Waste Heat Recovery in Marine Propulsion Systems

SNAME, Athens/Greece, February 2014

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Contents

- Introduction
- Mechanical Turbocompounding
- Electrical Turbocompounding
- Hybrid System
- Organic Rankine Cycle (ORC)
- Stirling Engine
- Ericsson Engine
- Thermo-Electric Generator (TEG)
- Comparison of technologies

Contents

- **Introduction (Ricardo / HRS)**
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- Electrical Turbocompounding
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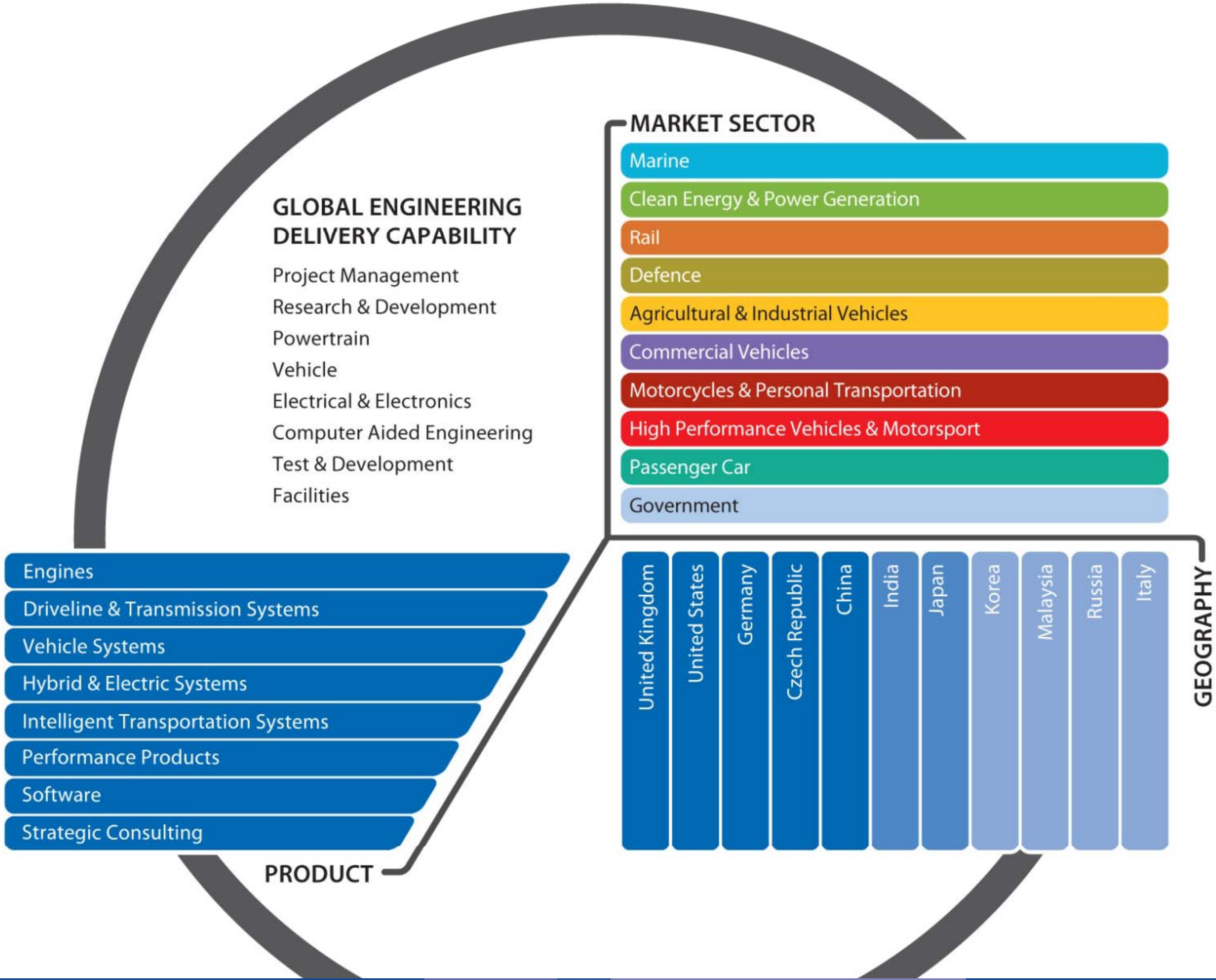
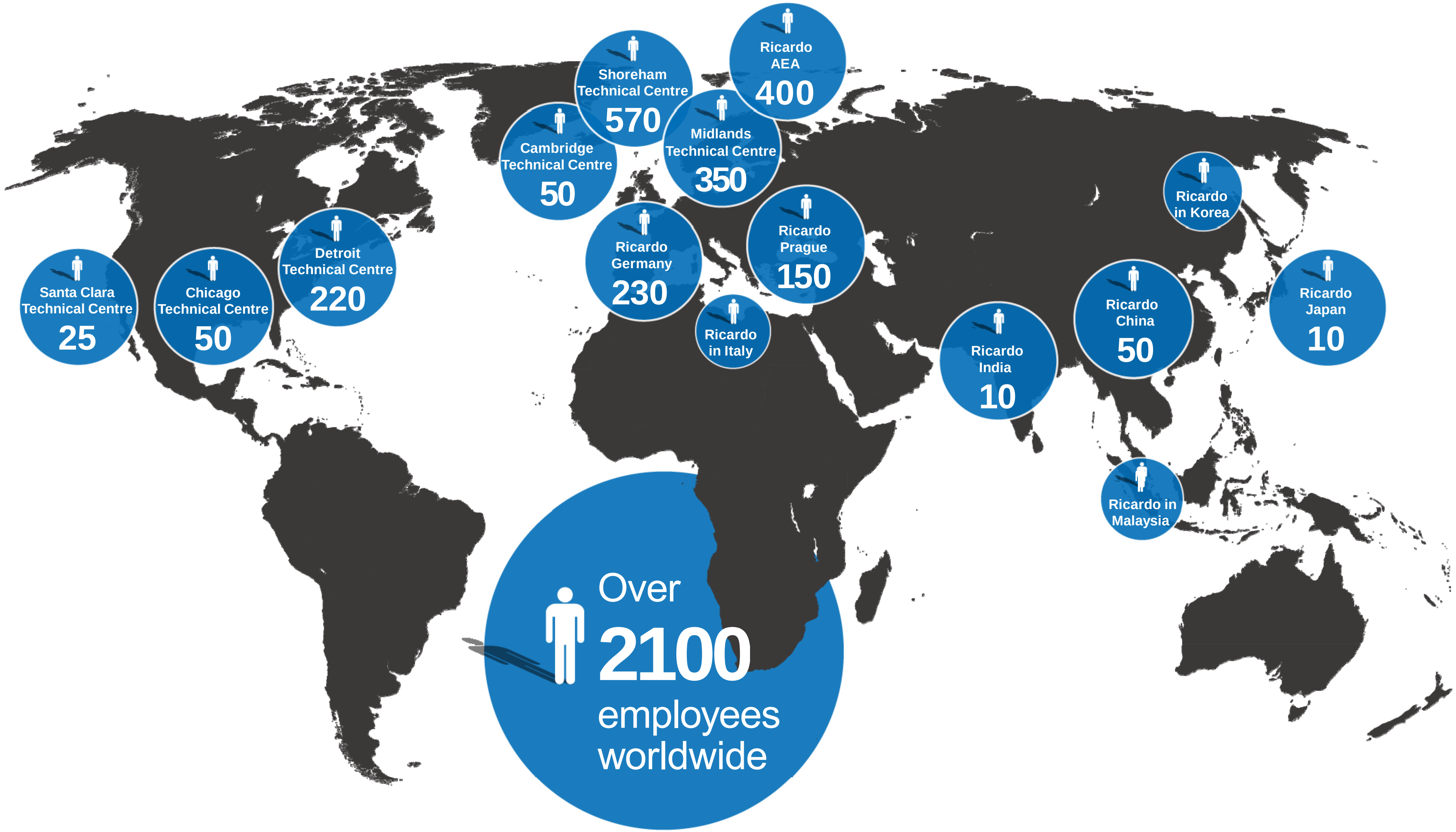
- Stirling Engine
- Ericsson Engine
- Thermo-Electric Generator (TEG)
- Comparison of technologies

Our Strategy

Market Sectors provide domain expertise and ensure relevance, Product Groups provide deep content technology and delivery via world class global engineering teams



Where we are



Shoreham Technical Centre 570
Ricardo AEA 400
Cambridge Technical Centre 50
Midlands Technical Centre 350
Ricardo in Korea
Detroit Technical Centre 220
Ricardo Germany 230
Ricardo Prague 150
Santa Clara Technical Centre 25
Chicago Technical Centre 50
Ricardo Japan 10
Ricardo China 50
Ricardo in Italy
Ricardo India 10
Ricardo in Malaysia
Over 2100 employees worldwide

