heat2power

Waste Heat Regeneration

A technology overview and its potential in racing applications

Professional Motorsport World – November 6th 2007 – Köln

Randolph Toom – Managing director

Agenda

1. Introduction to heat2power SARL
2. Engine power flows
3. Scope of the technology
4. Power flows in the exhaust
5. Engine efficiency
6. Waste heat regeneration : What for?
7. Overview of regeneration technologies
8. Why WHR is to be introduced
9. Introduction of WHR in racing
10. Choosing the right principle
11. The heat2power principle
12. Company profile
13. WHR benchmark study
14. Contact information

Introduction – the company

heat2power SARL is based in Paris – France.

Founded in 2007 by Frédéric Thévenod and Randolph Toom.

Core business : Waste Heat Regeneration technologies

Development started in 2003 – 4 years of WHR benchmarking with focus on automotive applications

Main focus : Getting the best of waste heat regeneration in exhaust systems of

- Trucks
- Boats
- Automobiles
- Power generation

First in-house concept : combines high power density with good efficiency

Patented September 2006

Conceived for industrialization in the automotive environment

Makes use of commonly applied powertrain components

Also suitable for motorsports applications

Introduction – the concept

heat2power concept combines properties to make it an excellent partner for internal combustion engines in vehicle applications:

- Independent of fuel type (gasoline, diesel, gas, hydrogen, ethanol or biofuels)
- Independent of combustion process
- Fully compatible and complementary for application in a hybrid powertrain
- High specific power (volume & weight)
- High level of efficiency
- Operates in range of exhaust temperatures
- No use exotic materials
- System built with conventional components and technologies

For **mainstream** production vehicles **heat2power** means

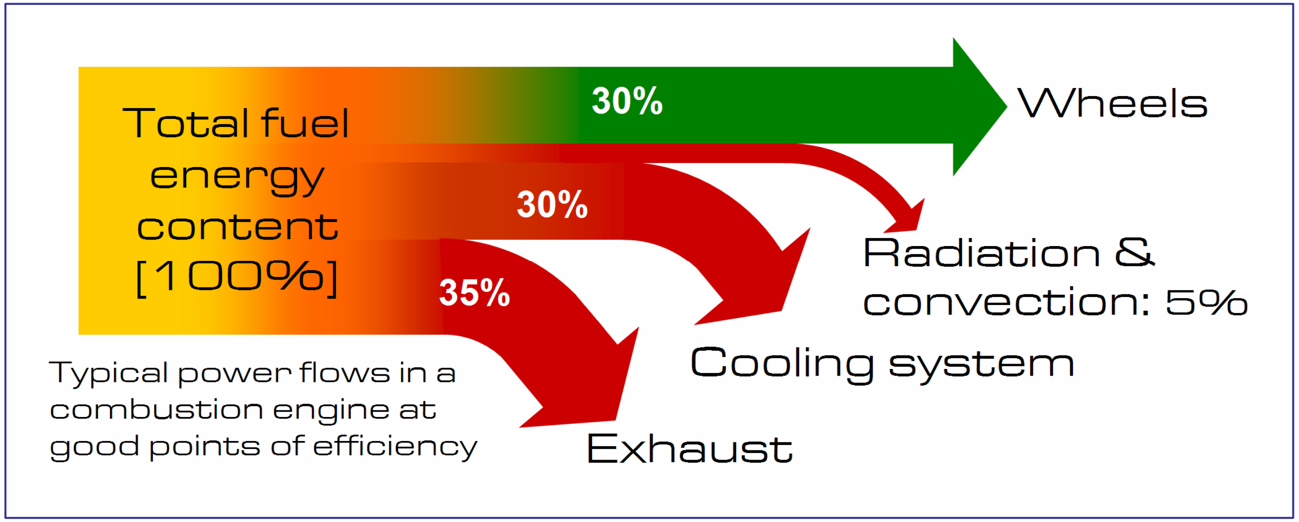
BETTER FUEL ECONOMY AT REASONABLE COST

For **racing** applications **heat2power** means

EXTRA POWER & BETTER FUEL ECONOMY AT REASONABLE EXTRA WEIGHT

Engine power flows

Examining the power flows shows that the exhaust has a big potential because of amount of lost power



Source : Slater, GM workshop DARPA/ONR 2002

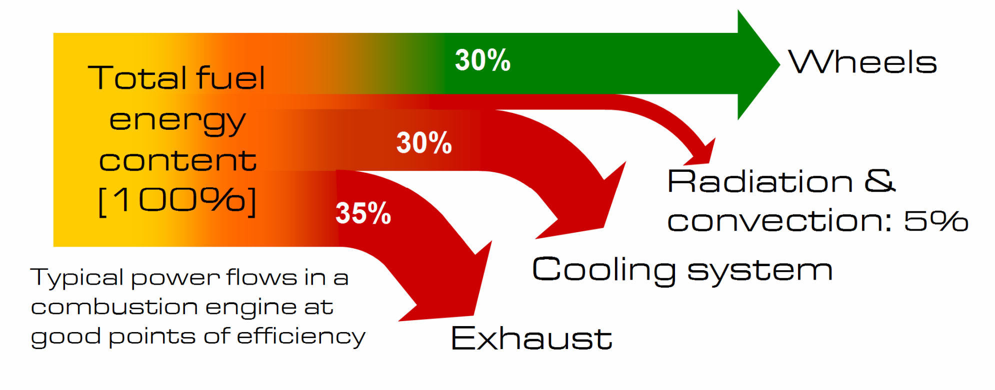
Scope of WHR Technology

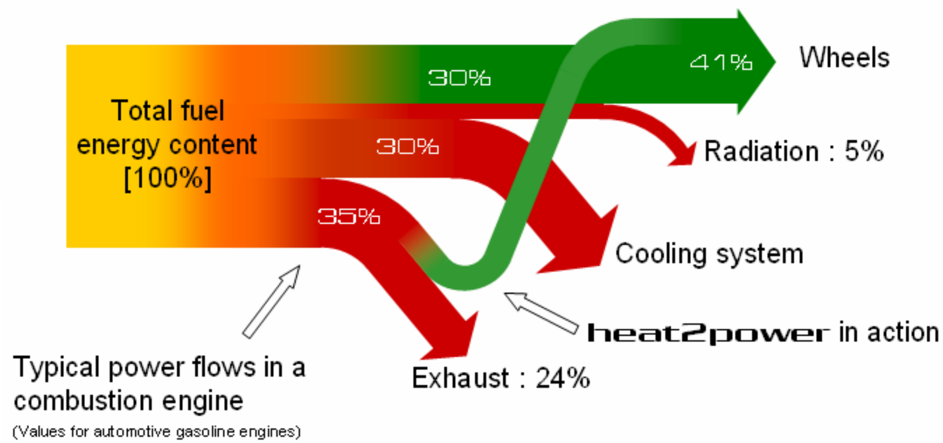
The scope of waste heat regeneration is to use the heat that is normally thrown away into the atmosphere in a dedicated machine in order to transform it into a usable form of energy.

Usually this is the same form of energy that is generated by the machine that also generates the waste heat but this is not always an absolute requirement.

The goal is the reduction of the speed of consumption of primary energy.

heat2power SARL has invented a system for regenerating heat directly into torque and claims to be able to achieve this with a high specific power and high degree of efficiency.





Power flows in the exhaust

What power flows exist in and ICE's exhaust ?

1. Thermal power flow
2. Kinetic power flow
3. Chemical power flow (non-combusted HC, CO, Soot)
4. Upper latent heat flow

The heat flow to the cooling system is outside of the scope of this presentation

Power flows in the exhaust

What power flows exist in and ICE's exhaust ?

BIG	**1.**	**Thermal power flow**
BIG	**2.**	**Kinetic power flow**
SMALL	3.	Chemical power flow (non-combusted HC, CO, Soot)
SMALL	4.	Upper latent heat flow

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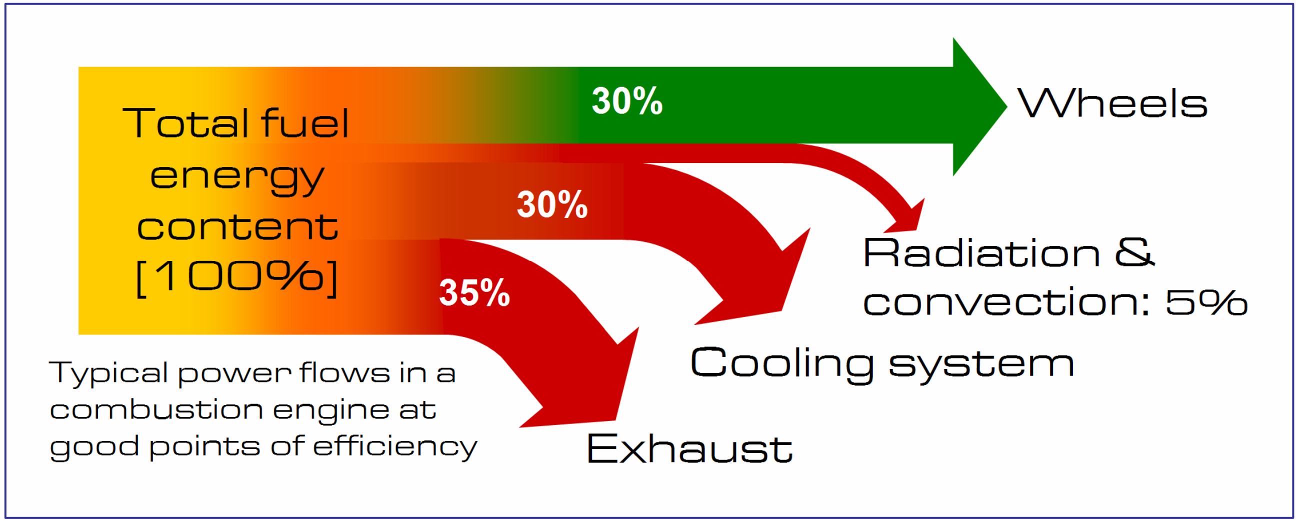
Engine Efficiency…

So this is the (near) optimal condition…



Engine Efficiency…

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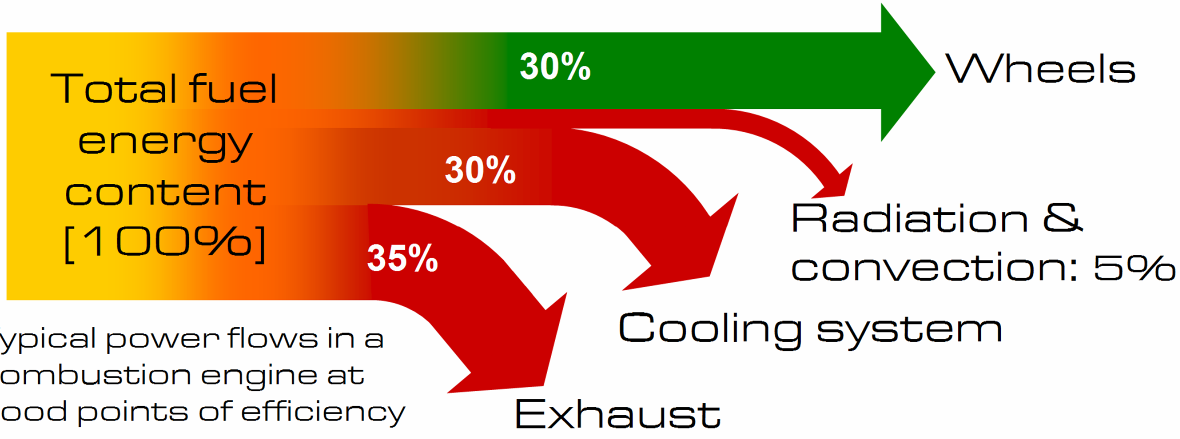
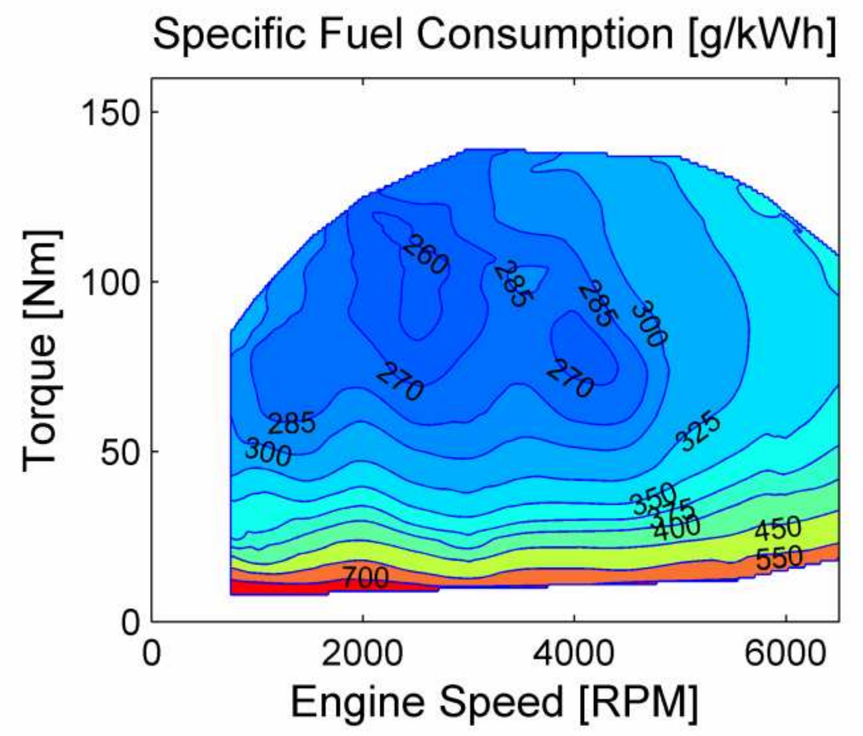


Typical power flows in a combustion engine at good points of efficiency

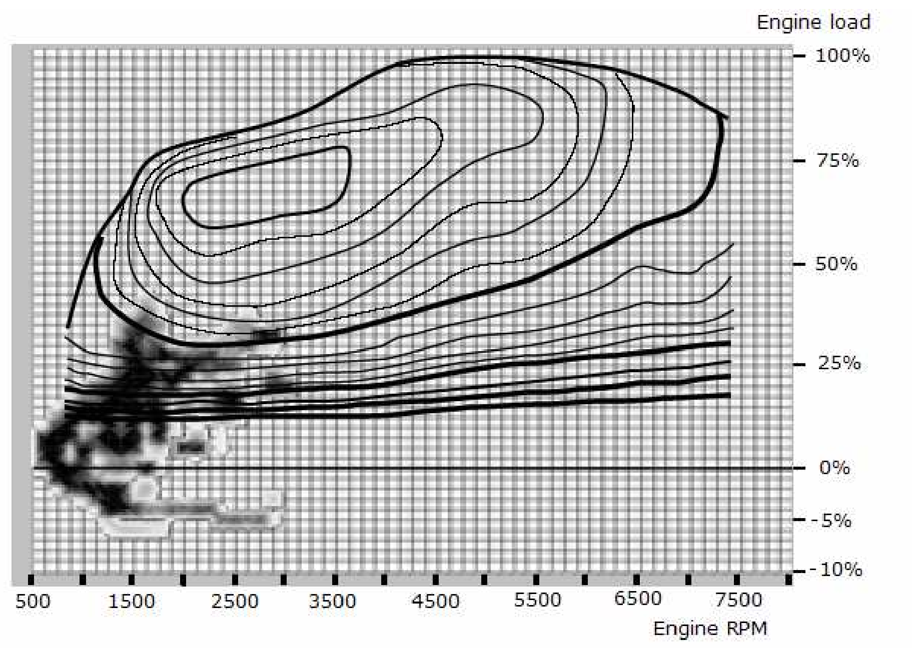
But what about the real life situation ?

Engine Efficiency...

The real life situation is different !



A typical mainstream European 1.6 liter gasoline engine



Residency plot of an 3.6 l engine on NEDC cycle with 6-speed AT.

(Source: Porsche, 2004 VDI congress)

Engine Efficiency...

