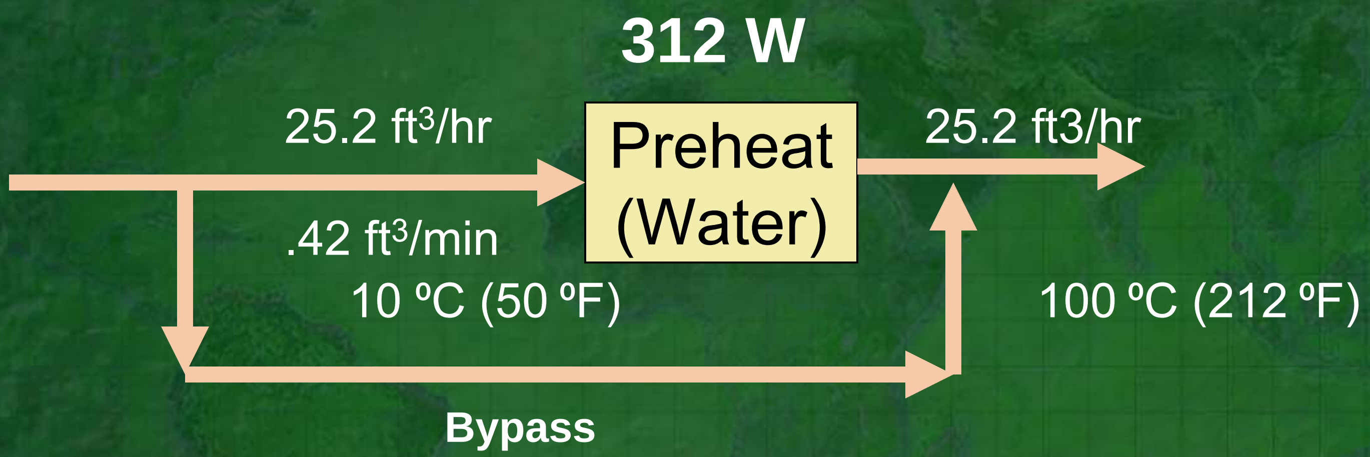


3.14g/min ∗ 60 ft^3min/7.48 g hr =25.2 ft^3/hr

25.2 ft^3/hr ∗ 62.4 lb/ft^3 ∗ 172F =270 kBTU/hr = 73.9 kW

Zone C: Water Pre-heating

Heating of 3.14 gallons of water per minute by use of engine liquid cooling system:



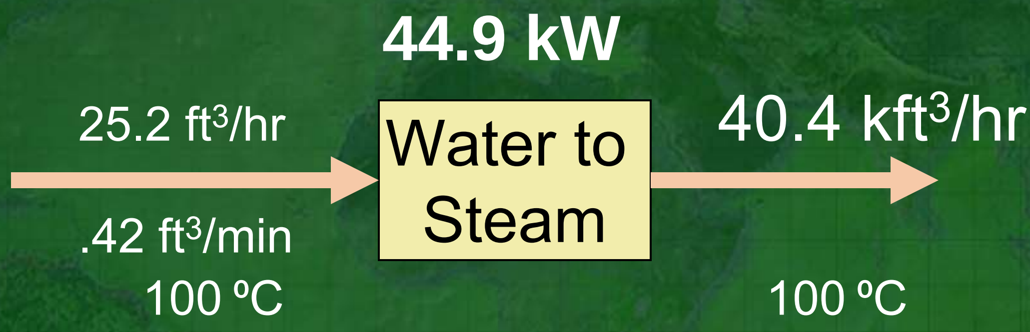
3.14g/min ⁎ 60 ft3min/7.48g hr = 25.2 ft3/hr

25.2 ft^3/hr ⁎ 62.4 lb/ft^3 ⁎ 172F =270 kBTU/hr = 73.9 kW

Zone D: Water Heating

Evaporating of 3.14 gallons of water per min

Requires 2,260 J/g or 97.4 BTU/lb



$25.2\ ft^3/hr * 62.4\ lb/ft^3 * 97.4\ BTU/lb = 153\ kBTU/hr =$

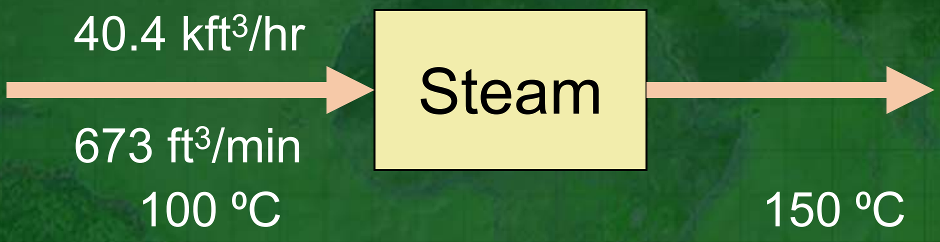
44.9 kW

Zone E: Steam Heating

Heating of 1,572 lb/hr per minute

Requires 45.24 BTU/lb

20.8 kW



1.572 lb/hr * 45.24 BTU/lb = 71.1 kBTU/hr =

20.8 kW

Thank You!

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