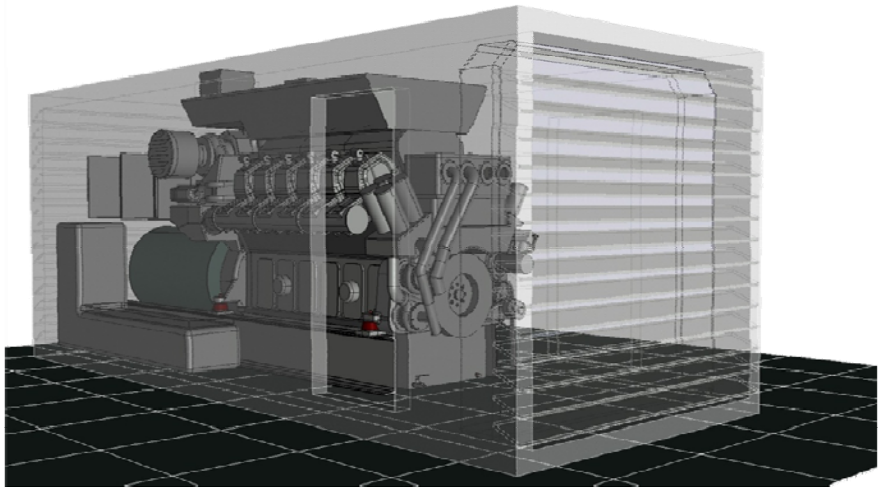
Our Heritage

More than 90 years of successful project delivery across multiple market sectors

Delivering excellence through innovation and technology

Cost effective solutions
CO_2 reduction
Product performance enhancements
Skills and capability transfer

New High Speed Diesel Engine Family - ~4.5L/Cyl for V12 / 16 / 20 Stationary and Off-Highway Applications in Development



Approach

- Global project team (>25 people) centred at Ricardo Schwäbisch Gmünd involved with customer in various work streams
  - Design
  - Controls
  - Combustion & Emissions
  - Analysis
  - Reliability

Situation and Objective

- Fast delivery of conceptual design in ~3 months with team of 25 engineers for basic decisions (bore, stroke, V-angle)
- Fast track programme for commercialisation of single market segment
  - 3D-design and analysis, drawings and supplier interaction to enable parts in time for
  - Concept design frozen and detailed design ongoing
- Platform development progressing in parallel

Value to Customer

- Ricardo offers great experience with many recent clean sheet engine design programmes for Large Diesel, Gas and DualFuel Engines
- Time to Market significantly reduced compared with typical OEM development duration
  - Experienced staff with broad background
  - Flexibility of team vs. Work stream needs
- Comprehensive learning from global extensive On- and Off-Highway experience brought into programme

25XXX

Our Clients

We have experience working with leading companies across a number of demanding market sectors

Passenger Car

Audi, Mercedes-Benz, BMW, VW, GM, Jaguar, Toyota, Mitsubishi, Ford, Nissan, Chery, Shengrui, Fiat, Honda, SAIC

High Performance Vehicles & Motorsport

Porsche, Lamborghini, Peugeot Sport, Bugatti, Renault Sport, McLaren, AMG

Commercial Vehicles

Volvo, Mitsubishi Fuso, International, Daimler, Scania, Paccar, Perkins, Freightliner, Detroit Diesel

Agricultural & Industrial Vehicles

IAI, Cummins, Deutz, JCB, Bosch Invented for life, Caterpillar, John Deere, Liebherr

Motorcycles & Personal Transportation

Piaggio, Harley-Davidson, Ducati Corse, Victory, Royal Enfield, Triumph, FPR, Indian, Honda, BMW

Marine

Volvo Penta, Fairline, Bergen Shipping, Suzuki, Hyundai Heavy Industries Co., Ltd., Mercury Marine, ExxonMobil

Rail

Bombardier Transportation, Bombardier, Indian Railways, FPT, LH Group, Scomi, Voith, mtu, Alstom

Clean Energy & Power Generation

bp, Duke Energy, Shell, EDF, openhydro, QinetiQ, Dresser-Rand, Guascor, British Gas, npower, UTC Fuel Cells, GDF Suez, Hansen Transmissions, WinWinD, David Brown Engineered around you, Samsung

Defence

TACOM, UK MoD, Land Rover, Steyr, Army, General Dynamics, International, Cummins, Oshkosh, DE&S, BAE Systems, FMV, Force Protection

Government

ICCT The International Council on Clean Transportation, United States Environmental Protection Agency, California Air Resources Board, European Union, Technology Strategy Board Driving Innovation, LowCVP low carbon vehicle partnership, energy technologies institute, NHTSA, Department for Transport

Engines

Engineering solutions of all types of engines from concept to production incorporating the very latest in technological innovations. Design, Test & Validation, and Low-Volume Manufacture.

Experienced delivery of all engine types

Motorcycle and Scooter

Passenger Car Diesel and Gasoline

Motorsport and High Performance

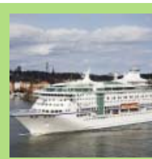
HEV and Waste Heat Recovery

Research and Advanced

Off Highway Heavy Duty Diesel

On Highway Heavy Duty Diesel

Alternative Fuels



Large Marine and Industrial

Bespoke Military and UAV engines

Targeted Solutions for the Global Industry

- Multi sector technology road maps for emissions & efficiency
- Minimum cost CO_2 reduction
- Upgrades for performance, emissions, efficiency and cost
- Turnkey project delivery combining innovative technical and business solutions
- High value low volume engine design, development and manufacture
- Objective and subjective NVH development for all engine types and applications

Capability

- Design and development of all types of gasoline, diesel, biofuel and gas engines
- Global competence for on & off highway engines up to 560kW
- Global expert teams specialise in specific engine types
  - Large Engines
  - Motorcycles
- Production calibration including OBD and homologation
- Control algorithm development
- Warranty and cost reduction
- Forensic services and failure analysis

Advanced Product Offerings

- TVCS -Twin Vortex Combustion System for minimum diesel particulate and DPF deletion
- SGDI - Spray-guided gasoline combustion technology for diesel equivalent efficiency
- High efficiency lean & EGR boosted DI
- Waste heat recovery systems for all engine applications
- High efficiency aftertreatment
- Novel concepts and new high efficiency combustion cycles
- Innovative piston technology for reduced cost, weight & friction

Driveline & Transmission Systems

Global 'One-Stop' Capability from Concept to Production for Transmission and Driveline Systems. Design, Prototype, Test & Validation, and Low-Volume Manufacture.

RICARDO

Experienced delivery of all transmission and driveline types

AT 6,7,8+ Speed | DCT | AMT | Hybrid | EV Drive | CVT | Manual | Motorsport | Advanced Drivelines | Transfer Cases

Targeted Solutions for the Global Industry

- Increased efficiency and reduced emissions / CO_2
- Compressed timescales through modular solutions and pre-developed IP
- Cost and weight reduction
- Integrated powertrain solutions
- Technology 'roadmapping'

Design & Analysis | Manufacture | Assembly | Test

'One-Stop' Capability

- Global delivery
- Mechanical, hydraulics, electronics and software
- In-house prototype manufacture and assembly
- Low volume production supply
- Full in-house test capabilities
- Hybridised and EV transmissions
- Benchmarking / target setting
- Advanced toolsets for geartrain design and shift quality
- Brand attribute development
- Productionisation

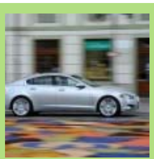
Advanced Product Offerings

- Modular DCT, AT, AMT and CVT control software and algorithms
- Flywheel-based energy capture and storage systems
- Advanced actuation and dry clutch solutions for efficiency, cost and performance
- Hydraulic module design and development
- Reliability and efficiency enhancing sub-system technologies for wind-turbines
- Torque vectoring and AWD

Vehicle Systems

The optimum use of digital tools to deliver high quality vehicles using the latest available technologies in the quickest possible time and at lowest cost.