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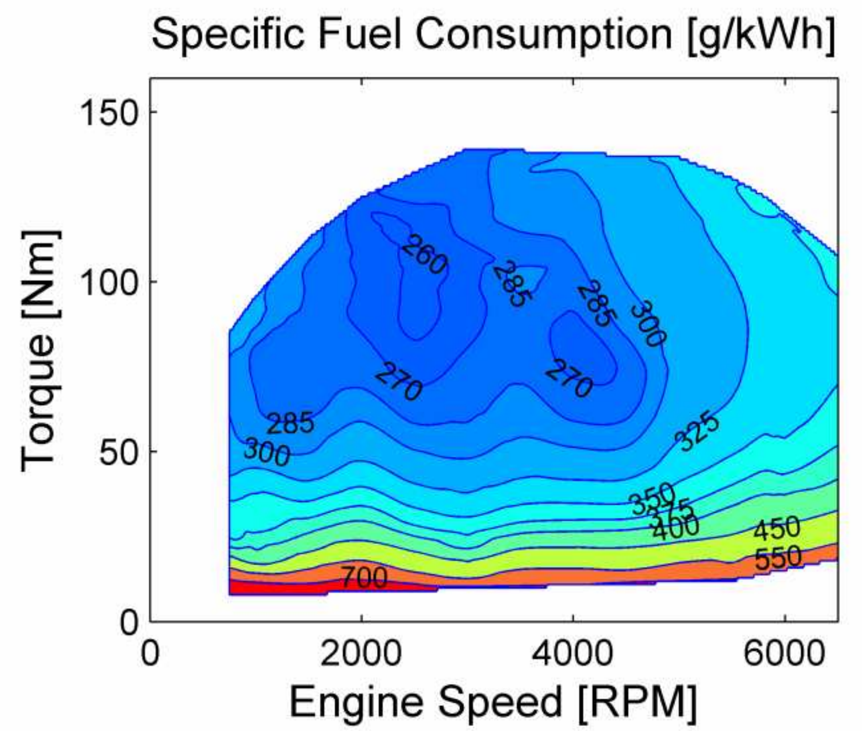

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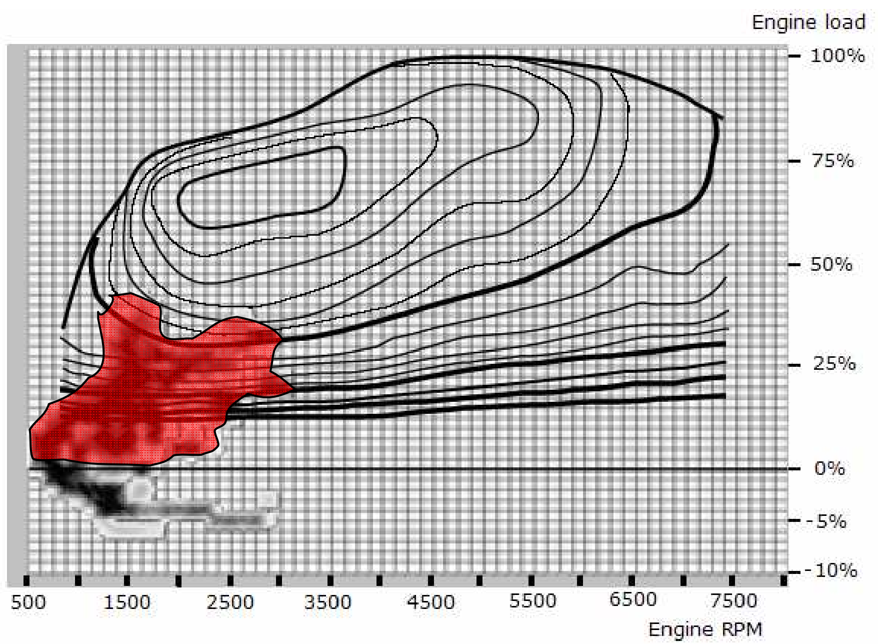

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Engine Efficiency…

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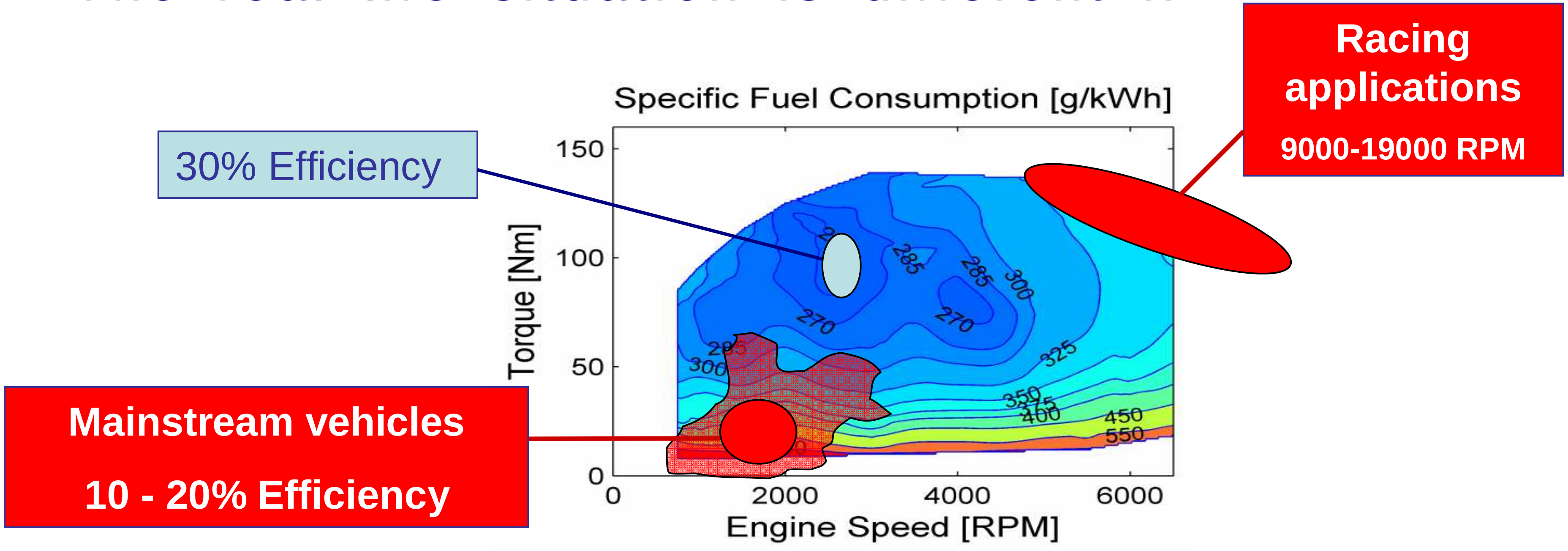
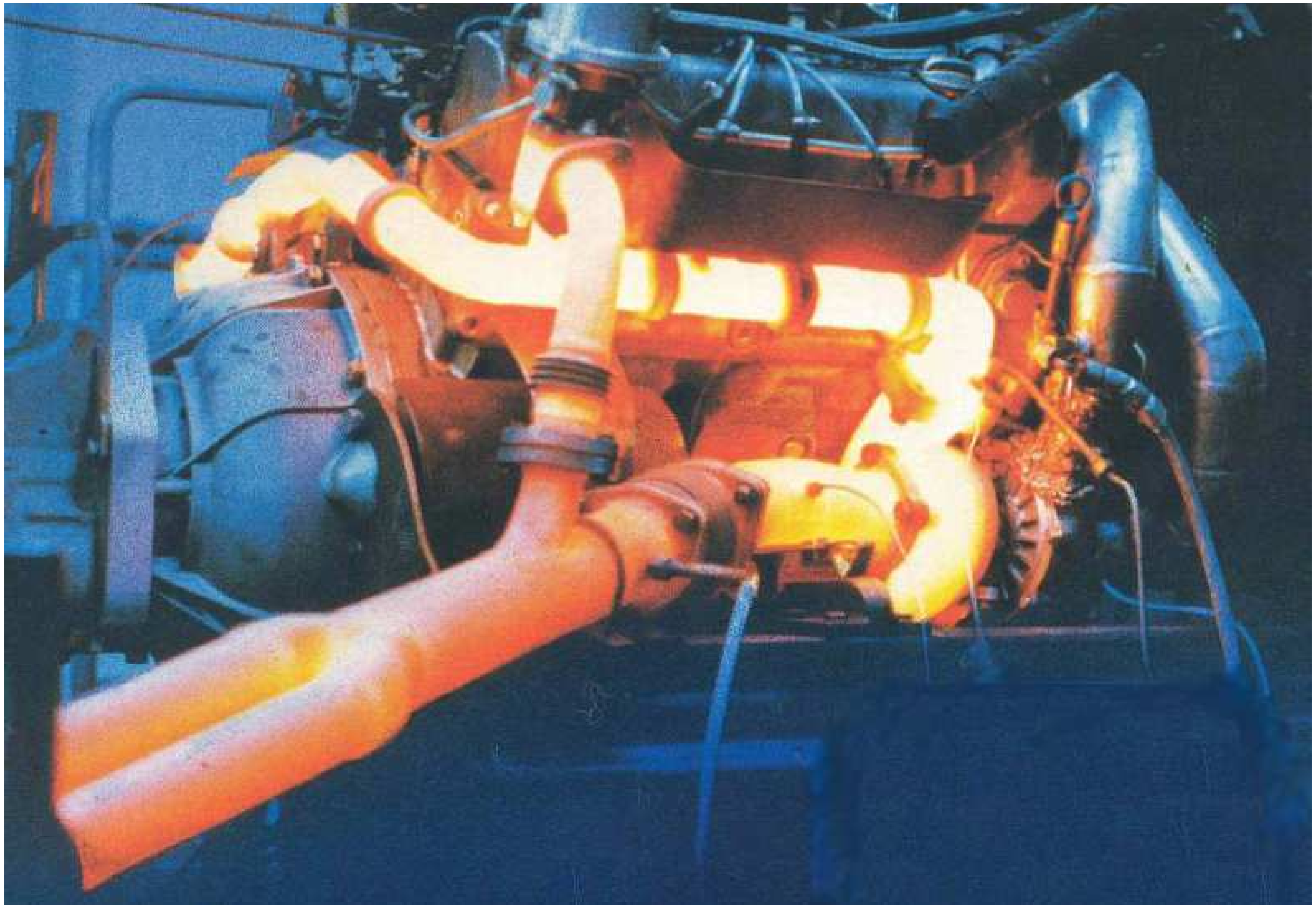


80 - 90% is LOST

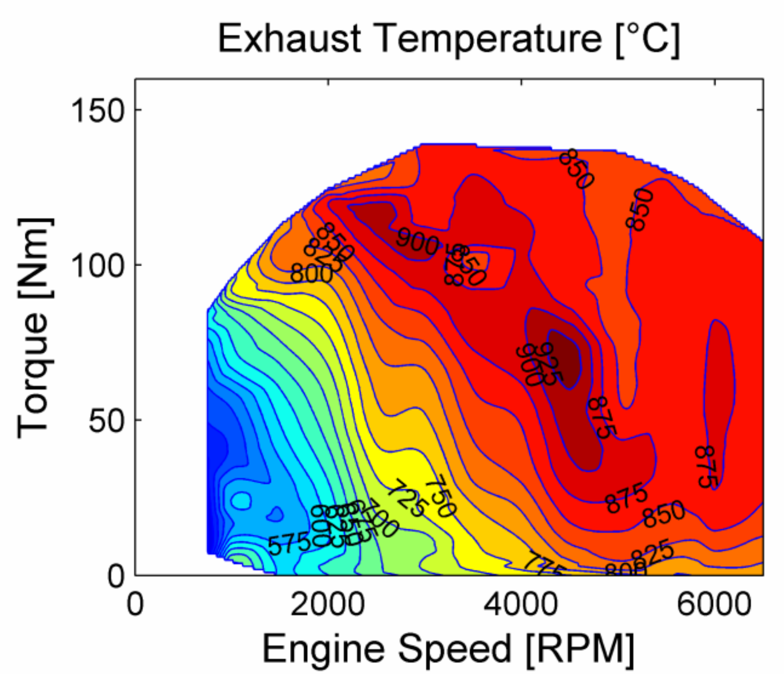
A big part of these 80 - 90% goes to the exhaust → **WHR makes sense**

Waste heat flow impression



Where the waste heat goes

Analysis of waste power flow and waste heat flow in the exhaust was conducted on a bench with a standard European 1600 cc gasoline engine. The measurements concerned temperatures, pressures, mass flows for a big number of torques and RPM. Following graph shows results of these measurements.



Measured after catalyst, values including +50℃ for potential with thermal insulation.

Example of exhaust of "mainstream" vehicle

In Formula 1 : Typical 500kW on crankshaft and 800 kW lost in exhaust @ 900℃ +.

Where the waste heat goes

The waste heat that goes to the IC-engine cooling system is about as important as the waste heat that goes to the exhaust.

This heat flow however is of low temperature

↓

The potential to exploit this is small.

↓

This power flow is not the subject of this presentation.

Waste Heat Regeneration

Several industries already apply WHR technologies, some even to a large extend and with high power outputs :

- Steel furnaces
- Cement factories
- Nuclear power plants
- Process industry (Refineries, Methanol plants, Sulphuric acid plants and other)
- Internal combustion engines (Turbo-charging, interior heating)
- Housing (Heatwheels, heatpumps, high efficiency boilers)
- Solar power plants (Heat is actually not waste but prime energy source)
- Geothermal power plants (Heat is the prime source as well)
- Desalination plants
- Glass ovens …

How to regenerate the power?

Waste heat regeneration , what for?

Mainstream vehicles :

- **Better fuel economy obtained from extra crankshaft power combined with a downsized engine**

Racing applications :

- **Extra crankshaft power for easier overtaking**
- **More laps before refueling thanks to a better fuel economy**

How to regenerate the power?

Waste heat regeneration based on power flows

1. **Thermal power flow**
2. **Kinetic power flow**
3. **Chemical power flow (non-combusted HC, CO, Soot)**
4. **Upper latent heat flow**

How to regenerate the power?

Converting the thermal power flow into another but desired power flow

Thermo-dynamics (to obtain mechanical power)

- Stirling engine
- Rankine cycle (steam or organic)
- Ericsson cycle
- Proe Afterburning cycle

Thermo-electric (to obtain electrical power)

- Seebeck effect
- Lithium-hydride cycle
- Thermo-photo-voltaic
- Thermo-ionic emission
- Thermo-tunneling

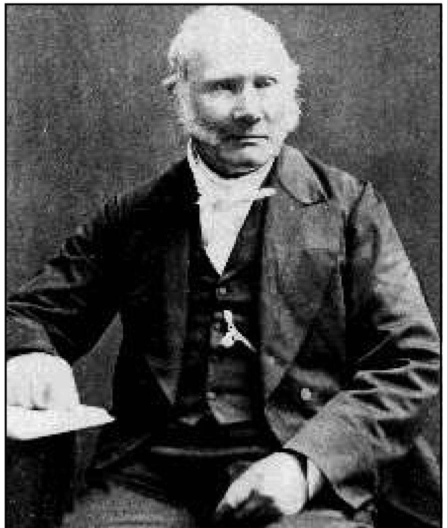
Thermo-chemical (to obtain chemical power)

- Endothermic vapo-cracking (H_2 generator)
- Autothermic fuel reforming (H_2 generator)
- MIT – Plasmatron (H_2 generator)
- Phase Transition (keep Catalyst hot longer)

Thermo-acoustics (to obtain mechanical power)

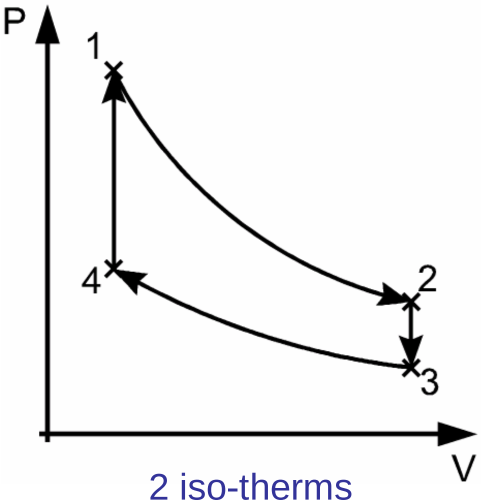
How to regenerate the power?

Stirling cycle



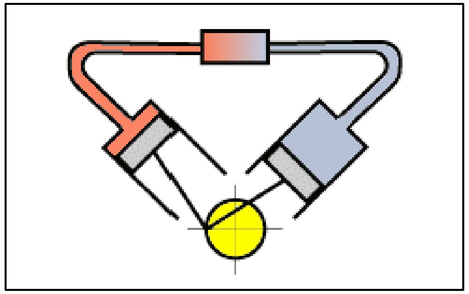
First patent in the year 1816 by Robert Stirling

- Engine with external combustion invented because of many explosions of pressure tanks of steam engines at the time.
- Much used in industry and farming until 1920's.
- Later versions worked with higher pressures of hydrogen or helium.
- Good performances were obtained for example with USAB 4-275 engine with 50 kW and 42 % global efficiency
- Stirling engines lost interest with increased performances of IC engines

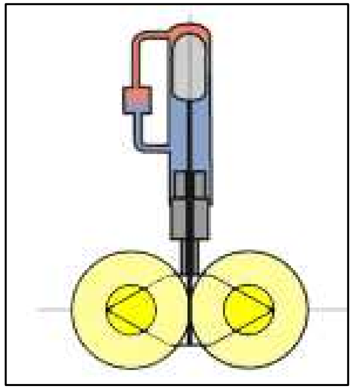


2 iso-therms

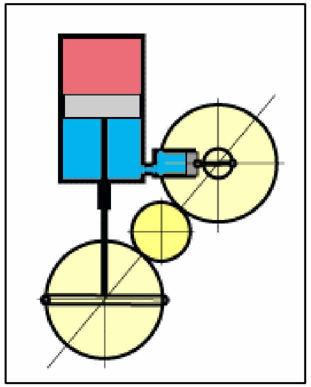
2 iso-volumes



α - type



β - type



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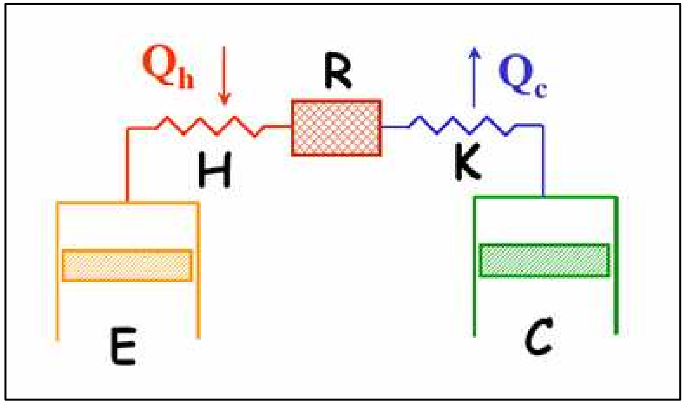
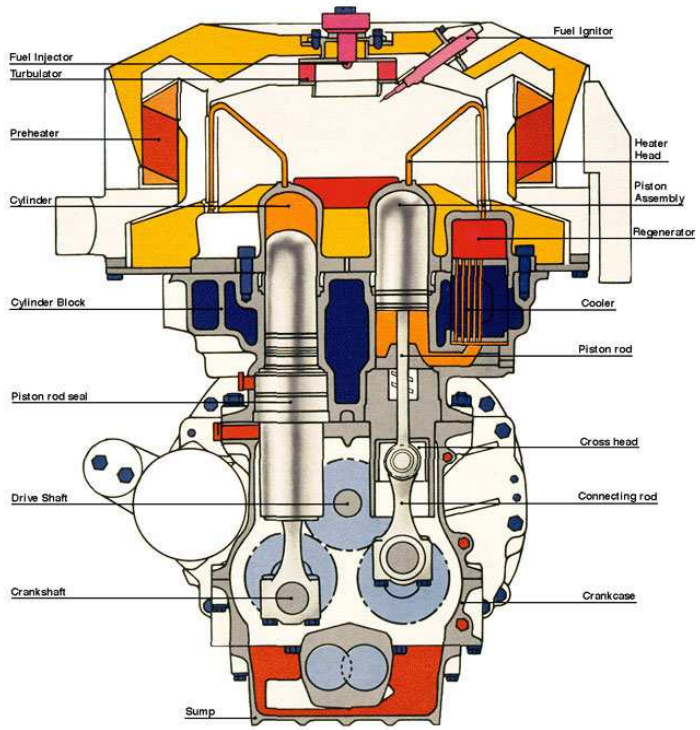


How to regenerate the power?