Experienced delivery of vehicle systems

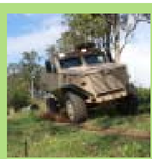


Complete Vehicle Design

Electrical Systems Integration

Lightweight Structures (incl crash)

Powertrain Integration (incl HEV/EV)



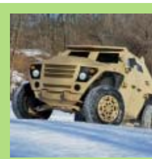
Thermal Systems Development

Chassis and Suspension Design

Vehicle Attribute Optimisation

Energy Recovery / Optimisation

Prototype Vehicle Build



Complex Systems Analysis

Targeted Solutions for the Global Industry

- Synergistic systems integration approach enabling cost, weight and fuel consumption optimised development
- Fast-track product development processes using a structured quality gateway approach
- Flexible and collaborative approach providing tailored, innovative and imaginative solutions on a global basis
- Technology transfer, training, and on site engineering support

Capability

- Full vehicle programme delivery capability on a global basis
- Powertrain integration
- Electrical systems integration
- Chassis and suspension
- Lightweight structures
- Thermal systems development
- Vehicle attribute optimisation (NVH, Crash, Vehicle Dynamics)
- Vehicle packaging and DMU
- Defence and special vehicle design, development & build
- Development /validation testing
- Prototype build

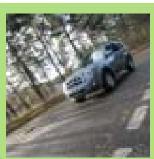
Advanced Product Offerings

- Complex systems modelling including Total Vehicle Fuel Economy approach
- Meeting aggressive CO_2 targets through innovative vehicle and future transport solutions
- Active and critical safety systems
- Energy recovery and machine optimisation through the integration of hybrid, EV and flywheel technologies
- Use of advanced materials, composites and lightweight structures

Hybrid and Electric Systems

Unparalleled experience and expertise in vehicle hybridization, electrification, and the deployment of next-generation energy management and storage solutions

Experienced delivery of hybrid and electric systems

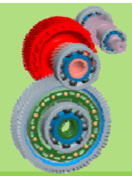


Micro to Full Hybrid

Full EV

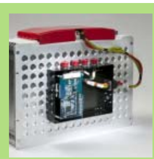
Range Extended

Energy Storage



EV Drive

Fuel Cells



Battery Dev

Control

Charging Stations

Grid distribution

Targeted Solutions for the Global Industry

- Reducing the cost and weight of energy storage
- Compressed development times
- Battery system development Centre of Excellence
- Complex programme management and delivery
- In-depth research of consumer attitudes and predicted behaviours based on the mass roll-out of plug-in vehicles

Capability

- World-class HEV development resources and facilities
- Solutions for the entire HEV product life-cycle
- Business case evaluation
- Safety critical design and control strategy development
- Design and simulation
- NVH
- Power electronics and e-machines
- Range extended EVs
- Systems integration
- Thermal systems

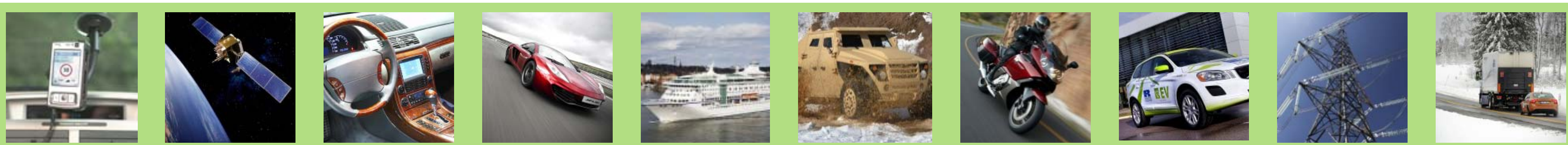
Advanced Product Offerings

- R&D for future hybrid and electric vehicle efficiency improvement
- Next-generation energy management and storage
- Charging station development expertise including smart metering and power distribution strategy development
- Solutions for latest legislation, regulation and safety

Intelligent Transportation Systems

Connected vehicle solutions that improve safety and performance, lower emissions, increase availability and lower the operating costs of mobile assets

Experienced delivery of intelligent transportation systems



Telematics & Fleet Management	Remote Monitoring & Prognostics	Infotainment and Connected Vehicle	Driver Coaching	Vehicle Control and Mechatronics	Total Vehicle Fuel Economy	Prototyping & Production Engineering	Safety Critical Software	Integrated H/EV Energy Management	Autonomous Vehicle Systems

Targeted Solutions for the Global Industry

- Mobile asset performance optimisation
- Reduced emissions
- Increased safety
- Increased convenience
- Efficient logistics
- Integration of vehicles with infrastructure
- Technology trend mapping and cost reduction studies

Capability

- Design and prototype development through to production
- Systems architecture, production engineering, and standardization
- Implementing connected vehicle hardware and services
- Wireless connectivity
- V2I and V2V safety and and mobility applications development
- Neural networks based prognostics systems design

Advanced Product Offerings

- Remote monitoring and prognostics
- Driver assistance systems
- Advanced vehicle control systems
  - Intelligent grade negotiation
  - Automatic acceleration and braking
  - Energy-efficient heating and cooling
  - Dynamic route guidance
- Connected vehicle technologies

Ricardo Software

A portfolio of innovative analysis solutions enabling engineers to accelerate powertrain development from concept to delivery.

RICARDO

Component and system analysis of powertrains and vehicles

FEARCE | ENGDYN | PISDYN | RINGPAK | SABR | VALDYN | WAVE | WAVE RT | VECTIS

Mechanical Dynamics Solutions for predicting durability, fatigue, NVH and performance

Fluid Dynamics Solutions for predicting performance and emissions

Targeted Solutions for the Global Industry

- Software designed by powertrain engineers, for powertrain engineers
- Proven accuracy, functionality and value
- Applicable to any powertrain system, from small two-stroke to large stationary/marine Diesel
- Tutorials and documentation
- Global footprint of local sales and support staff
- Multi-language support

Capability

- Fast concept and layout studies - rapidly test ideas and focus development
- Component analysis - refine designs, predict performance and reduce reliance on early physical testing
- Connect components for detailed system analysis - test interactions and focus expensive physical testing on critical issues
- Robust and accurate physics solvers, specifically developed for current and future powertrain technologies

Advanced Product Offerings

- Native CAD import
- Native coupling to Matlab/Simulink
- Industry leading physical solvers for powertrain NVH, durability and combustion
- Patent-pending realtime engine models using WAVE-RT
- Specialized spray and combustion models for direct injected engines
- All tools migrating to a common user interface

Strategic Consulting

Ricardo offers a comprehensive portfolio of proven management consulting services covering the whole vehicle lifecycle:

Strategy

Market and technology studies

Strategy Development

Business planning

Key account management support

Mergers & acquisition support

Post-merger integration

Change Management

Business turnaround

Product Development

- Product specification
- Technology road mapping
- Complexity reduction
- Process reengineering
- PD organisation redesign
- Supplier management
- Core competencies
- Site and facility strategy

Manufacturing / Supply Chain Management

- Plant network strategy
- Remanufacturing
- Factory of the future
- Plant optimisation
- Asset management
- Launch support
- Supply chain management / Order-to-delivery strategy
- Logistics improvement

Procurement / Supplier Management

- Global sourcing
- Negotiation target setting
- Purchasing process reengineering
- Purchasing organization redesign
- Distressed supplier management
- Supplier development
- Value chain restructuring

Sales, Marketing & Aftersales

- Product and brand positioning
- Market segmentation
- Margin models
- Distribution strategy and processes
- Network optimization
- Pricing strategies
- Retail management
- Market launch

Integrated Cost Reduction

Quality and Warranty Management

Introduction HRS

- We will concern ourselves here with combustion engines like Diesel-engines, gas-turbines etc. and the options of converting the heat they can not convert (predominantly the exhaust gas heat) into additional useful work*
- There are a number of physical effects that can be utilised for this
  - Thermodynamic – this embraces cycles (and the respective machines) that can be combined with advantage to the cycle of the primary engine
  - Chemical – these options convert exhaust heat plus available substances (e.g. Diesel-fuel and water) into a new fuel of higher energy content
  - Electro-chemical and electronic – there are physical effects like the Seebeck-Effect and the properties of fast ion-conductors (e.g. BASE), which generate electricity directly from a heat flux over a temperature difference
- Following is a wide overview of these technological options, a quantitative assessment is made of some candidates in order to generate a more detailed impression of the Situation on board ships and ways to adapt WHR plant to that

Contents

- Introduction
- **Mechanical Turbocompounding**
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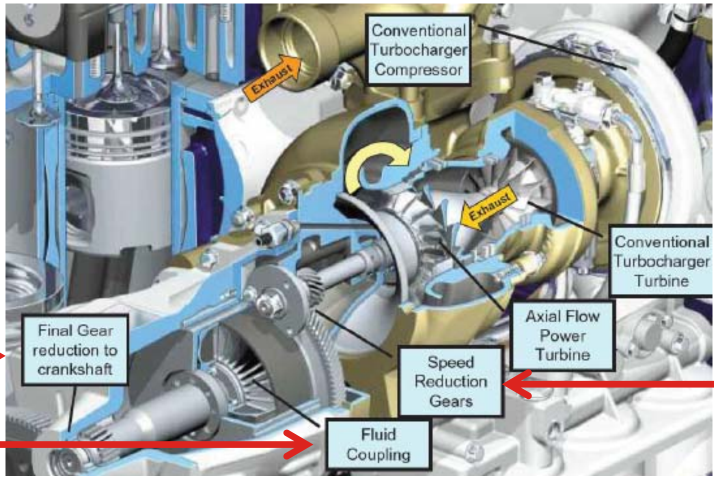
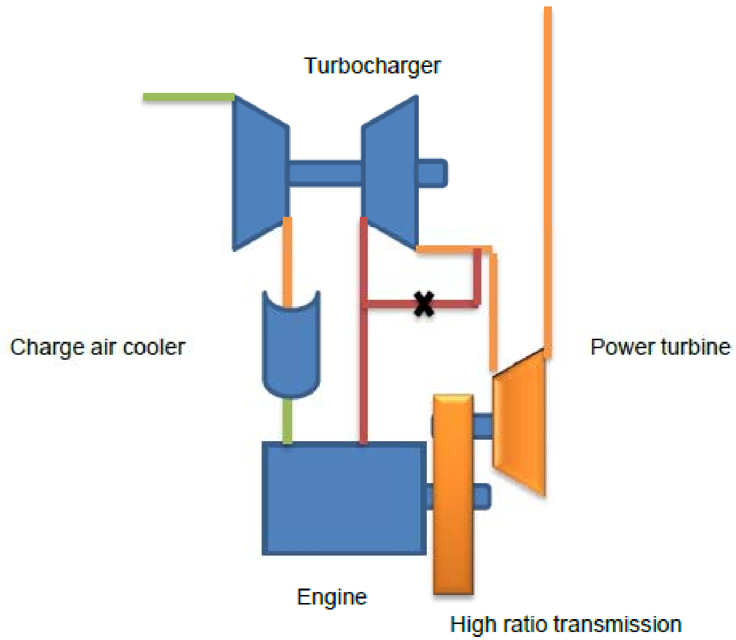
- Comparison of technologies