Stirling cycle

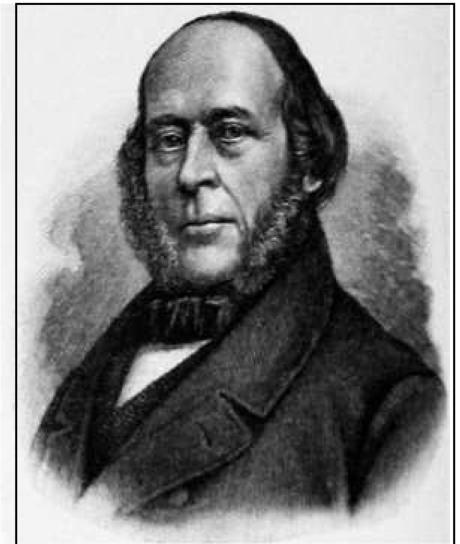
- High efficiency of regeneration (30 to 45% thermo-mechanical efficiency on current concentrated solar units)
- Silent running (submarine applications)
- Operating temperature within IC-exhaust temperature range
- Low power density (weight and volume)
- Requires a good heat sink
- Limited RPM range of high efficiency. (efficiency drops a lot above 2000 RPM)

Not adapted for vehicle applications



How to regenerate the power?

Ericsson cycle

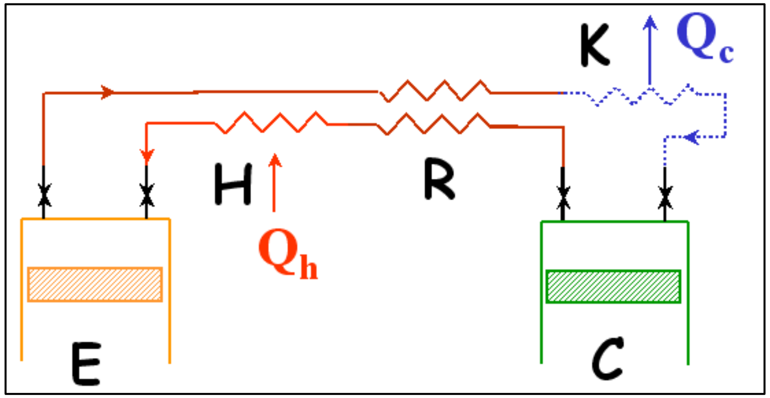


John Ericsson (1803-1889)

An Ericsson engine is a reciprocating engine working on a JOULE cycle.

Open system , runs on air

Difference with Stirling engine: double connection between cylinders and presence of valves



Isothermal compression and expansion

producing more net work per stroke than with adiabatic

Cycle/Process	Compression	Heat Addition	Expansion	Heat Rejection
Ericsson (First, 1833)	adiabatic	isobaric	adiabatic	isobaric
Ericsson (Second, 1853)	isothermal	isobaric	isothermal	isobaric
Brayton (Turbine)	adiabatic	isobaric	adiabatic	isobaric

The use of regeneration in the Ericsson cycle increases efficiency by reducing the required heat input.

How to regenerate the power?

Rankine cycle

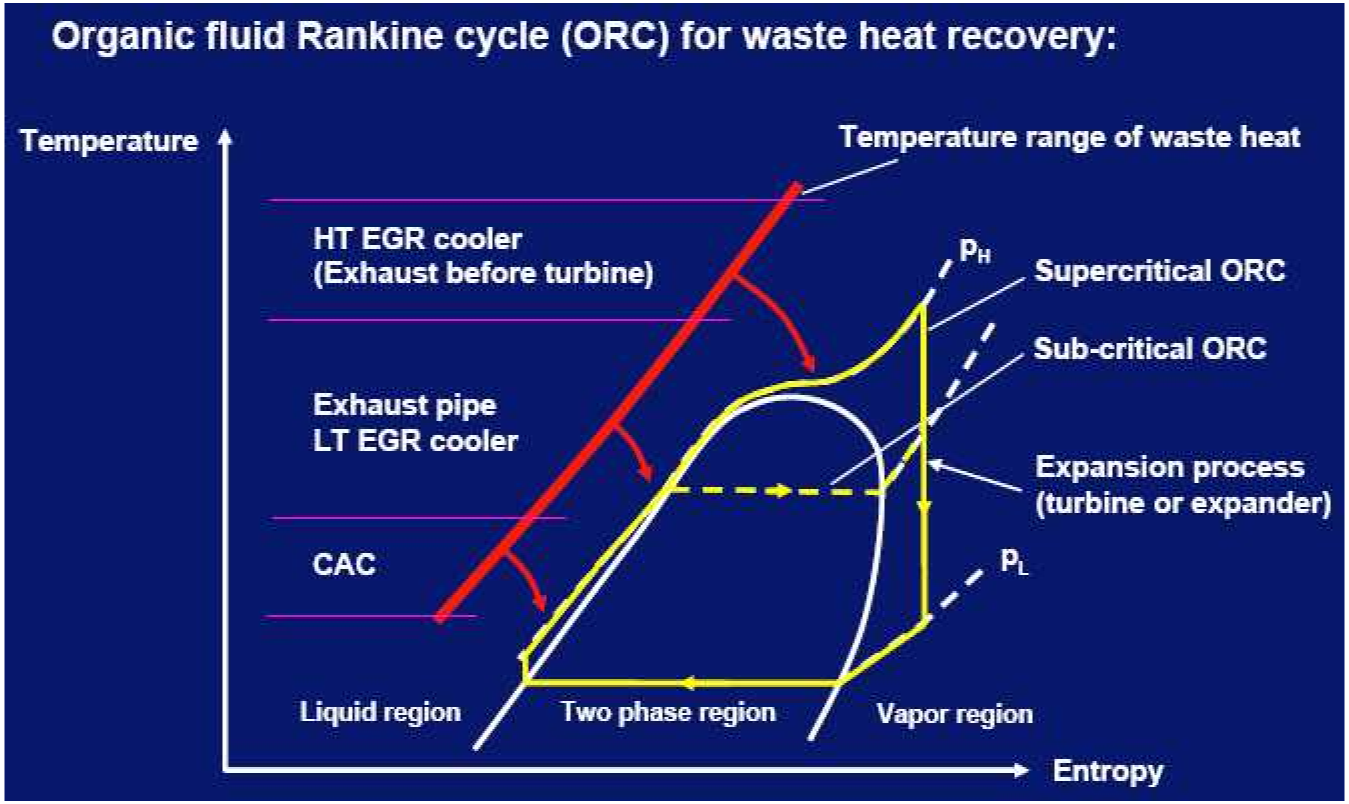
Thermodynamic cycle with phase change of medium

For engine with external heat source

Traditionally water/steam is used

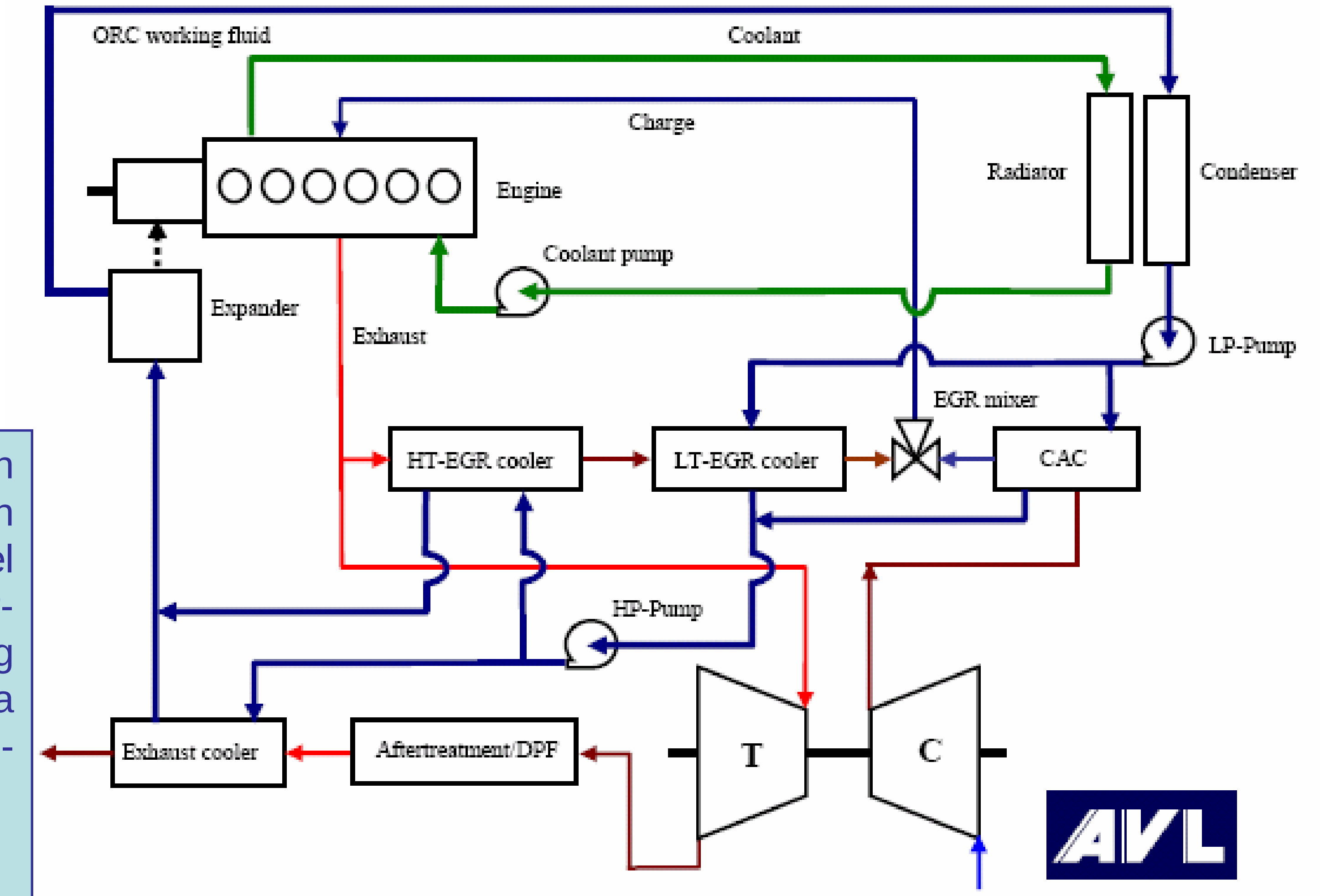
Other liquids can be used to take advantage of other phase change temperatures.

When organic liquids such as propane, butane, R134a, R234fa or ammonia are used we speak about Organic Rankine Cycle (ORC)



How to regenerate the power?

Rankine cycle



AVL calculated with 29,5% regeneration efficiency for a diesel engine with a super-critical reciprocating Rankine engine a total efficiency impro-vement of 18%

Efficiency up from 42% ⇨ 50%

How to regenerate the power?

Rankine cycle

An example : Kitson-Still

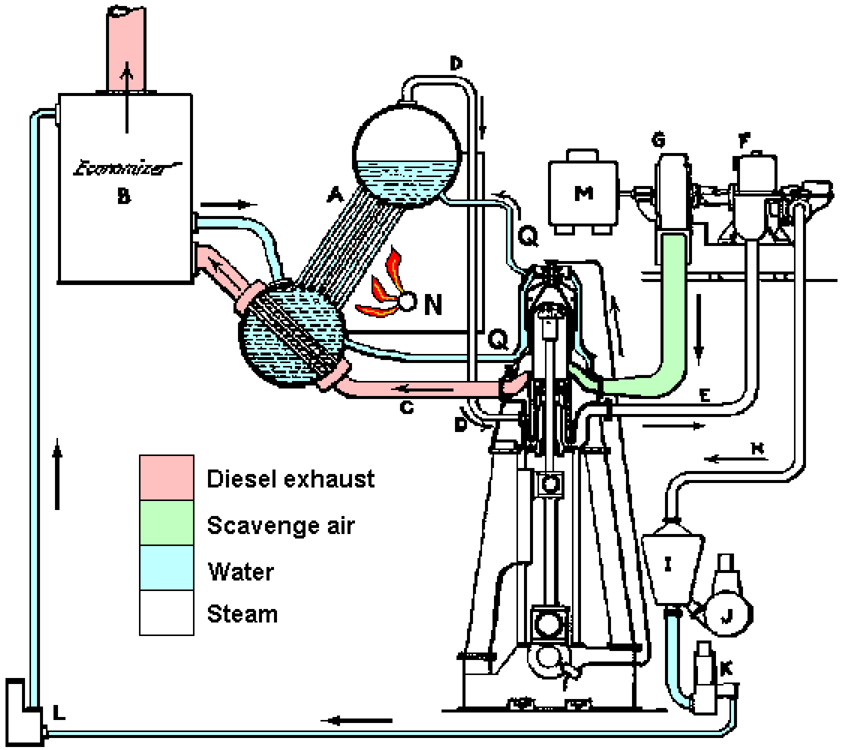
The Kitson diesel locomotives with Still engines had a steamer attached to the IC engine to regenerate the waste heat. With exhaust temperatures of 700-900℃ an additional 15-30% power was obtained with the same fuel consumption.

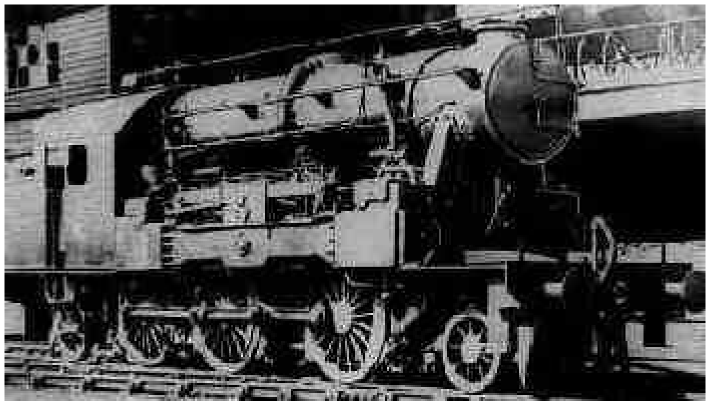
The development had started because of the rising prices of…. COAL.

The Kitsons were finally equipped with diesel engines. Total efficiencies of 40-45% were obtained… in 1924

True waste heat regeneration

more than 80 years ago.





How to regenerate the power?

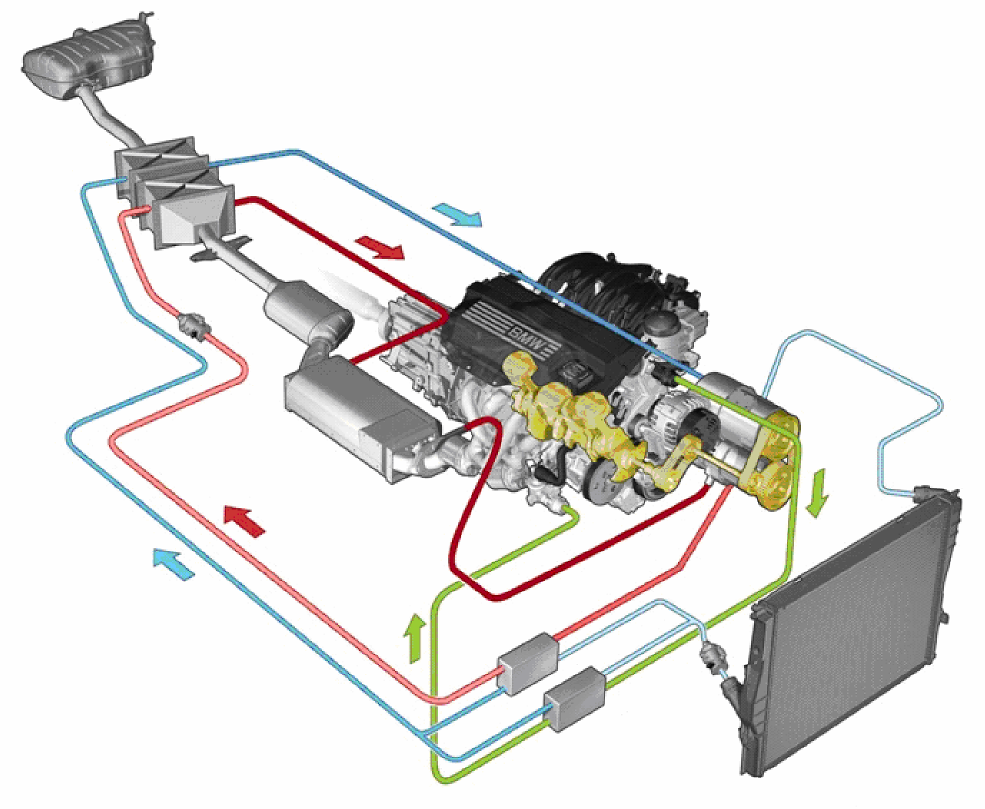
Rankine cycle

An example : Turbosteamer

The BMW Turbosteamer uses the heat from the exhaust to transform a liquid (water ???) into gas which in turn is led through an expansion module (add-on) that transmits torque to the crankshaft. The reduction of fuel consumption of the complete engine system announced by BMW is in the order of 17%.