Operating concept

- Power turbine installed after T/C turbine
- Pressure difference across power turbine used to convert exhaust gas heat energy to mechanical work
- Energy converted to shaft power and fed into the engine via a transmission mechanism, including:
  - a first gear reduction
  - a fluid coupling between power turbine and crankshaft, and
  - a second gear reduction



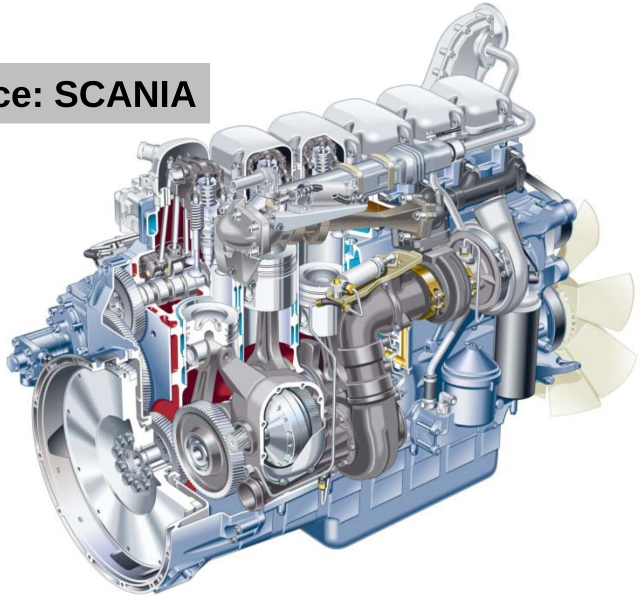


Source: VOLVO

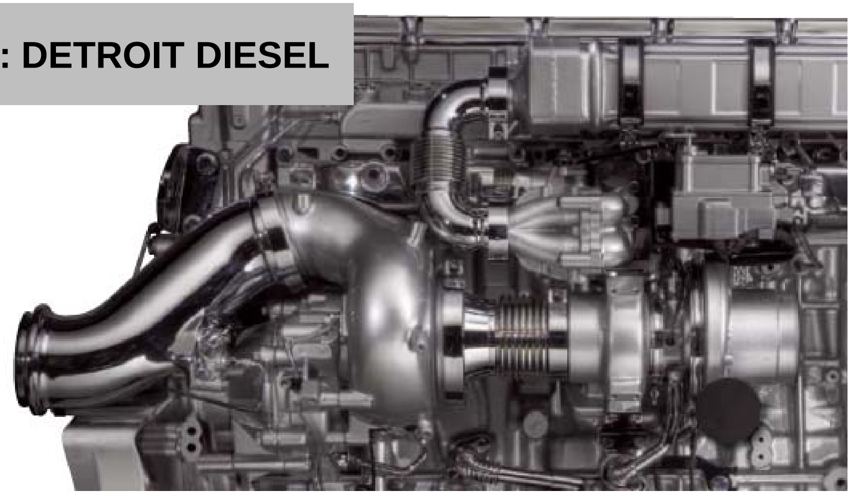
Current status of development/implementation

- Commercial system installation in truck engines

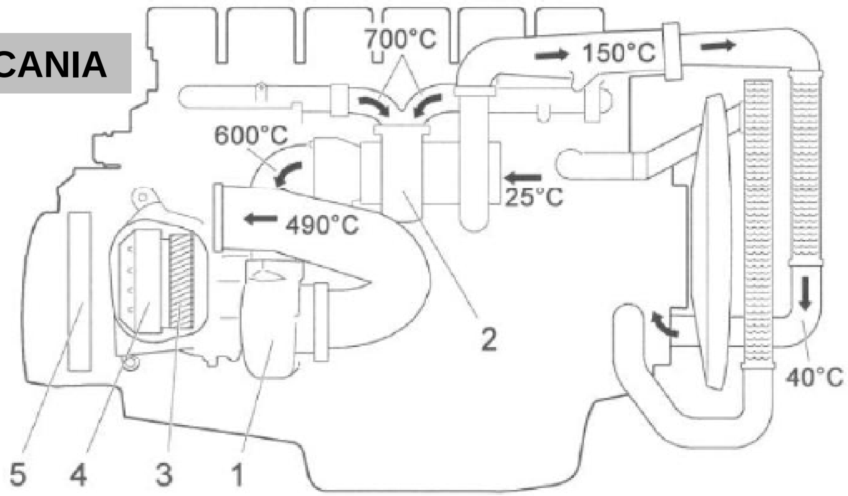
Source: SCANIA



Source: DETROIT DIESEL



Source: SCANIA

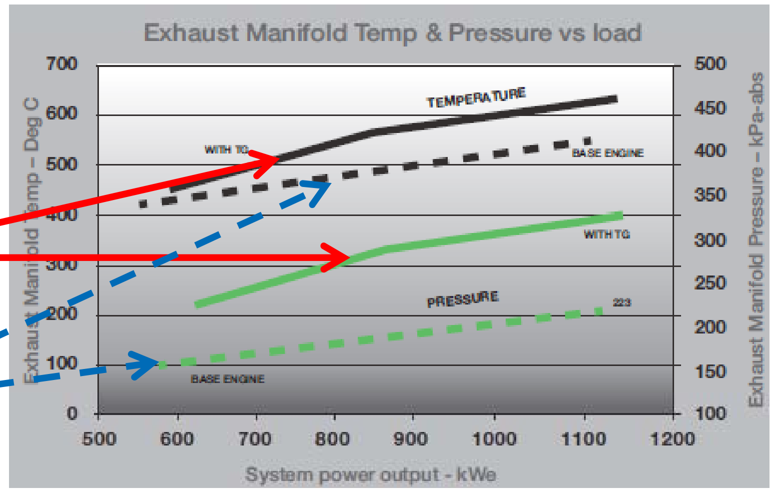


Example of gas temperature distribution in the system

1: Power turbine
2: T/C turbine
3: First gear reduction
4: Fluid coupling
5: Second gear reduction

Limiting factors

- High gear ratios, in combination with high power turbine rotational speeds, make gearbox construction very complex; torsional vibrasions issues
- Additional cooling of exhaust gases reduces aftertreatment systems effectiveness
- Control issues due to complexity
- Impact on T/C operation
  - Need for T/C rematching/optimization - advanced T/C development - due to increase in exhaust manifold pressures (up to ~1 bar) and temperatures (up to ~70 K)
- Impact on engine operation
  - Increase in pumping losses and internal EGR due to increased backpressure; efficiency reduction issues
  - Valvetrain system risks due to more severe exhaust gas conditions
  - Possible solution: derating of engine; same power output with lower fuel consumption



Overall system performance improvement

- BSFC improvement ~ 3% at steady-state full load conditions
- Minimal to negative impact on BSFC at some points, especially at low loads
- Narrow speed range engine with turbocompounding coupled to a CVT with 95% efficiency: fuel efficiency improvement ~ 5%

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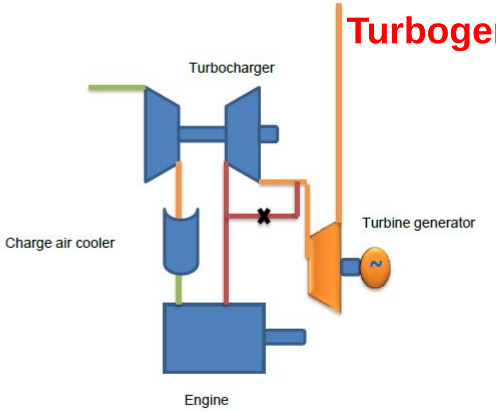
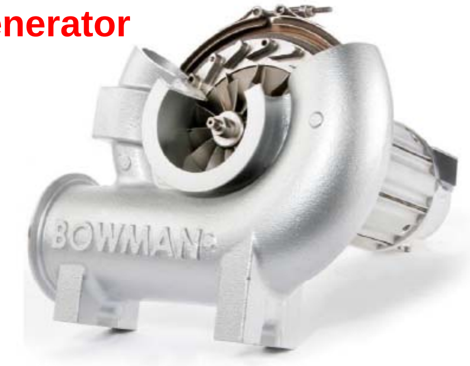
Operating concept