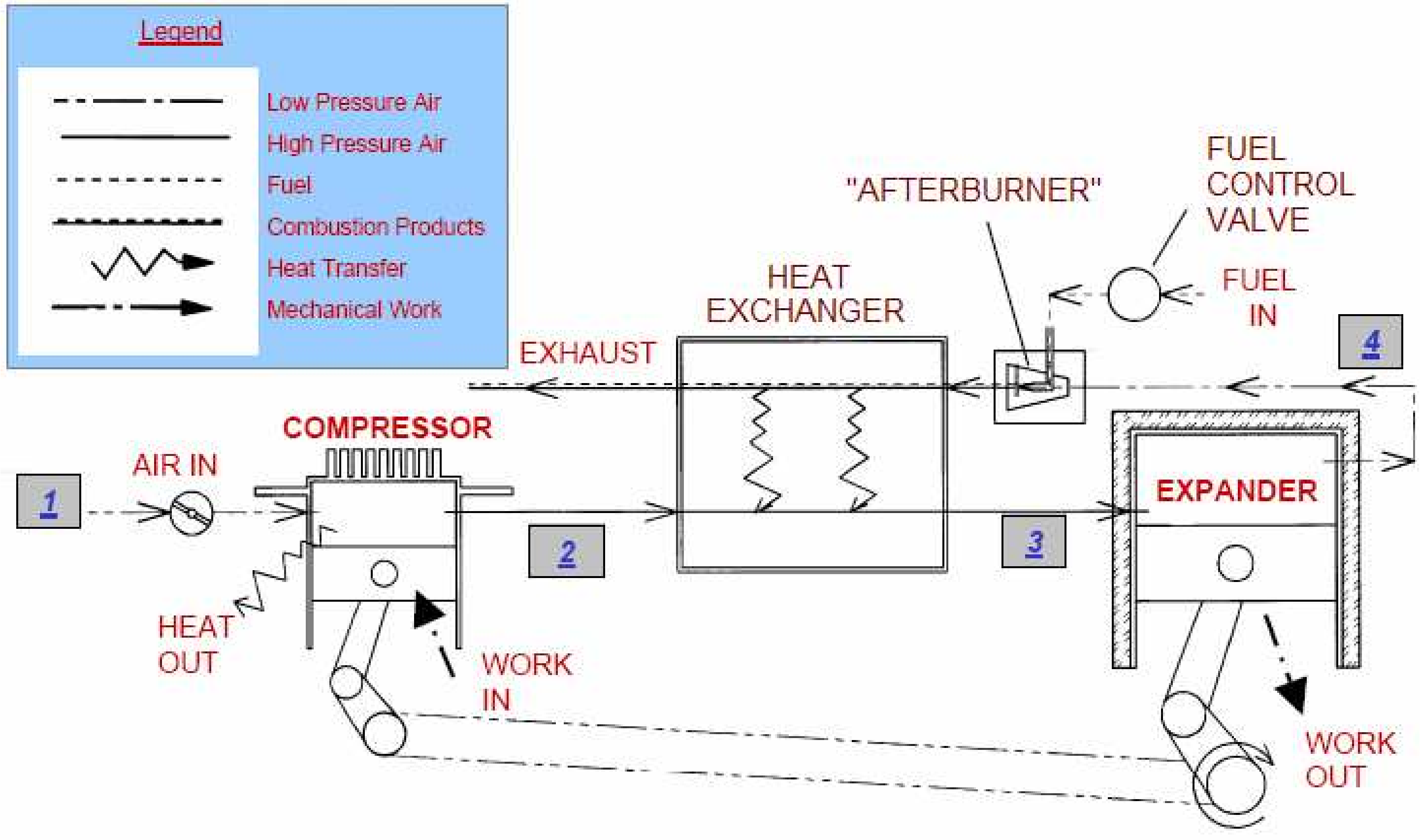
Water is not the most appropriate medium as the system must also work under very cold conditions and may not freeze.

Liquids as R134a, R234fa or ammonia seem more appropriate.



How to regenerate the power?

Proe afterburning cycle



How to regenerate the power?

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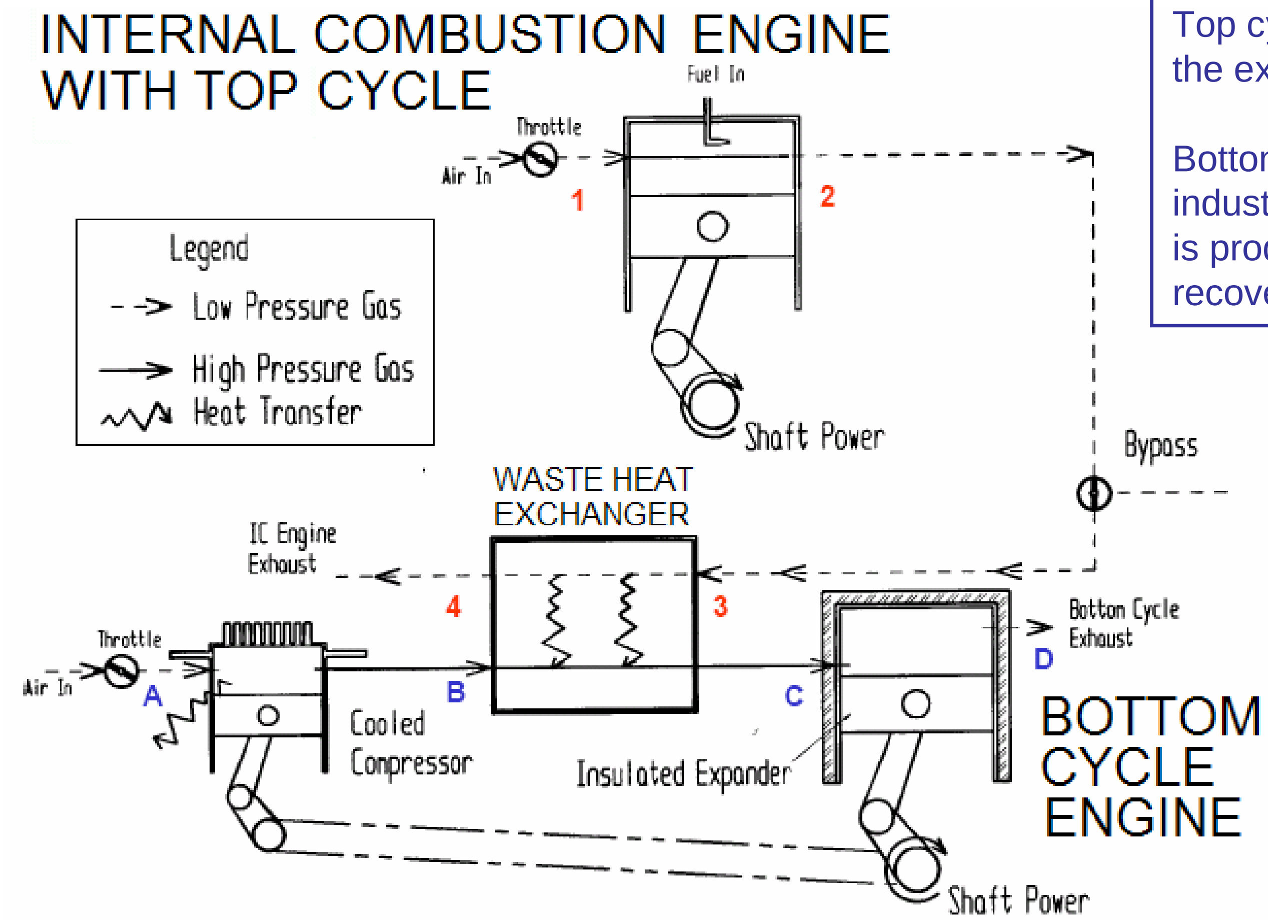


Top cycle produces torque first, then the exhaust is used for heating.

Bottoming cycle produce heat for an industrial process first, then electricity is produced using a waste heat recovery boiler.

How to regenerate the power?

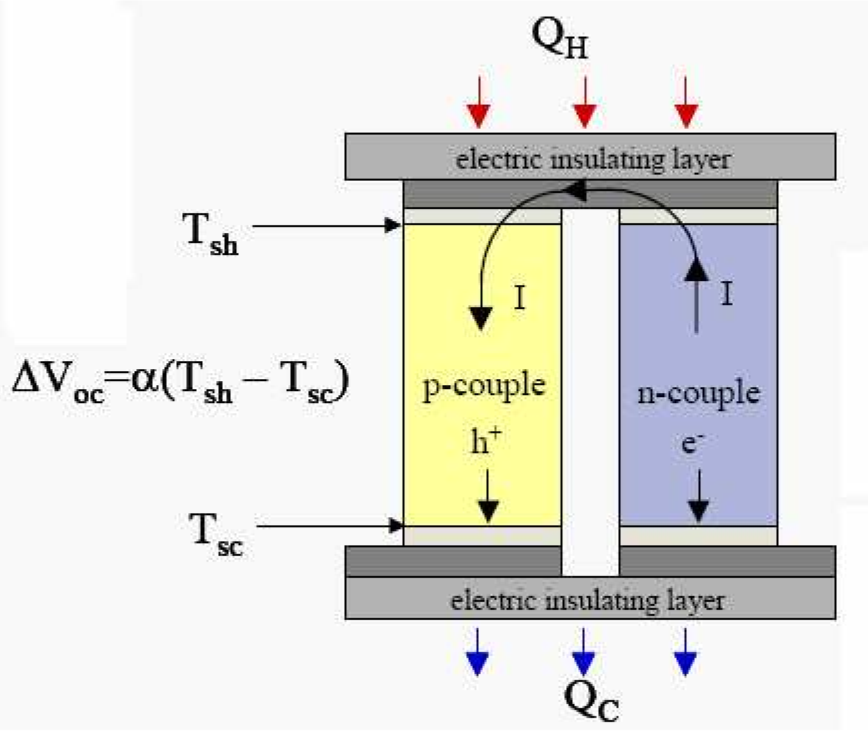
Seebeck effect thermo-electricity

A technology subject of many research projects

High Volume Cost for Bulk TE: <$1/Watt

High Volume Cost for QW TE:
Goal of 0.20 to 0.50 $/Watt

Thermoelectric efficiency is based on the material's non-dimensional figure of merit (ZT) and the ΔT across the device



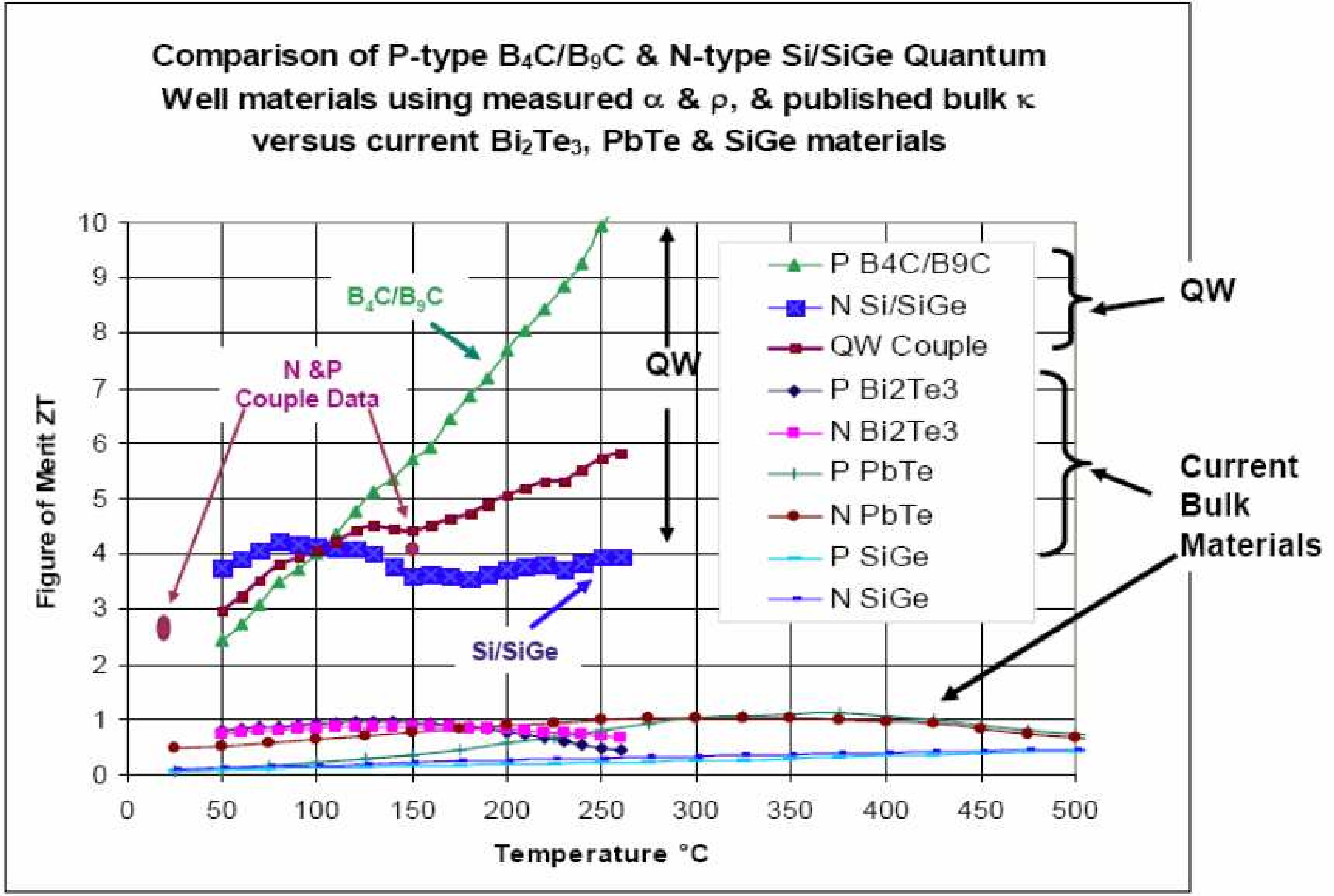
- Generate voltage $\alpha\ (T_{sh} - T_{sc})$ across the junctions
- Generate current as a function of heat flux through couples
- Ideally with low thermal conductivity and high electrical conductivity

Current developments at :

- Quantum Well TE
- High-Z Technology Inc.
- Teledyne Energy systems
- NRE Lab
- Monash University
- Delphi
- Clarckson University and others.

How to regenerate the power?

Seebeck effect thermo-electricity



How to regenerate the power?

Seebeck effect thermo-electricity

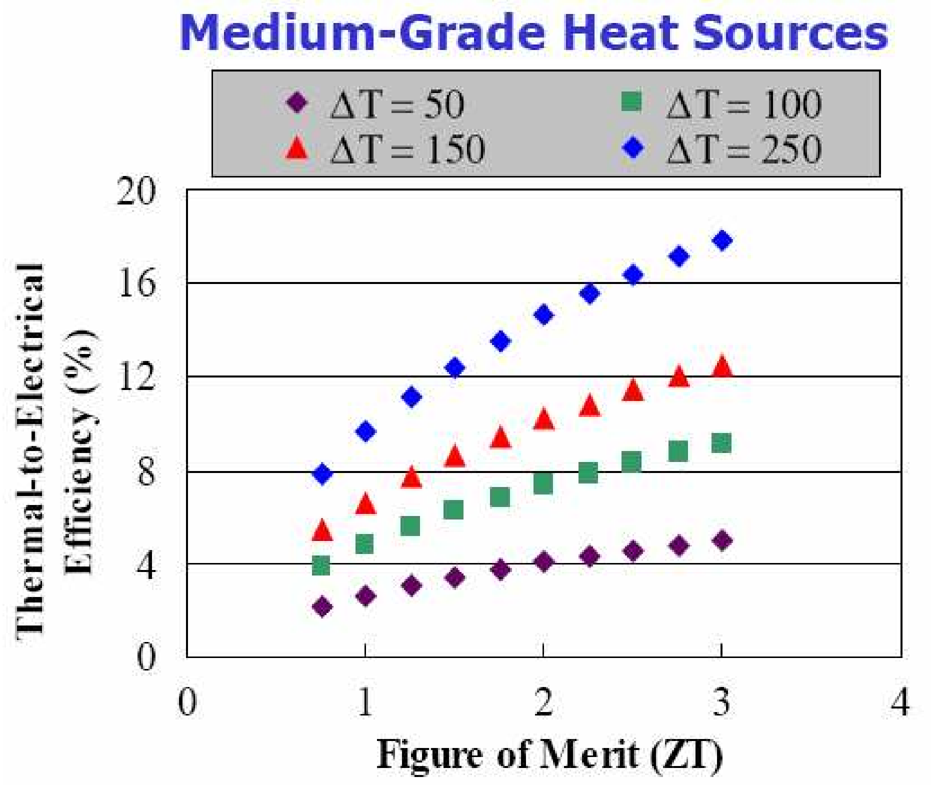
High Volume Cost for Bulk TE: <$1/Watt

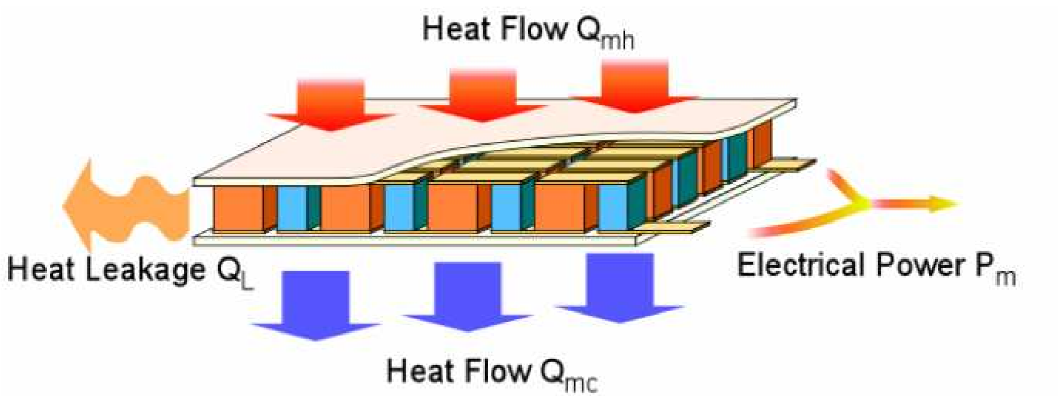
High Volume Cost for Quantum Wells TE: currently 0.20 $/Watt

A system that can convert 25% of its input fuel energy to electric power can potentially replace some internal combustion engines

A system that can convert 50% of its input fuel energy to electric power could potentially replace most gasoline and diesel engines and would even challenge fuel cells.

Francis Stabler, GM , MRS Nov 28th 2005



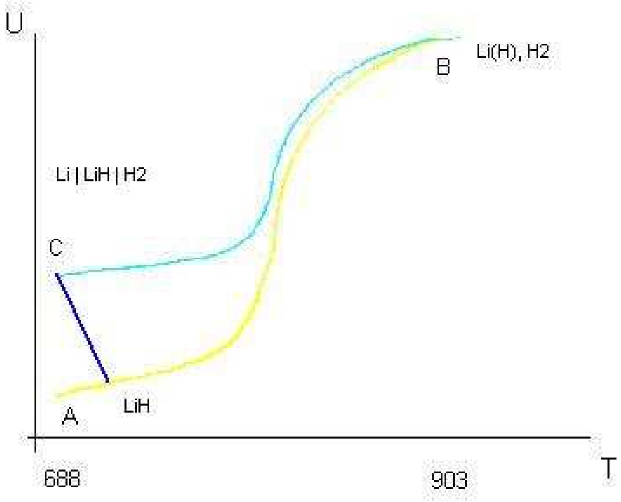


- ***High material costs and low efficiency***
- ***Progress can still be expected for the coming years***

How to regenerate the power?