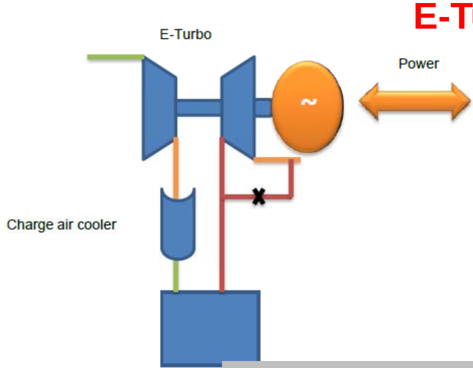
- Turbogenerator
  - Power turbine, with permanent magnet generator on the same shaft, installed after T/C turbine
  - Power Electronics Module for: a) converting generated electrical energy into grid standard AC current, and b) controlling turbine speed
- E-Turbo
  - Electrical machine placed onto T/C shaft
  - Recovered turbine power higher than consumed compressor power - net power used for electricity generation
  - T/C shaft can be motored for boost increase and transient performance improvement



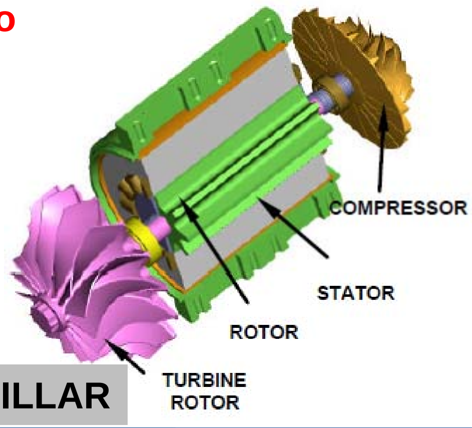
Turbogenerator



Source: BOWMAN



E-Turbo



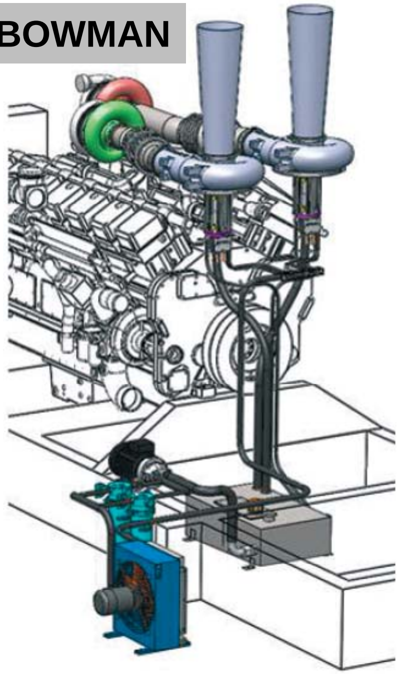
Source: CATERPILLAR

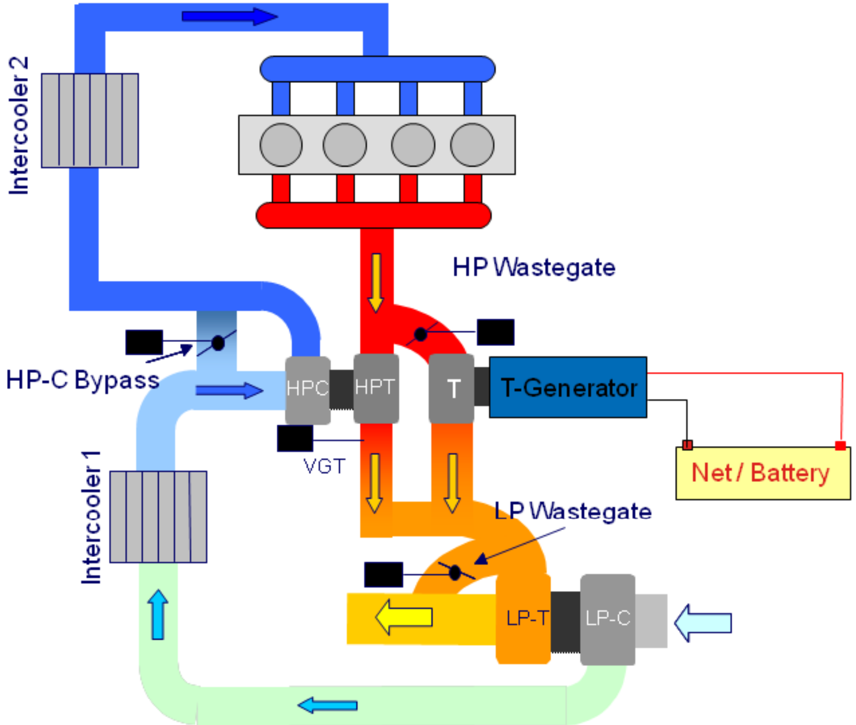
Current status of development/implementation

- Turbogenerator

Source: BOWMAN

Source: BOWMAN

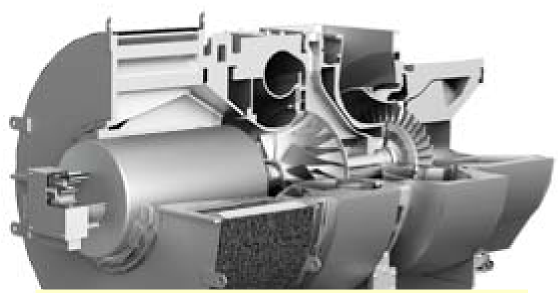




- Commercial system installation in Gensets
  - Fixed geometry turbine for better efficiency at full load
  - Variable geometry turbine for increasing part load and part speed output
  - Due to turbine operation at very low pressure ratios, where the efficiency of the conventional turbines is unacceptably low, extensive design and development effort for new highly efficient turbine geometries is still needed
- Potentiality for incorporation in advanced turbocharging architectures

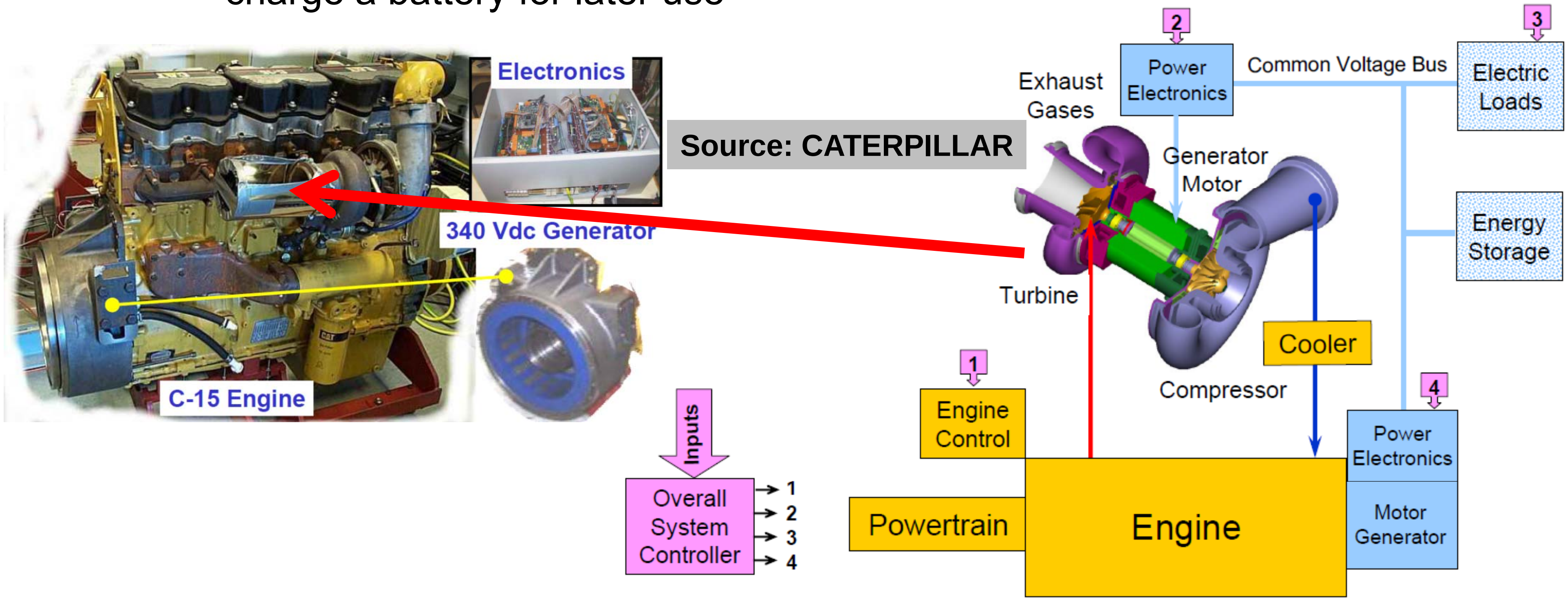
Current status of development/implementation (cont'd)

- E-Turbo
  - Generated electrical energy can be used to:
    - drive a crankshaft motor
    - drive ancillaries
    - charge a battery for later use



MET Hybrid turbocharger

Source: Mitsubishi



Pros & Cons

- Turbogenerator
  - Pros
    - Potentially effective operation over a broad range of speeds and loads due to turbine decoupling from engine
    - Isolated coupling; improved transient performance and emissions
    - Simple addition to existing platforms
  - Cons
    - Operational constraint due to electric machine efficient performance only at an optimum speed over the entire engine speed range

Pros & Cons (cont'd)

- E-Turbo
  - Pros
    - Very small package
    - Shaft can be motored to control boost and improve transient performance and emissions
  - Cons
    - Relatively low energy recovery possibilities due to compressor power demands
    - Durability challenges of electric machine due to high exhaust gas temperatures

Overall system performance improvement

- Turbogenerator
  - BSFC improvement ~ 7% with T/C rematching/optimization
  - High-duty cycle steady state operation for maximum benefit
- E-Turbo
  - BSFC improvement ~ 5% on a cycle basis; ~ 9-10% with high efficiency T/C components at full load conditions

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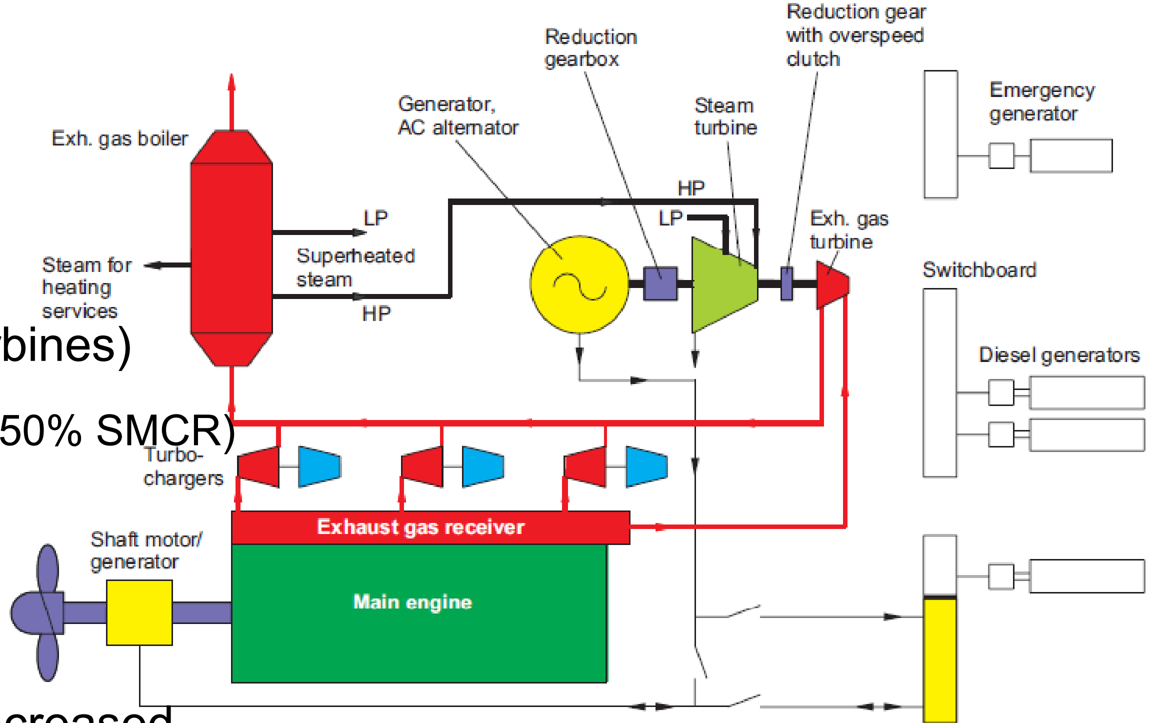
General power concept & arrangements

- Based on water-steam Rankine cycle
- Components
  - Exhaust gas boiler
  - Steam turbine
  - Exhaust gas turbine
  - Generator (common for both turbines)
- Exhaust gas bypasses T/Cs (load>50% SMCR)

  => amount of air reduced

  => exhaust gas temperature after T/Cs and bypass increased

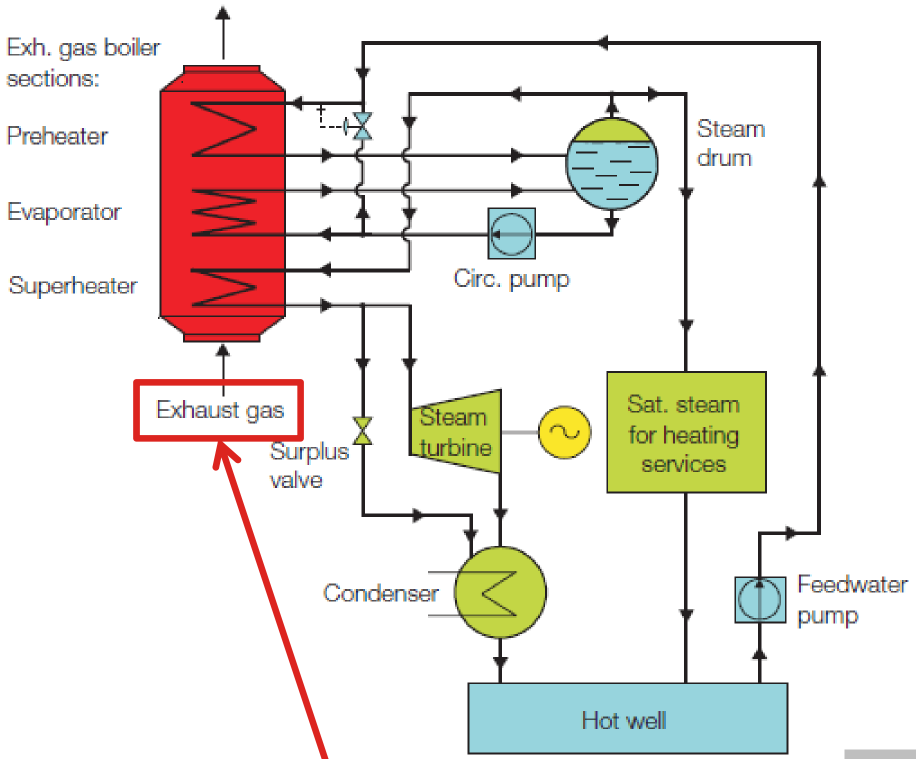
  => steam production from boiler increased

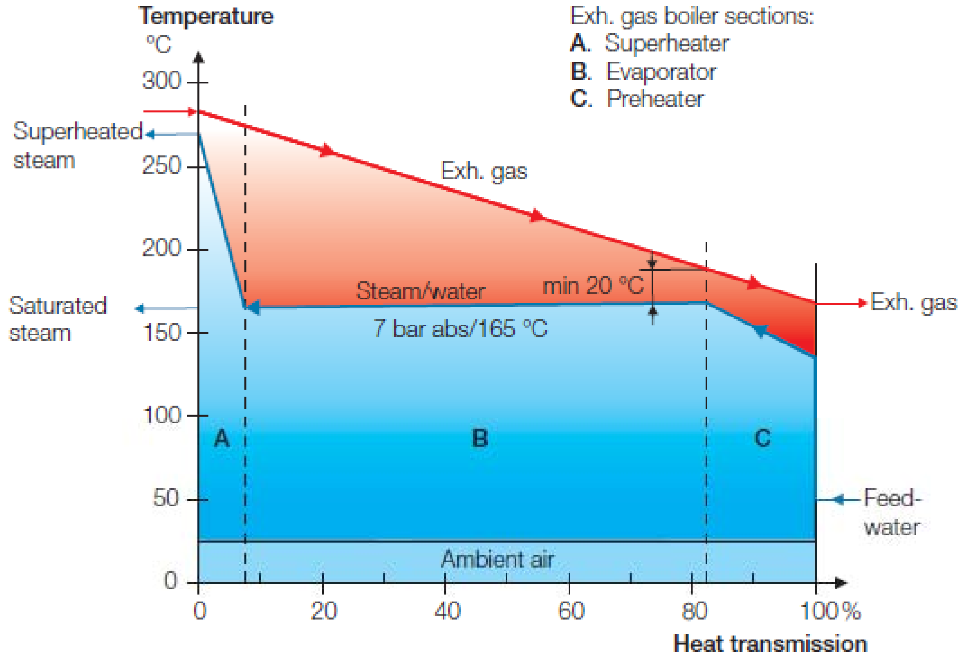


Source: MAN B&W

- Arrangements
  - PTG - Power Turbine Generator: Stand-alone power turbine
  - STG - Steam Turbine Generator: Stand-alone, single- or dual-pressure steam turbine
  - ST-PT - Steam Turbine-Power Turbine Generator: Power turbine and single- or dual-pressure steam turbine