Lithium hydride cycle

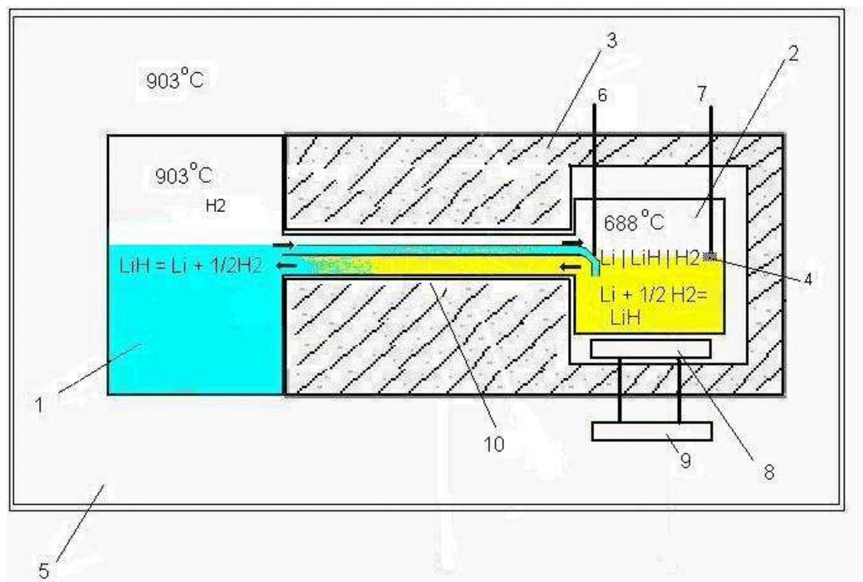
Thermally regenerative ionic hydride galvanic cell



Point A: Energy of the LiH at the temperature of the discharged cell

Point B: Energy of the system of hydrogen and lithium with dissolved hydrogen (H2 + Li(H)) heated to 903°C.

Point C: Energy of the system composed of Li metal and H2 gas separated from each other and of LiH re-formed from Li and H2 during cooling due to imperfect separation, at the temperature of the operation of the cell, T=688°C.

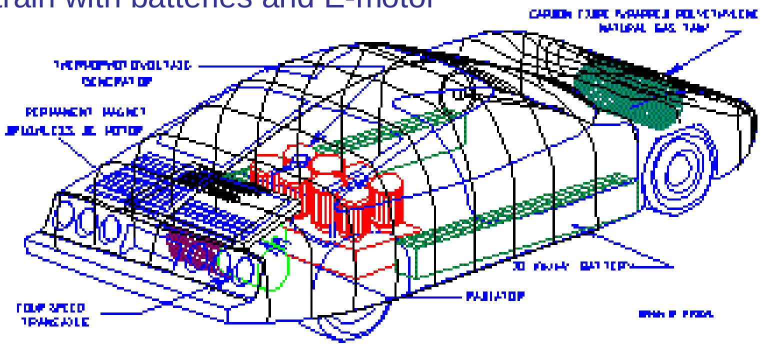


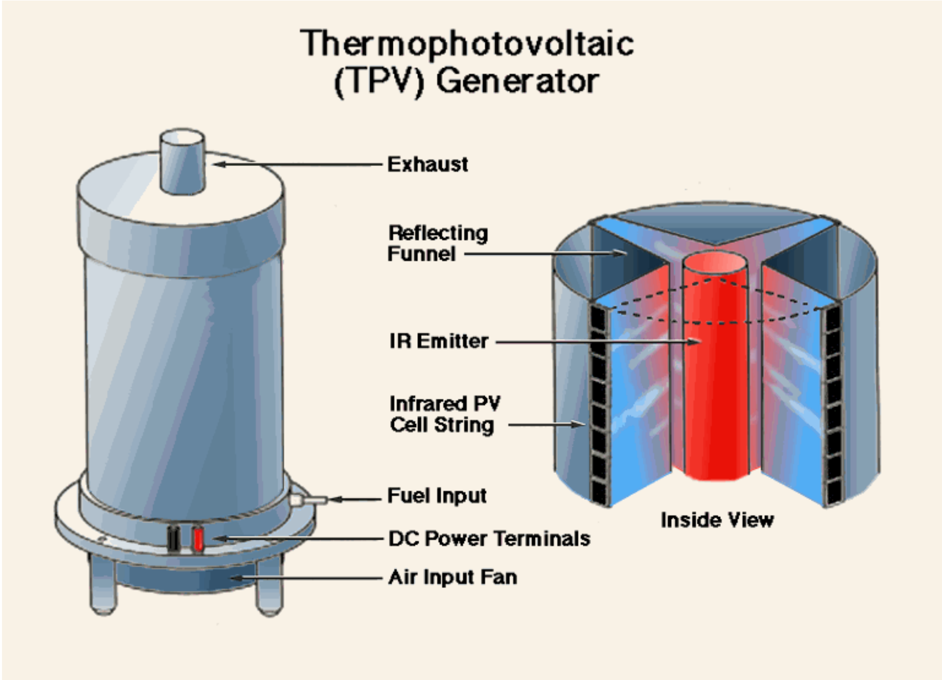
- **Very high efficiency (80 - 97%)**
- **Low specific power**
- **Temperature range above that of IC engines exhausts**
- **Dangerous materials**

How to regenerate the power?

Thermo-photo-voltaics

- Vehicle Research Institute (VRI) at Western Washington University
- Industrial partner, JX Crystals Inc.
- Funded by Department of Energy (DoE) and Department of Defense (DoD)
- Research since 1993
- Top speed of > 160 km/h : it can easily maintain freeway speeds
- Acceleration of 0-100 km/h : 10 seconds : OK for safe city driving
- The eight cylinder unit is 432 mm long x 864 mm wide x 696 mm tall
- Results to date : **900 Watts** from a single burner with an **efficiency of 7%** and **burner temperature of 1700K.**
- Thermo-photo-voltaic generator integrated in electric powertrain with batteries and E-motor





Thermo-photo-voltaic array

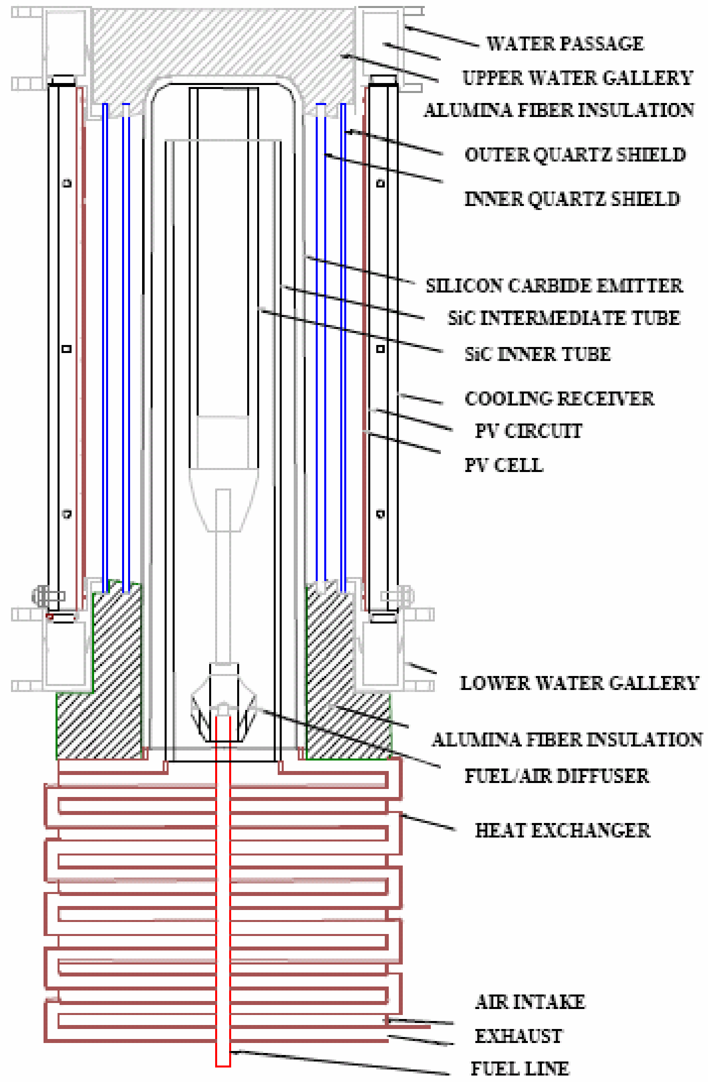
Viking 29 : the World's first thermo-photo-voltaic powered automobile

How to regenerate the power?

Thermo-photo-voltaics

The technology:

1. Hot black surface from silicon-carbide emits Infrared light when hot
2. Infrared sensitive gallium antimonide (GaSb) cells manufactured by JX Crystals convert light into electricity
3. The emitter is heated by natural gas to a temperature of 1700C.
4. A stainless steel recuperator preheats incoming air.
5. A diffuser mixes the gas and air as they enter the combustion zone (3).
6. Photovoltaic circuit boards are bonded to aluminum receivers that conduct excess heat into the cooling water through fins.
7. Two quartz crystal shields surrounding the emitter help to reduce convective losses and reduce exposure of cells to excess temperatures.
8. Polished aluminum mirrors mounted in the gaps between cells reflect back photons that would other wise be lost as waste heat.

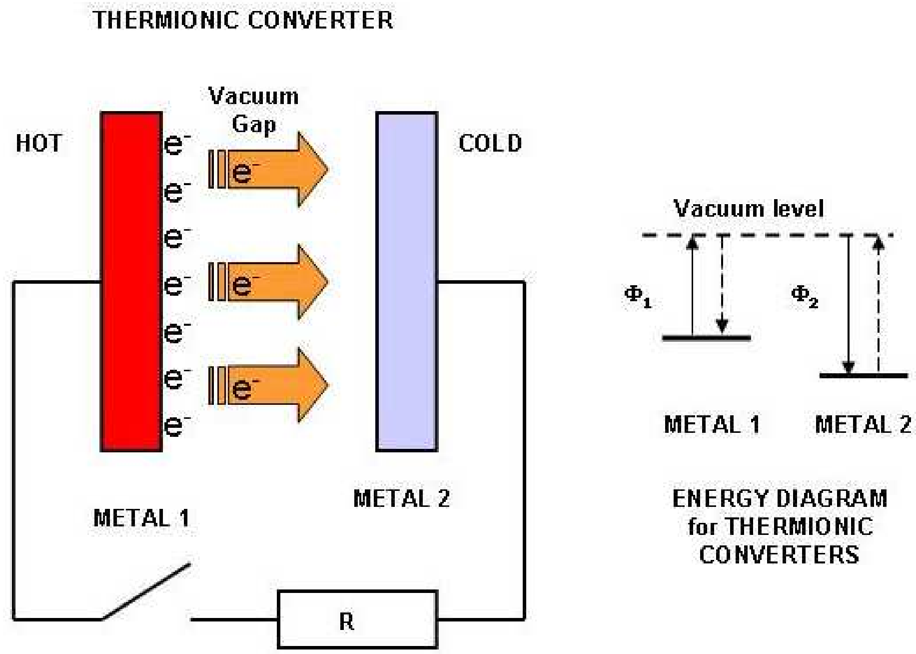


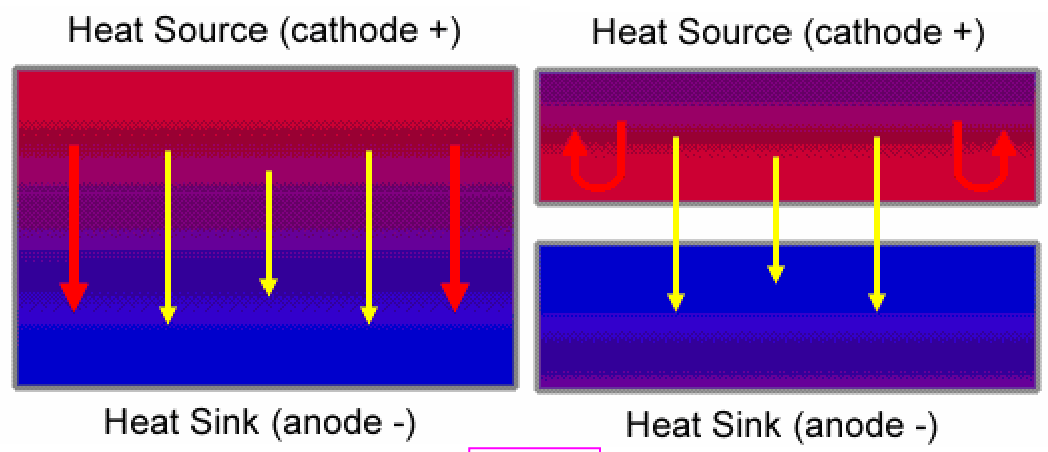
Thermo-photo-voltaic array

How to regenerate the power?

Thermo-ionic emission / Thermo-tunneling

- Similar to Seebeck effect thermo-electrics
- Nano gap allows electrons with energies less than the potential barrier to move from one side to another
- Nano gap retains heat as much as possible on hot side where Seebeck effect lets heat flow freely.
- Avto effect is used to increase gap over which electrons can jump
- Quantum mechanical thermo-tunneling is thus used to efficiently generate electricity from heat
- Requires **1000℃** + to produce significant currents
- In laboratory conditions, efficiencies as high as **40%** are reported.





High conversion efficiencies but at

Temperatures outside of engine waste heat range.

How to regenerate the power?

Thermo-chemical processes

Purpose = To obtain (increased) chemical power

- **For increased fuel energy content**

  Endothermic vapo-cracking (generating H_2 from water)

  Autothermal fuel reforming (generating H_2 from fuel)

  MIT – Plasmatron (generating H_2 from fuel)

  Other…

- **For "thermal" storage and rapid release of heat when needed**

  Phase Change Materials (keep Catalyst hot longer)

  Other…

- **For enhancement of exhaust gas after-treatment**

  Enhance NOx-trap function with on-board generated H_2

How to regenerate the power?

Endothermic vapo-cracking

- A multitude of processes, at various temperature ranges
- Processes at IC exhaust temperatures are often very complex
- Processes with or without use of chemicals (other than regular fuel)
- Use of chemicals generally not adapted for vehicle applications

⇓

Focus on : **Catalytic processes without use of cycling of chemicals**

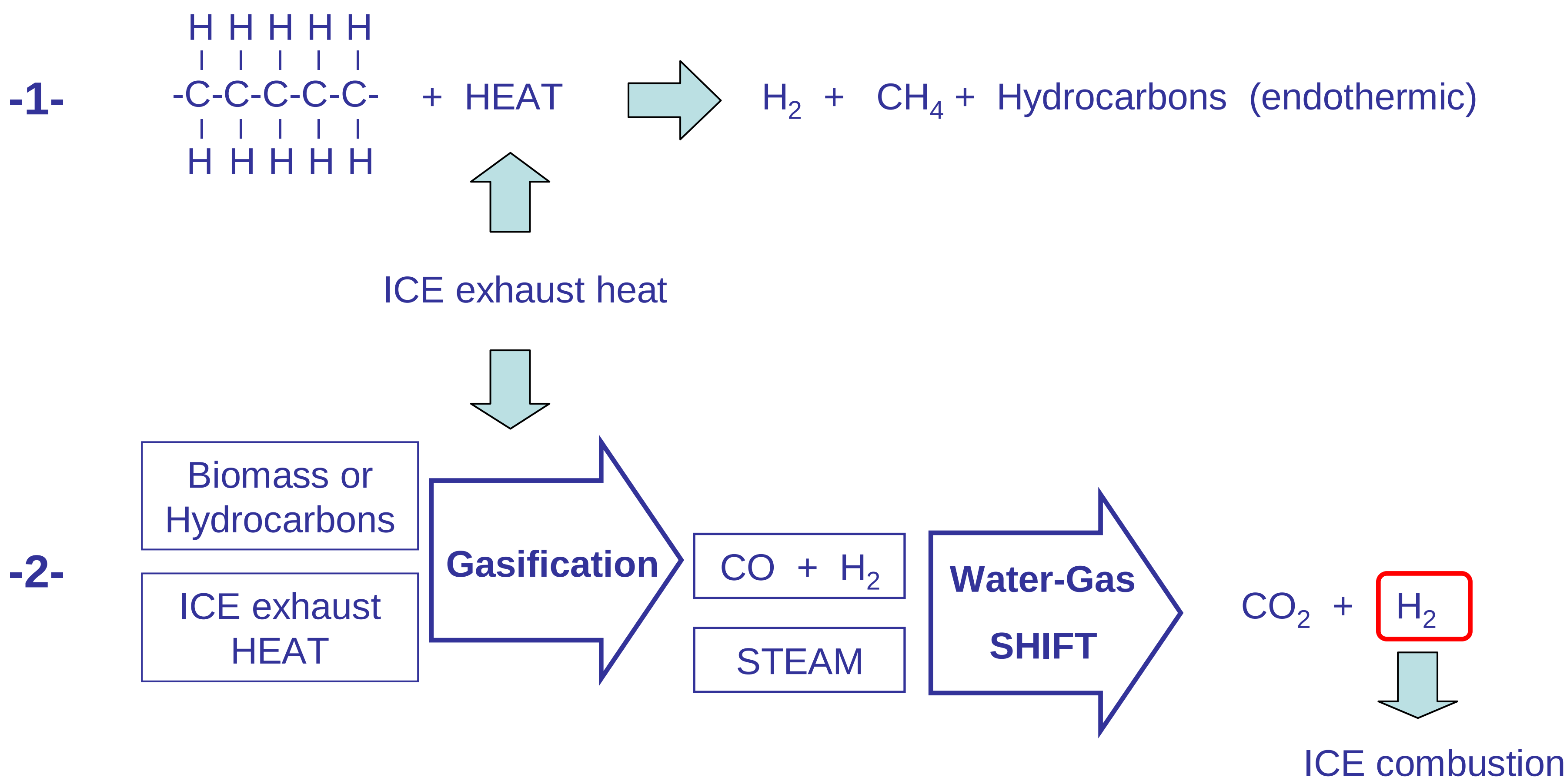
OR

Reforming of hydrocarbons with Hydrogen generation

How to regenerate the power?

Endothermic vapo-cracking

Two more examples : Pyrolysis (1) and Gasification followed by water-gas shift (2)



How to regenerate the power?

Endothermic vapo-cracking

An example obtained at Florida University based on Citrus peels :

1 kg feed

↓

3 Nm^3 of gas with 17% H_2, 10% CH_4, 18% CO, 16% CO_2, 3% O_2 and 36% N_2

↓

After steam reformation/shift reaction

↓

Yield increases to 4.7 Nm3 gas with 47% H_2, 28% CO_2, 2% O_2 and 23% N_2

Overall gasification efficiency is 81% (considering LHV of feed to LHV of Gas Output)

How to regenerate the power?

Auto-thermal fuel reforming

Among all the methods that produce hydrogen, auto-thermal reforming reaction (ATR) is considered to be one of the most effective processes. This innovative hydrogen producing method consists of two traditional reactions: catalytic partial oxidation (CPO) and steam methane reforming reaction (SMR).

Catalytic Partial Oxidation

$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$ Δh = -36 MJ/kmol CH_4 (exothermic)

Traditionally this happens at temperatures of about 1200℃.

Newly developed catalysts have brought this down to 650℃-900℃

Steam Methane Reforming

$CH_4 + H_2O \rightarrow CO + 3H_2$ Δh = 206.16 kJ/mol CH_4 (endothermic)

Nickel catalyst speed up the reaction and makes it more efficient.

This reaction can achieve an energy efficiency as high as 85% with optimal waste heat recovery and can achieve the reaction efficiency of 80%.

How to regenerate the power?

MIT Plasmatron

Adding hydrogen to gasoline makes an engine run cleaner and more efficiently.

Plasma electrical discharge

↓

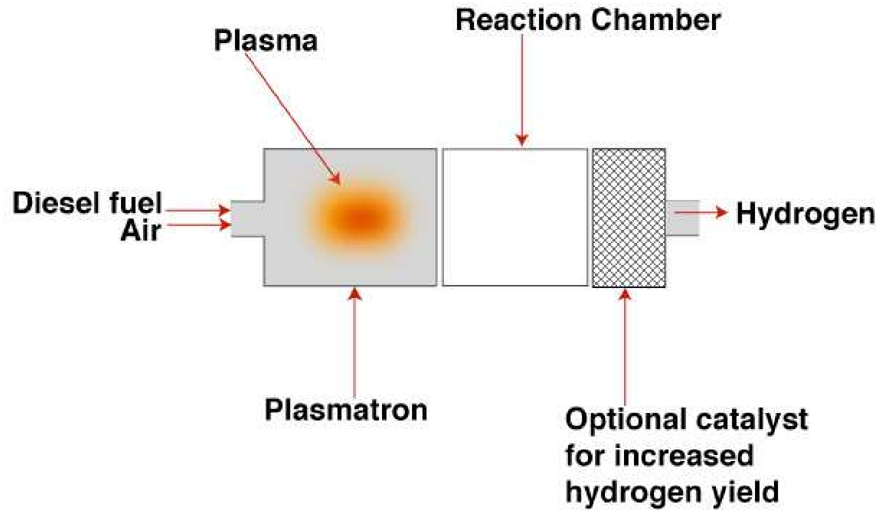
Partial oxidation reactions between gasoline and air

↓

Production of hydrogen-rich gas

↓

Added in air intake of engine



Hydrogen Generation Process
Plasma initiates and maintains the chemical reaction which liberates hydrogen from diesel fuel.

MIT PLASMA SCIENCE AND FUSION CENTER
(L. BROMBERG AND D. COHN)

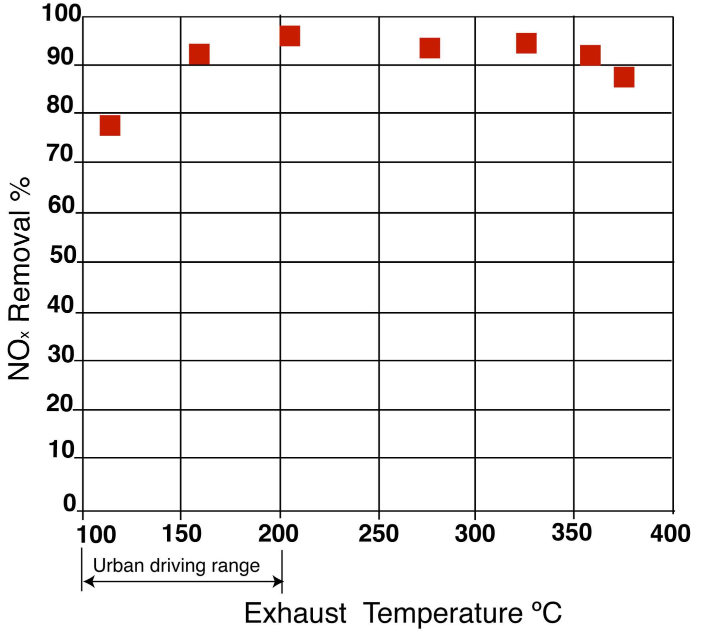
MIT SLOAN AUTOMOTIVE LABORATORY
(J. HEYWOOD AND V. WONG)

How to regenerate the power?

MIT Plasmatron

Features :

- Rapid response
- Compact (2 liters for 100 kW of reformate)
- Robust
- Efficient (1 -3% of reformate's combustion power)
- Relatively low net cost
- No reduction of vehicle range
- No sacrifice of vehicle performance
- Has the potential to increase gasoline engine efficiency by 20 to 25% (partload)
- Decreases level of HC, soot in exhaust



Plasmatron is complementary to endothermic vapo-cracking

Fast response
Increase of temperature where needed

But also : Plasma hydrogen added to NOx-trap reduces NOx emissions

How to regenerate the power?

Hydrogen fuel-additive

Features :

- Hydrogen addition provides a large increase in fuel octane number.
- High octane fuel allows higher performance engines (turbocharging, high compression ratio).
- Engines can be smaller and more efficient.
- Hydrogen has 8-10 times combustion speed of diesel and can make the diesel combustion progress faster for more complete burn.
- Hydrogen addition also facilitates ultralean burn.
- Thermal efficiency could according to some sources be increased by up to 30%.
- Reforming product CO requires special attention (catalyst converter)

How to regenerate the power?

Diverting the thermal power flow to another application

Thermo-acoustics (as a heat pump)

Interior heating through a heat exchanger

Heat storage for quick operation of catalyst

Adsorption cooling (air conditioning)

How to regenerate the power?

Diverting the thermal power flow to another application

Thermo-acoustics (as a heat pump)

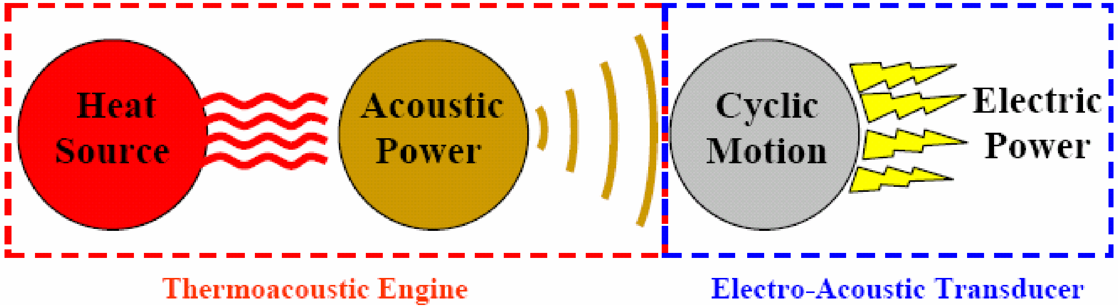
Interior heating through a heat exchanger

Heat storage for quick operation of catalyst

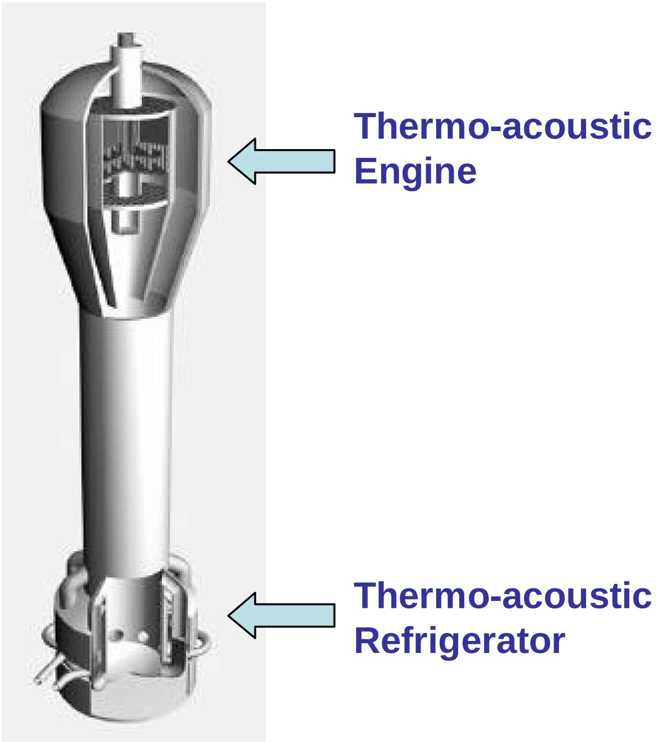
Adsorption cooling (air conditioning)

Los Alamos researchers started development in 1980s and began considering acoustic technology to eliminate moving parts.

They produced the first powerful thermo-acoustic engines and the first thermo-acoustic refrigerators.



Example : TADOPTR (Thermo-acoustically Driven Orifice Pulse Tube Refrigeration)



No moving parts !!!

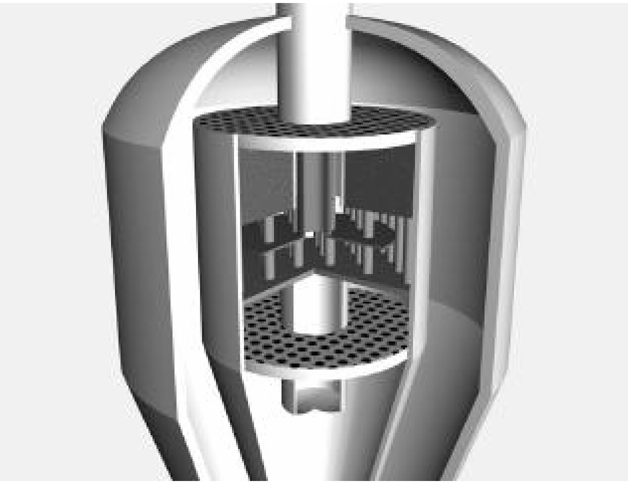
How to regenerate the power?

Diverting the thermal power flow to another application

Units too large for automotive applications

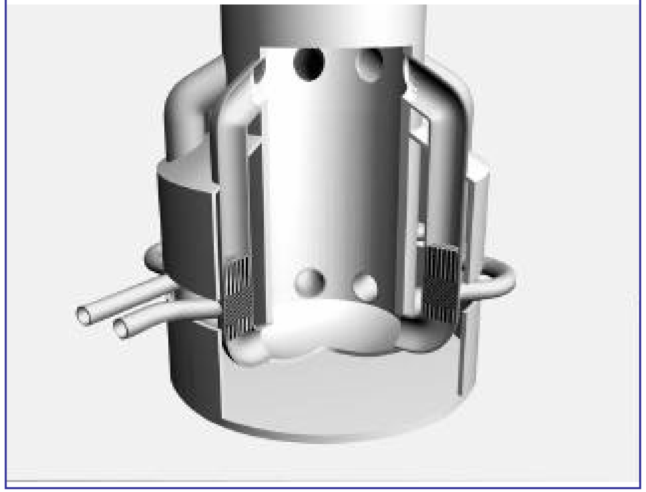
Thermo-acoustics (as a heat pump)

Thermo-acoustic Engine



The steep temperature gradient across the hot heat exchanger and the ambient heat exchanger causes the Helium to oscillate up and down. During this process heat is exchanged with the stack in between the heat exchangers in a way that thermo-acoustic work is produced.

Thermo-acoustic Refrigerator



The work is then transferred to the Refrigerator at the other end of the resonance tube, where the reverse process takes place, i.e. thermo-acoustic work is converted to cooling power. Fig. 2b shows the refrigerator and the flow of the liquefied gas through the heat exchangers.

How to regenerate the power?

Diverting the thermal power flow to another application

Thermo-acoustics (as a heat pump)

Another example : Thermo-acoustic engine for deep space applications

- Main energy source for deep space travels is heat from the decay of a radioactive fuel
- This is used to generate electricity
- Current thermoelectric devices used for the onboard generation of electricity have an efficiency of only 7%
- The traveling-wave thermo-acoustic engine converts 18 percent of the heat source energy into electricity and is thus more than twice as efficient.
- Since the only moving component in the device besides the helium gas itself is an ambient temperature piston, the device possesses the kind of high-reliability required of deep space probes.

How to regenerate the power?

Diverting the thermal power flow to another application

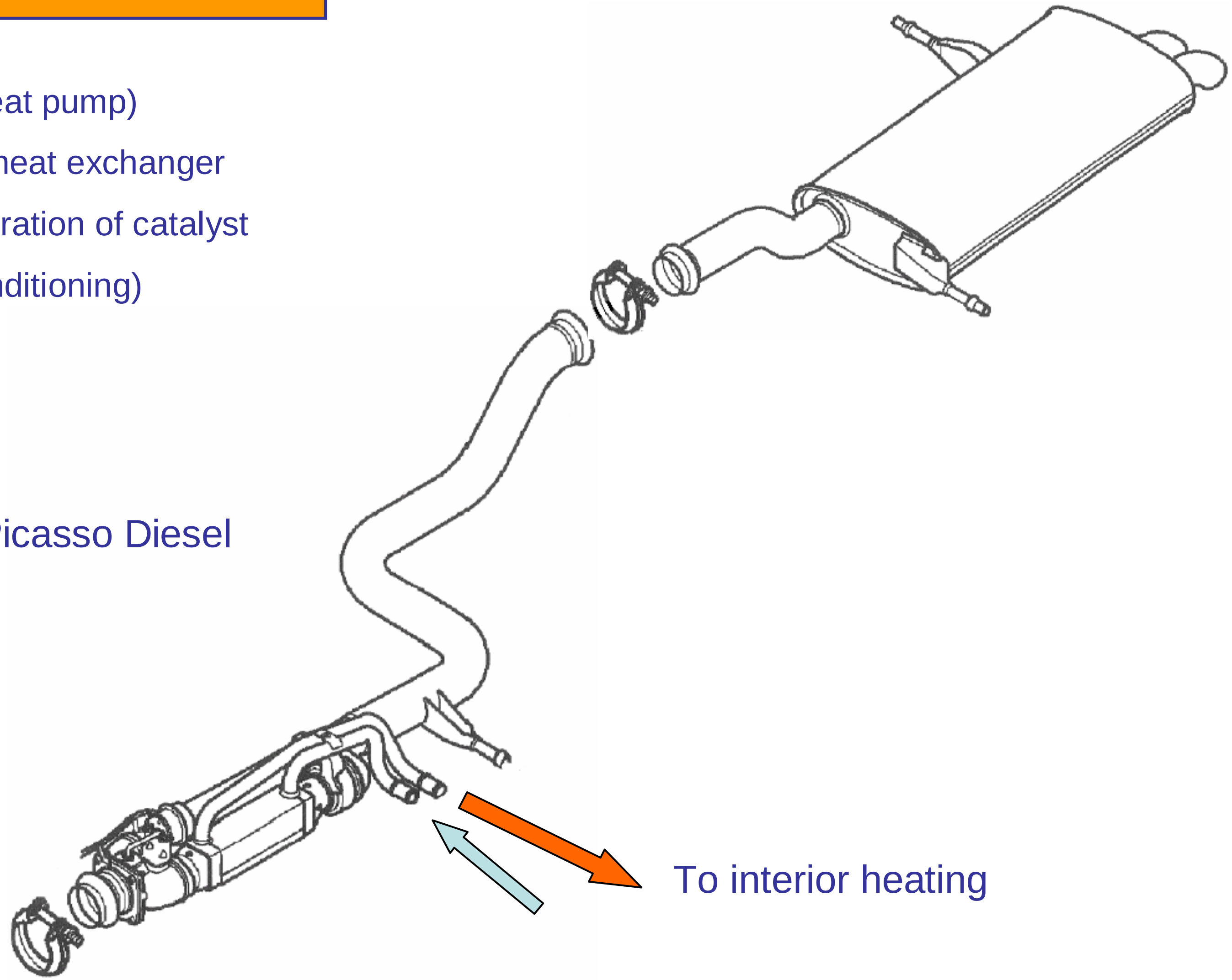
Thermo-acoustics (as a heat pump)

Interior heating through a heat exchanger

Heat storage for quick operation of catalyst

Adsorption cooling (air conditioning)

Example on Citroën C4 Picasso Diesel



How to regenerate the power?