Heat recovery potential from single-pressure Rankine cycle

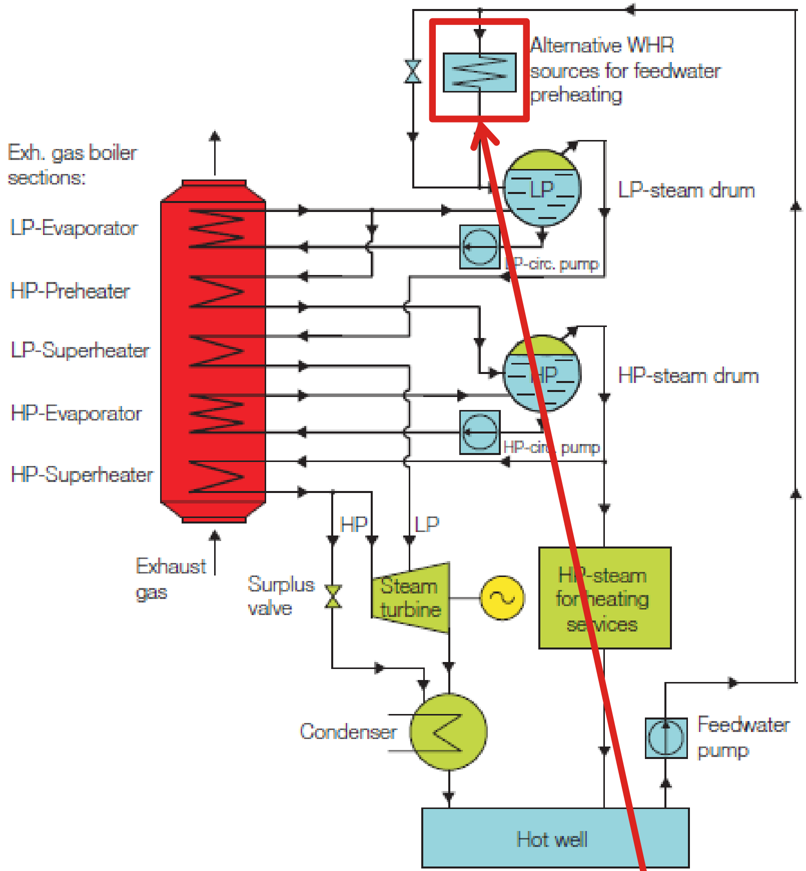


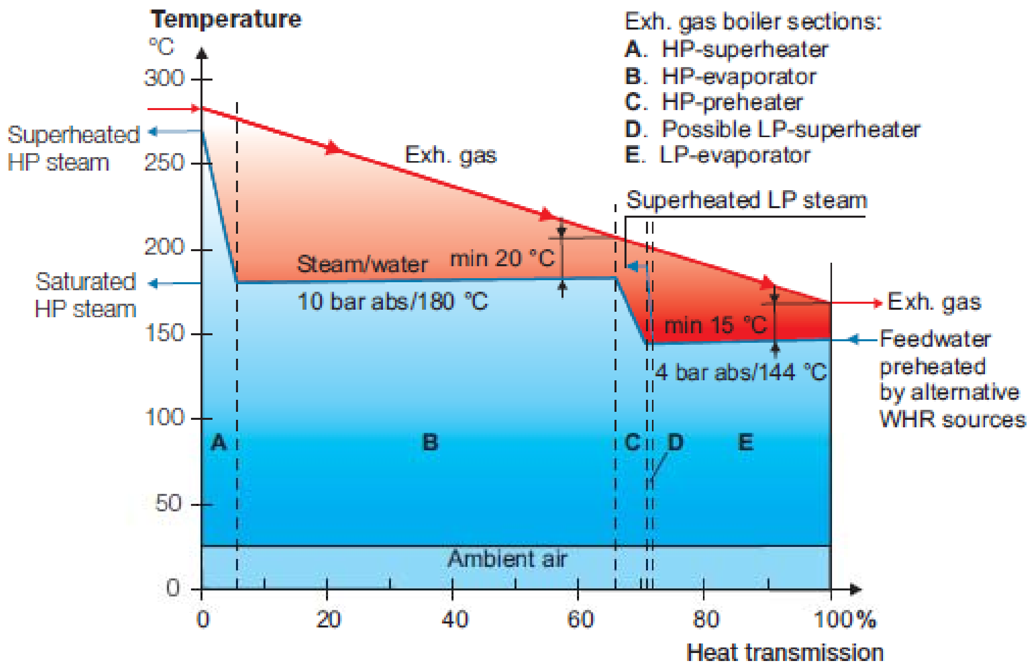


Source: MAN B&W

- Only exhaust gas heat is utilized
- No jacket water heat or scavenge air heat is utilized

Heat recovery potential from dual-pressure Rankine cycle





Source: MAN B&W

- LP preheater cannot be included at the last section of the boiler due to possibility for sulphur oxides condensation on preheater tubes
- Instead, jacket water heat or scavenge air heat is utilized for LP water preheating
- This way, exhaust gas heat exclusively available for increased steam production

Gain from hybrid systems – Dependency on main engine size

- ST-PT single-pressure system
  8-10% fuel consumption reduction
- ST-PT dual-pressure system
  9-11% fuel consumption reduction

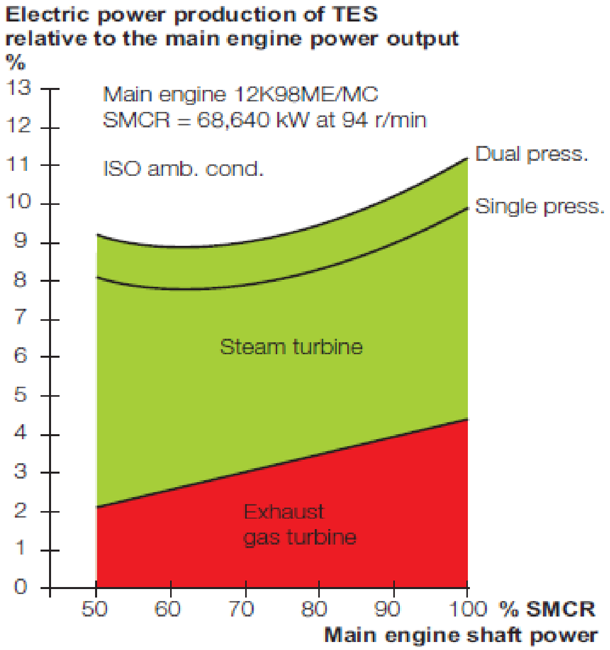
- Engine power / Max. relative power production

Engine power	Max. relative power production
20,000 kW	6.5%
80,000 kW	8.5 %

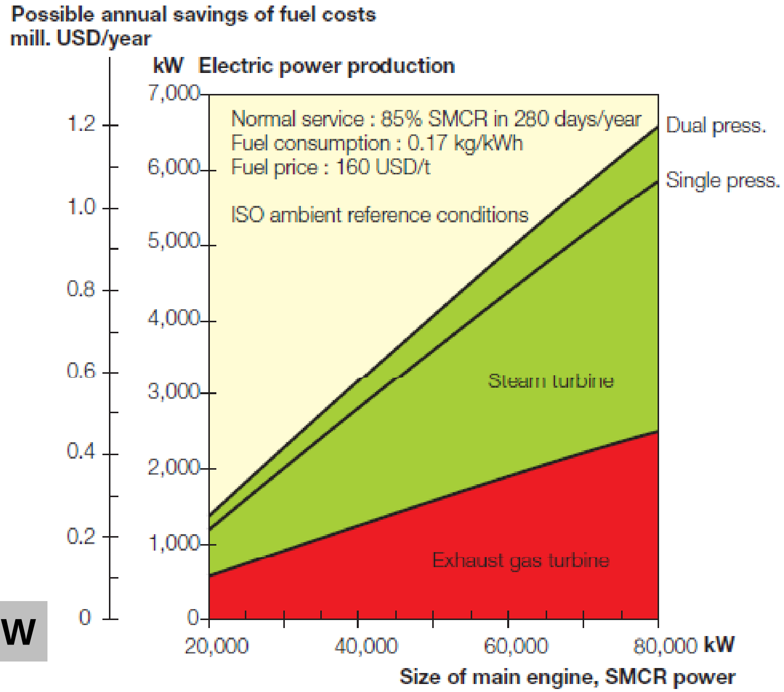
(data for 85% SMCR)

- Rule of thumb

Engine power	System
> 25,000 kW	ST-PT
< 25,000 kW	PTG or STG
< 15,000 kW	PTG or ORC



Source: MAN B&W



Contents

- Introduction
- Mechanical Turbocompounding
- Electrical Turbocompounding
- Hybrid System
- **Organic Rankine Cycle (ORC)**
- Stirling Engine
- Ericsson Engine
- Thermo-Electric Generator (TEG)
- Comparison of technologies