Diverting the thermal power flow to another application

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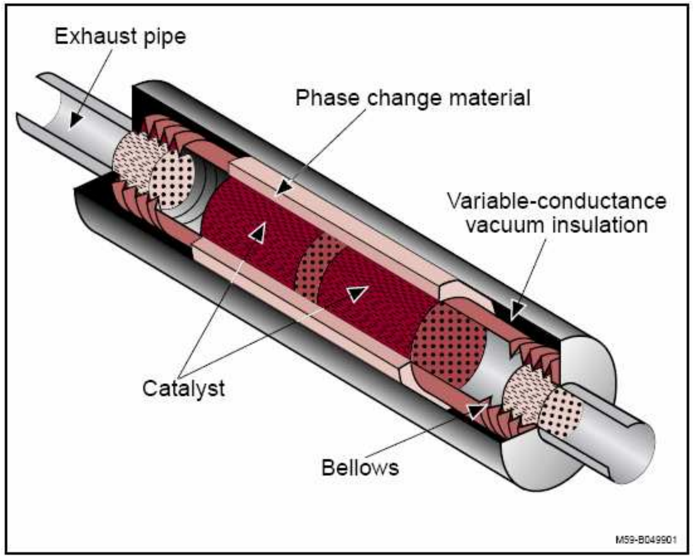
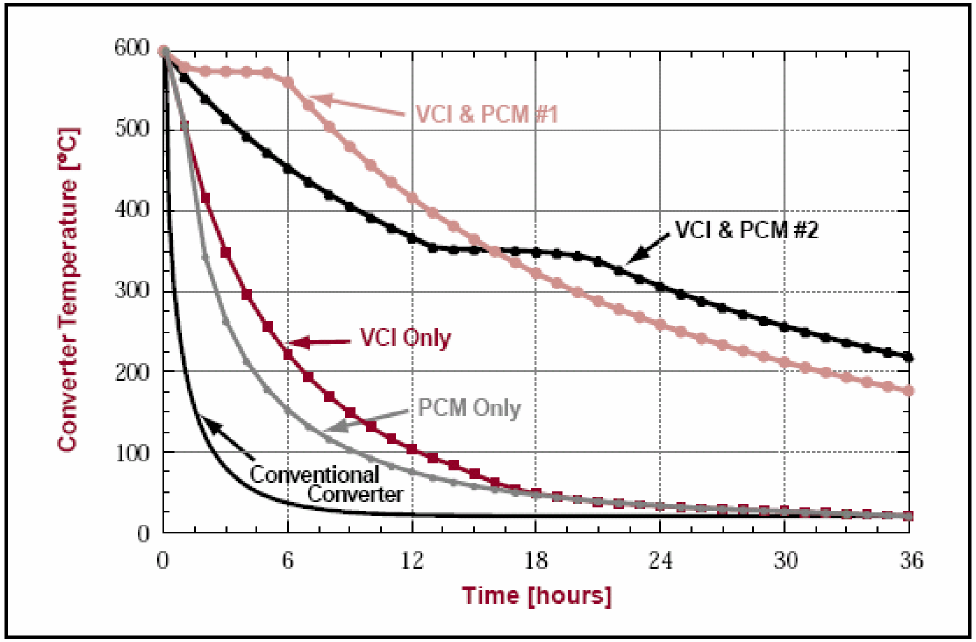


Phase change materials are used to keep variable-conductance-insulation (VCI) catalytic converter hot between two trips. The heat up time is them strongly reduced or eliminated.

Total hydrocarbon emissions were reduced by 84% and total carbon monoxide emissions by 91%. Even greater emission reductions were obtained with an ethanol-fueled (85% ethanol/15% gasoline) vehicle.



How to regenerate the power?

Diverting the thermal power flow to another application

Thermo-acoustics (as a heat pump)

Interior heating through a heat exchanger

Heat storage for quick operation of catalyst

Adsorption cooling (air conditioning)

Variable Conductance Insulation

With insulation good enough to keep the converter temperature greater than 300℃ for 24 hours after the engine is turned off, what keeps the converter from overheating while the engine is running at high speed?

Certain compounds of hydrogen and metals release their hydrogen above a particular temperature and then reabsorb hydrogen below that temperature.

Because hydrogen gas is a good heat conductor, releasing it into a vacuum "turns off" the insulation provided by the vacuum. The VCI catalytic converter has a small amount of metal hydride within the vacuum envelope.

As the converter approaches its maximum safe temperature (about 900℃), the hydride releases its hydrogen, allowing excess heat to escape.

As the converter cools back down, it reabsorbs the hydrogen, thus reestablishing the vacuum.

How to regenerate the power?

Waste heat regeneration based on power flows

1. **Thermal power flow**
2. **Kinetic power flow**
3. **Chemical power flow (non-combusted HC, CO, Soot)**
4. **Upper latent heat flow**

How to regenerate the power?

Converting the kinetic power flow

The turbine, in which not only kinetic energy but also some thermal energy is regenerated, is the basic element that serves in a variety of applications:

Turbocharger (widely used on cars and trucks)

Mechanical Turbo-Compound (Napier Nomad, Cummins-Scania, Volvo)

Electrical Turbo-Compound (John Deere, Caterpillar)

Exhaust turbine generator (Visteon TIGERS)

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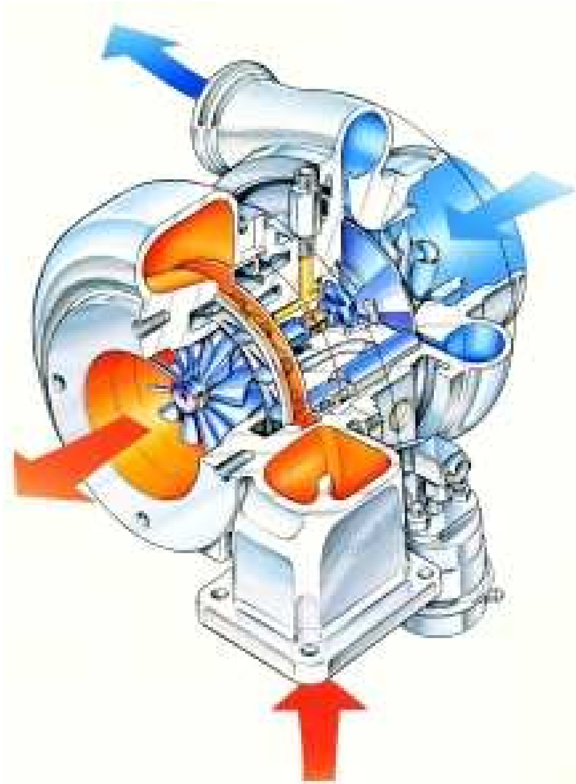

Waste kinetic power is used to drive a turbine and supercharge the engine without loosing power on crankshaft.

- To obtain higher power output
- To allow better fuel economy with downsizing for same torque levels

How to regenerate the power?

Converting the kinetic power flow

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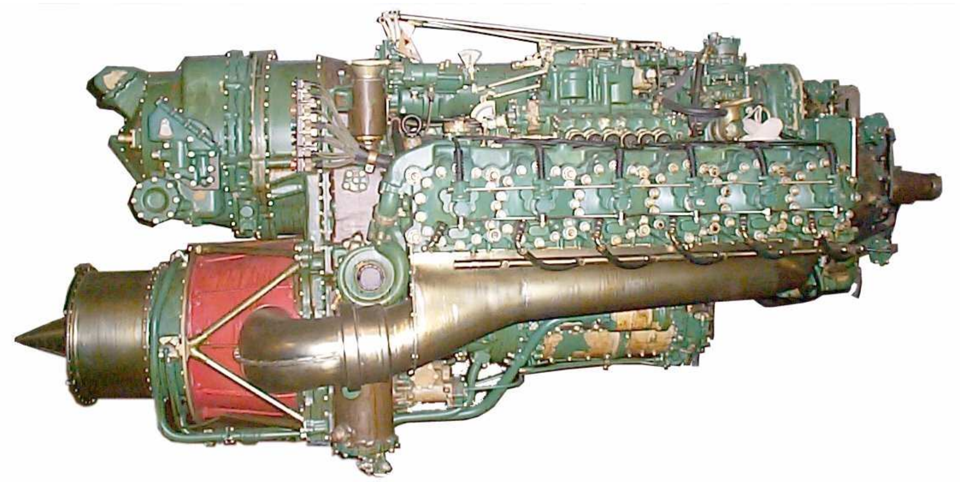
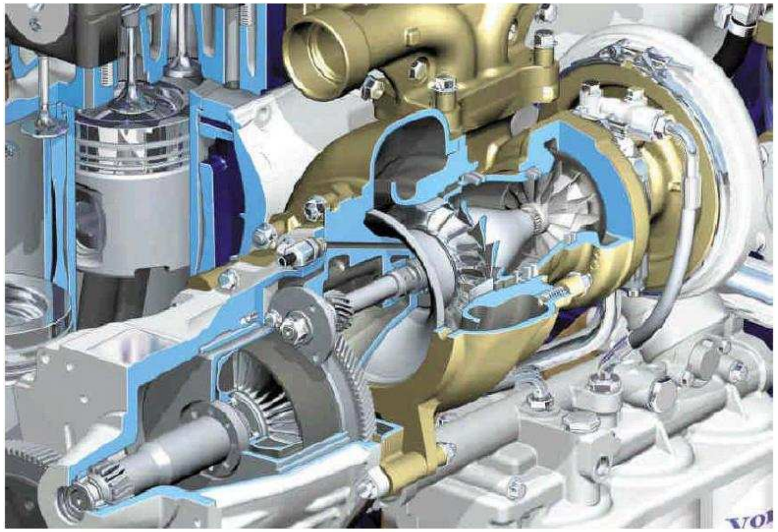


Napier Nomad diesel aircraft engine (1952)

(< 213 g/kWh)



VOLVO D12D Truck engine

How to regenerate the power?

Converting the kinetic power flow

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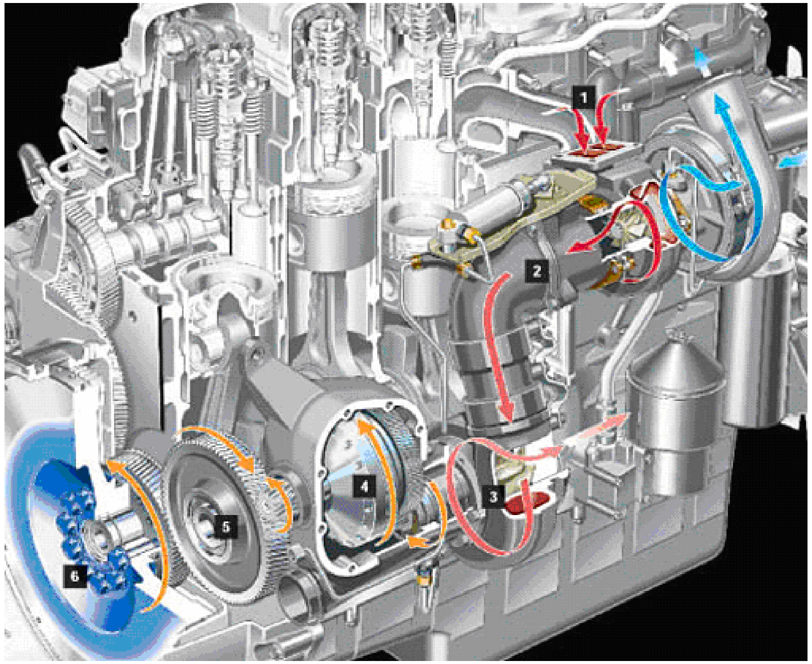
Electrical Turbo-Compound (John Deere, Caterpillar)

Exhaust turbine generator (Visteon TIGERS)

A second turbine in the exhaust spinning at 55,000 RPM further expands the exhaust gas.

The rotation is demultiplied and transferred through a hydraulic coupling to the crankshaft.

Fuel economy obtained on Scania trucks is about **5 to 10%.**



Cummins turbo-compound on Scania DTC11 Truck engine

How to regenerate the power?

Mechanical Turbo-Compound in racing applications.

Mechanical Turbo-compound in racing can add significant power with "acceptable" extra weight.

Stable engine speeds of Offshore Powerboats are a perfect type of application.

High dynamics of a race engine on the track is not optimal for working points.

Still a lot of heat available after the second turbine.

How to regenerate the power?

Converting the kinetic power flow

The turbine, in which not only kinetic energy but also some thermal energy is regenerated, is the basic element that serves in a variety of applications:

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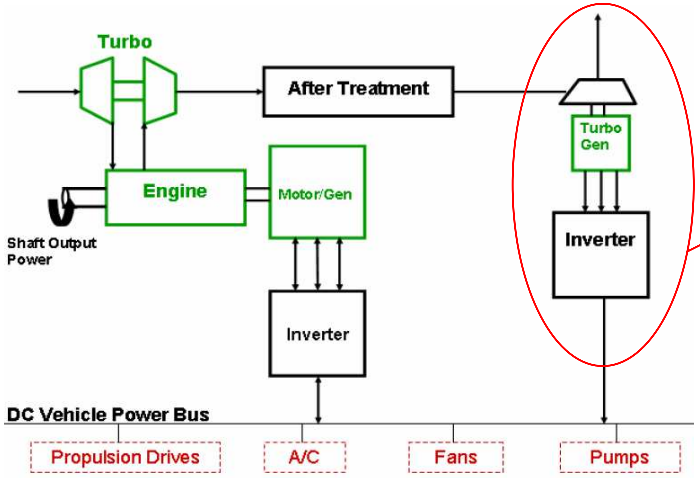
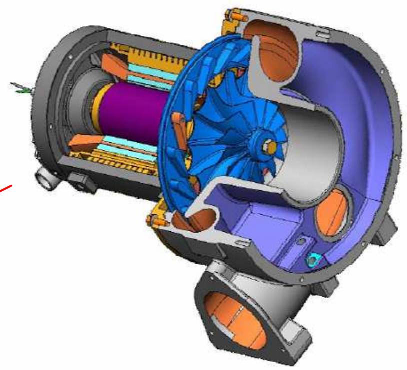
Electrical Turbo-Compound (John Deere, Caterpillar)

Exhaust turbine generator (Visteon TIGERS)

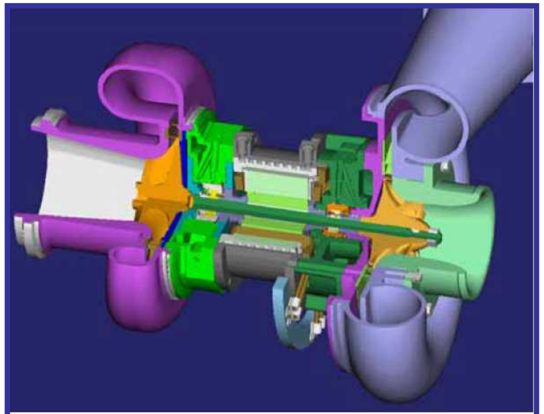
Electrical turbo-compound as a separate module





John Deere electrical turbo-compound

Electrical turbo-compound integrated into turbocharger



Caterpillar electrical turbo-compound

How to regenerate the power?

Converting the kinetic power flow

The turbine, in which not only kinetic energy but also some thermal energy is regenerated, is the basic element that serves in a variety of applications:

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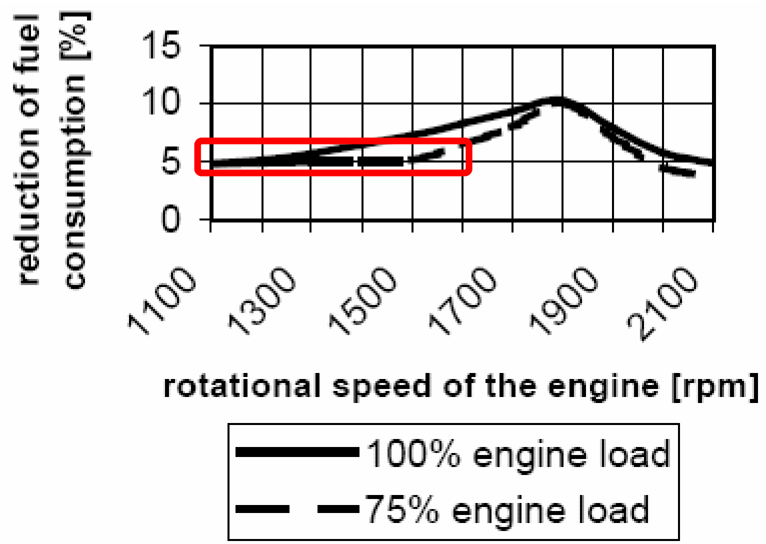
Electrical Turbo-Compound (John Deere, Caterpillar)

Exhaust turbine generator (Visteon TIGERS)

Fuel economy of about 3 to 5% on cycle

Up to 10% for the peak values.



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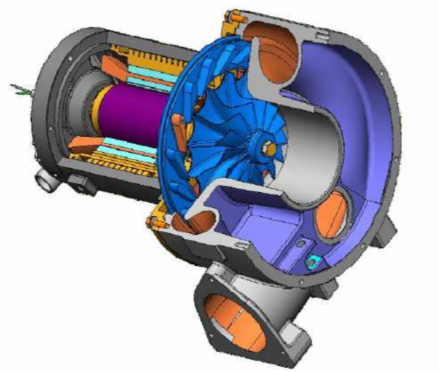

John Deere electrical turbo-compound

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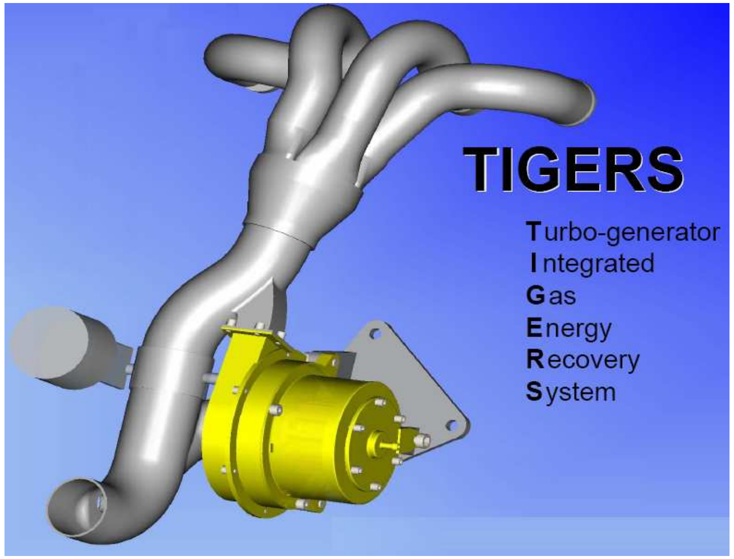
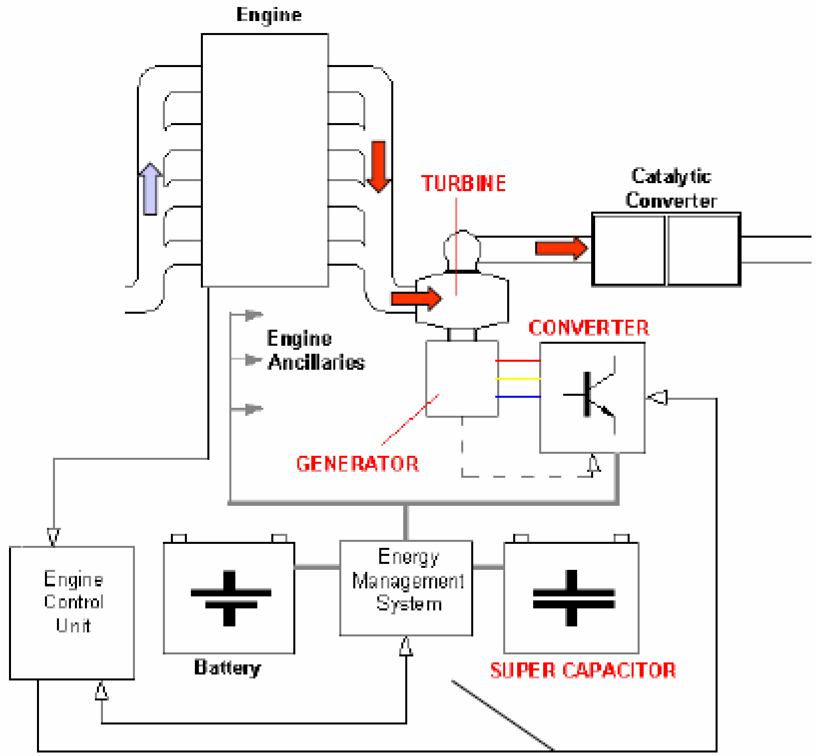


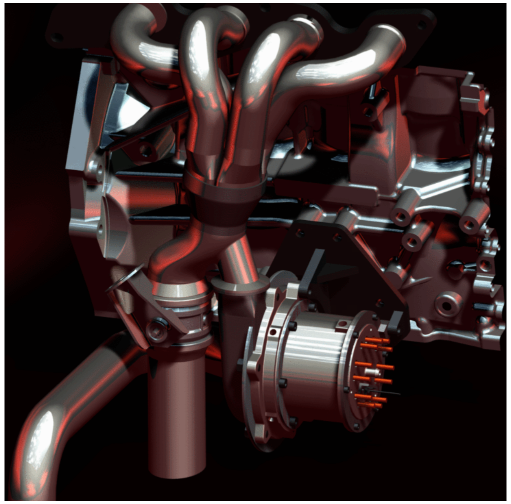


How to regenerate the power?

Converting the kinetic power flow

TIGERS - Turbo-generator Integrated Gas Energy Recovery System

- Drives a small switched reluctance generator
- Creates enough electricity (6 kW) to power a car's electrical system and engine accessories.
- Small turbo-generator installed in a by-pass waste pipe fitted just below the engine exhaust manifold.
- A valve linked to the ECU allows some of the high-energy exhaust gases to pass through a turbine to drive the generator, depending on engine load conditions.
- Typically the 800º C gases have a velocity of 60m/s and a mass flow rate of 0.05 kg/s, providing enough energy to spin the generator at up to 80,000 rpm and create electrical power of up to 6kW—sufficient to handle the car's electrical systems.
- Fuel consumption could be reduced from between 5%–10%.
- Merit of being small and low cost for interesting benefits.



TIGERS Group

- Visteon UK Ltd in Coventry
- Switched Reluctance Drives of Harrogate
- The University of Sheffield Electrical Machines & Drives Research Group.

How to regenerate the power?

Waste heat regeneration based on power flows

1. **Thermal power flow**
2. **Kinetic power flow**
3. **Chemical power flow** **(non-combusted HC, CO, Soot)**
4. **Upper latent heat flow**

How to regenerate the power?

Chemical power flow (unburnt fuel)

Carbon-monoxide – Directed to catalyst where converted to CO2 without heat regeneration

Hydrocarbons – Directed to catalyst where converted to CO2 without heat regeneration

Soot – Stored in Soot filter and burnt once in a while

These power flows are responsible for the temperature increases in the exhaust catalyst. (+30 – +85K)

Exothermic reactions in catalyst are currently not exploited

The heat is blown out of the exhaust into the atmosphere

These power flows can only be regenerated when the exhaust heat after the catalyst is regenerated.

Waste Heat Regeneration is to be done after the catalyst

How to regenerate the power?

Waste heat regeneration based on power flows

1. **Thermal power flow**
2. **Kinetic power flow**
3. **Chemical power flow (non-combusted HC, CO, Soot)**
4. **Upper latent heat flow**

How to regenerate the power?

Converting the power flow of upper latent heat

Thermo-dynamics (to obtain mechanical power)

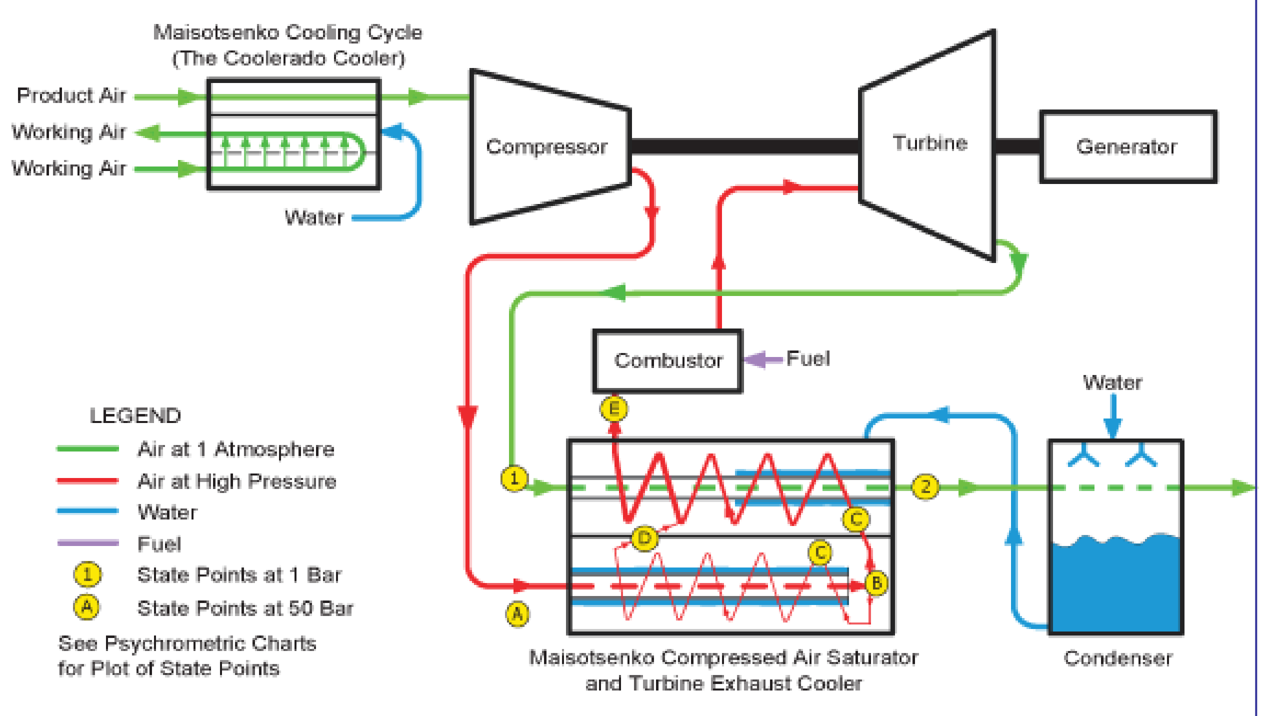
Maisotsenko Combustion turbine cycle (with heat and mass transfer)

Condensing boilers

Exhaust gases are cooled to temperature below condensation point with water

Warm water is used for first stage of heating of fresh air

Exhaust gases of turbine system can be as low as 50℃



Maisotsenko Combustion Turbine Cycle (MCTC) with a Maisotsenko compressor inlet cooler

How to regenerate the power?

Converting the power flow of upper latent heat

Thermo-dynamics (to obtain mechanical power)

Maisotsenko Combustion turbine cycle (with heat and mass transfer)

Condensing boilers

1 m^3 natural gas

10 m^3 air

COMBUSTION

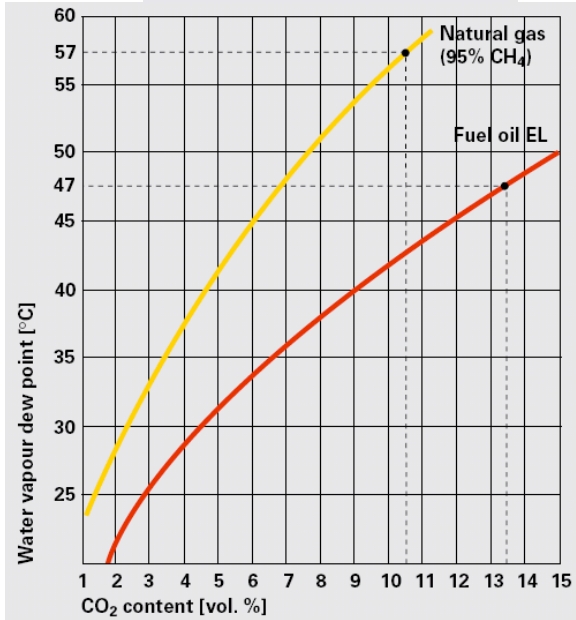
HEAT

8 m^3 N_2

1 m^3 CO_2

2 m^3 H_2O

- Condensation temperature = **57 °C**
- Cooling down of water below this temperature liberates upper latent heat which represents **11%** of total heat content
- This is realized in a stainless steel heat exchanger and is used for heating water
- Condensate requires adapted exhaust and heat exchanger materials



Why WHR is to be introduced

Technologically speaking : WHR is interesting for racing and mainstream vehicles

There are many technical possibilities

More options expected from recent and future developments.

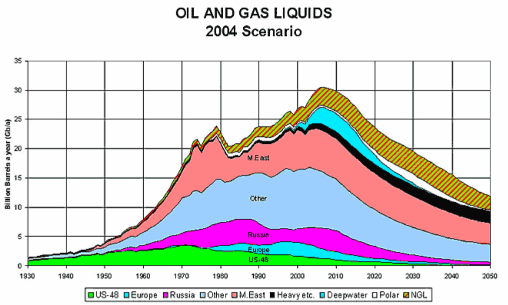
In 2007, apart from a very few applications, WHR is still not applied in mainstream vehicles, nor in racing

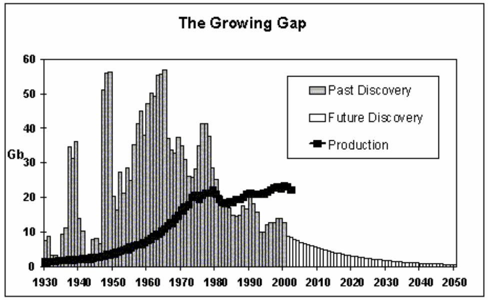
We believe that is going to change

Why WHR is to be introduced

Because the World is changing…

Peak Oil





We need to reduce

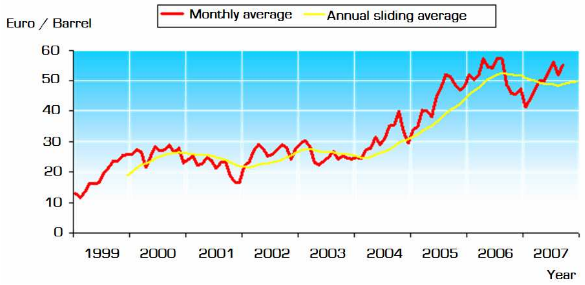
fuel consumption

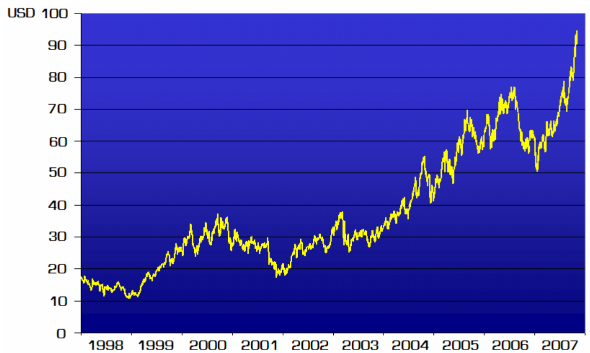
Changing Climate

We need to reduce

CO_2 emissions

Oil price is going up





We want to reduce

fuel consumption

…Waste Heat Regeneration fits in the global picture

Introduction of WHR in racing

Motorsport has a role to play as a technology driver

May 2007

Formula One 2011: Power-Train Regulation Framework

A Briefing Note for the Formula One Manufacturer s' Advisory Committee

Dr Burkhard Goeschel	Chairman, FOMAC
Max Mosley	President, FIA
	BMW Group Ferrari Ford Motor Company Honda Motor Company Mercedes Renault Toyota VW-Audi Group

NOTE: *PRELIMINARY DOCUMENT – CHANGE MAY OCCUR DUE TO ONGOING DISCUSSIONS WITH THE MANUFACTURERS AND SIMULATION WORK BY RICARDO*

Version 1.3	*Tony Purnell and Peter Wright, 4/5/07 updated 23/5/07*
Reviewed by:	*Prof. Neville Jackson, Technical Director, Ricardo* *Max Mosley, President, FIA* *Prof.Burkhard Goeschel, Chairman, FOMAC* *F1 Engine Representatives, Barcelona, 13th May*

October 24, 2007

FEDERATION INTERNATIONALE DE L' AUTOMOBILE

PRESS RELEASE
WORLD MOTOR SPORT COUNCIL

The World Motor Sport Council met in Paris on 24 October, 2007. The following decisions were taken:

FORMULA ONE WORLD CHAMPIONSHIP

There will be a total freeze on engine development for a period of 10 years, starting from 2008. A change can be made after five years but only with the unanimous agreement of all stakeholders and following a further two-year notice period. Total freeze means that there will be no exceptions for development of certain parts of the engine, as is the case under the current regulations.

A number of amendments were adopted for the 2008 Sporting Regulations and the 2008 and 2009 Technical Regulations. For full details please refer to www.fia.com.

Introduction of WHR in racing

Motorsport has a role to play as a technology driver

- Increase social acceptance of racing
- Engine performances in high end racing are very close anyway
- Teams that successfully introduce WHR technologies can increase the gap with their competitors, a new race in racing is starting
- Engineers will pick up WHR as the subject that makes the difference in a race, and meanwhile work toward better fuel efficiency for road going vehicles
- Various WHR technologies need to compete on the track (ORC – H2P – TE-…) (keeping in mind the different trade-off between specific power / efficiency)

Heat2power offers solutions for racing and mainstream vehicles

Choosing the right WHR principle

The automotive WHR solution needs the following characteristics:

- Operate within the waste heat temperature range of the ICE's exhaust gases
- Compact (needs to fit in existing cars)
- Lightweight
- High specific power
- Best possible efficiency level in all working points
- Easy to adapt in an industrial equipment
- Easy to adopt (no hazardous materials, chemicals)
- Free of particular maintenance
- Cost effective

Choosing the right WHR principle

The racing WHR solution needs the following characteristics:

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- Compact (needs to fit in existing cars)
- Lightweight
- High specific power
- Best possible efficiency level in all working points
- Easy to adapt in an industrial equipment
- Easy to adopt (no hazardous materials, chemicals)
- Free of particular maintenance
- Cost effective

Choosing the right WHR principle

We found that apparently interesting technologies have serious drawbacks :

- In a too early phase of development (Thermo-tunneling)
- Too expensive (Thermo-electricity based on Seebeck effect)
- Insufficient fuel economy (Turbo compounding)
- Too difficult to put in place (Organic Rankine cycle, endothermic vapo-cracking)
- Too bulky/heavy (Lithium-hydride cycle, Stirling engine)
- Very complex to integrate in an existing industrial processes (Proe cycle)

We had to come up with our own solution that combines all the characteristics that we judge necessary

The heat2power principle

We have come up with a WHR concept that combines all requirements for application in series production of cars and trucks and in racing :

- Novel thermodynamic principle (patented Sept 2006)
- Heat regeneration efficiency of 18 - 35 % (gasoline engine equivalent)
- Combining this with high specific power (simulated at 45 kW per liter)
- Cost effective (less than 500 Euro for mass production)
- Compact
- Uses conventional technology
- Various configurations possible (add-in or add-on) (simple or optimized)

The heat2power principle

Since the patent is not international yet, the system can only be disclosed after signing a confidentiality agreement. Its main claimed characteristics are :

- High part load regeneration efficiency
- Add-in solution maintains engine block, architecture and associated tooling
- Add-in solution adds approximately 30% to a turbocharged gasoline engine

  (Whereas a Diesel engine costs approximately 100% more than a comparable turbocharged gasoline engine)

- No negative impact on compatibility with expected EU6 emissions regulations
- Complementary with Hybrid Electric Powertrain concepts (with gain on extra-urban)
  - For racing applications an add-on solution is initially proposed
  - No need to change existing engine.
  - For endurance racing : fits between engine and gearbox but could be mounted elsewhere.

Our business

heat2power is not a manufacturing company

heat2power is a know-how company

- Guiding OEMs and racing teams through the different WHR technologies
- Selling engineering services, mainly on truck and automotive applications
- Offers possibility to do WHR prototypes for OEMs and racing teams
- Selling <u>development</u> license agreements around the WHR patents to OEMs and engine developers (including both hardware and control strategies).
- Selling <u>production</u> license agreements around the WHR patents to OEMs and engine manufacturers (including both hardware and control strategies).

WHR Benchmark study

The benchmark study describes more than 20 different WHR systems

These systems are organized by:

- Application
- Type of technology
- Performances
- Cost

For each system an evaluation is made on the eventual possibility for using the technology in the transportation sectors. For the systems that show such a potential, a closer look is made at the financial aspects such as the cost per unit and the levels of investment required for high volume production.

Also is discussed how the WHR performances match an automotive application with various points of part load operation, the power density, the weight and how such a system would be integrated into a vehicle.

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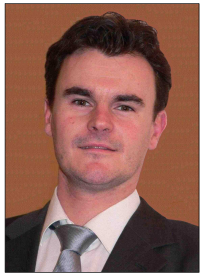

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