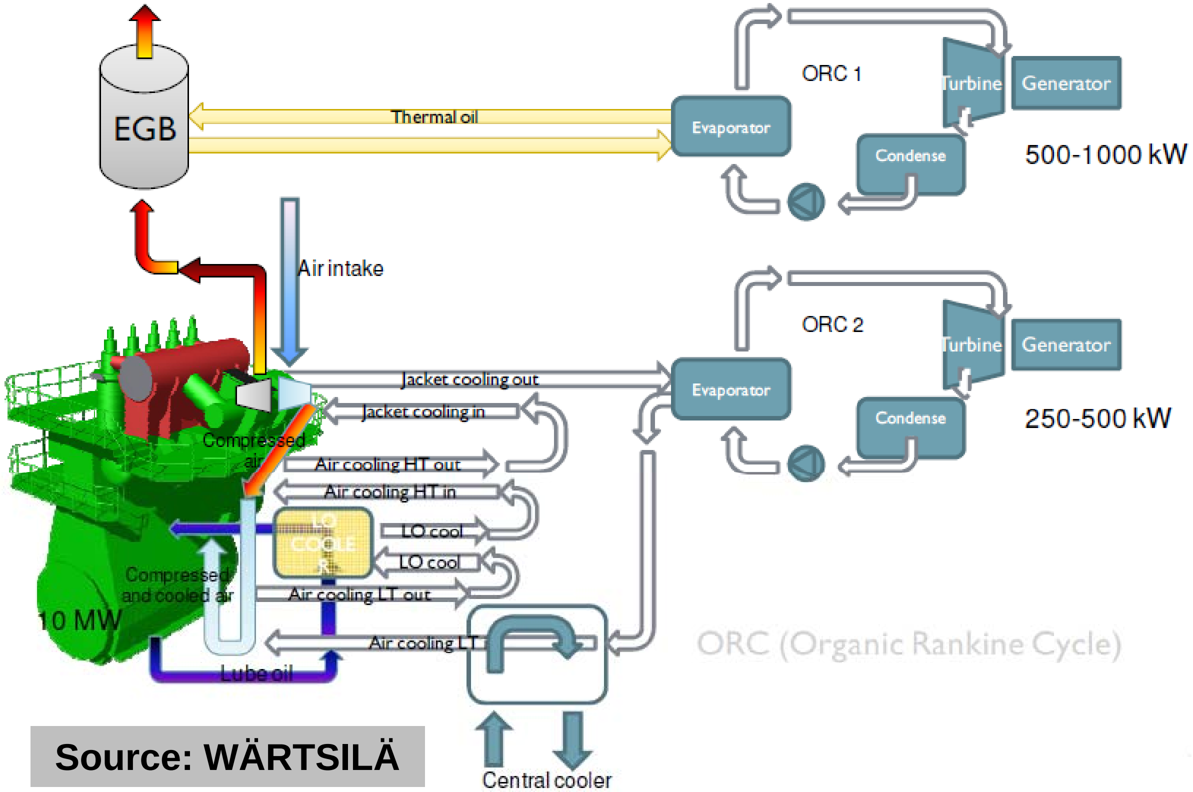
Clausius – Rankine cycle machines in application

- The steam engine that drove the industrial revolution has found its definitive embodiment in large scale (GW) power station employing water as their working fluid and multi stage axial (Parsons) turbines as expanders
- The case for waste conversion is more complicated
- Organic working fluids are of some interest
- After application in large scale electricity production, geothermal/biomass applications, ORC systems are currently developed for:
  - Genset applications
  - Marine applications

  using heat sources such as: exhaust gas and cooling circuit of IC engine and gas turbine exhaust gas
- Ricardo is involved in the development of ORC systems for automotive applications and also for those new applications

Cycle configuration

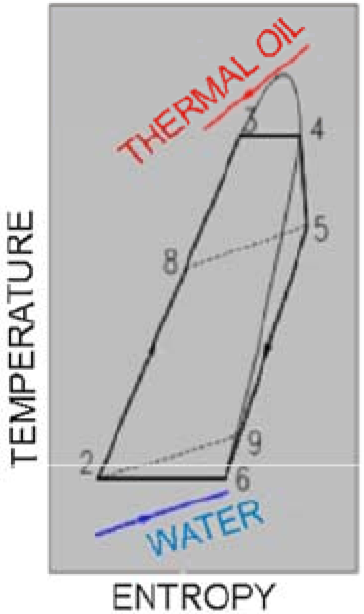
- Based on Rankine cycle with organic working fluids
- Dependence on availability of heat sources (e.g. exhaust gas, jacket cooling water, lube oil, charge air)
- Flexibility of system architecture in case of more than one heat sources, e.g. boilers in series, in parallel, in two individual circuits

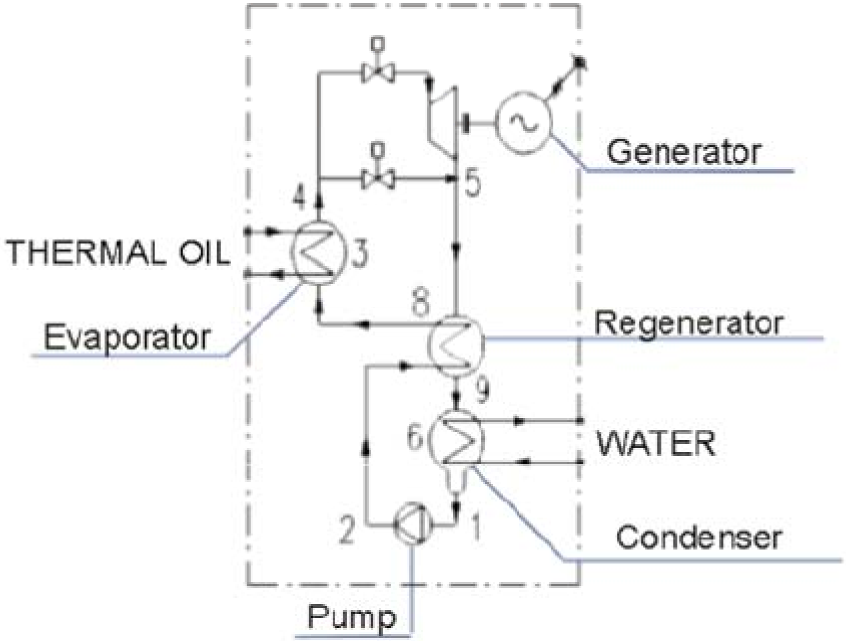


Source: WÄRTSILÄ

Cycle configuration (cont'd)

- System configuration for exhaust gas heat utilization
  - Intermediate thermal oil used since organic fluid is kept only in the primary cycle
  - Regenerator used for cycle efficiency increase





Source: WÄRTSILÄ

Heat exchangers design issues

- Typical **minimum** pinch points for heat exchangers' design:
  - Evaporators & recuperators : 10 ^{o}C
  - Air-cooled condensers: 35 ^{o}C
  - Water-cooled condensers: 3 ^{o}C
- Mediums with high **critical temperature**
  - Lower temperature difference with heat source at the evaporator - reduction in heat transfer irreversibilities
  - Higher mass flow rates and therefore larger and more expensive evaporator
  - Therefore, a compromise must be made for the decision of the **evaporation temperature**

Boundary conditions for marine applications

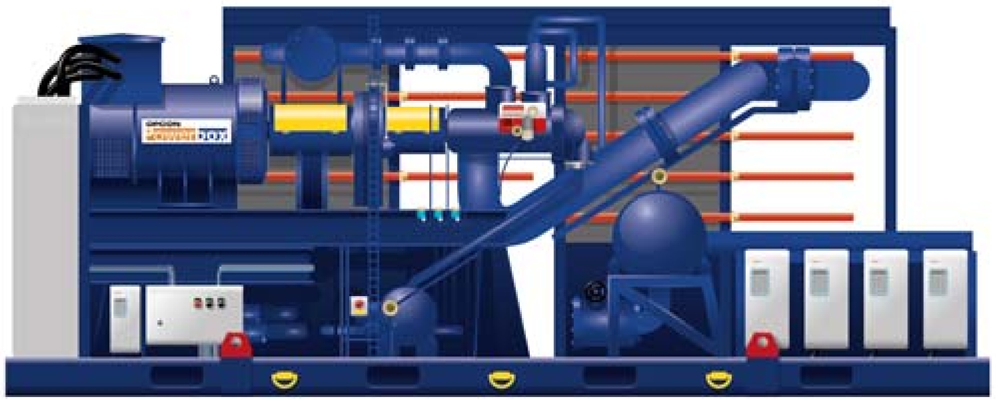
- Exhaust gas input temperature : 250 - 300 ^oC (2-S) / 300 – 350 ^oC (4-S)
- Exhaust gas output temperature : > 160 ^oC

  (for avoiding sulphur acid condensation - dependent on fuel sulphur content)
- Jacket cooling water temperature : 85 ^oC
- Lubricating oil temperature : 60 ^oC
- HT charge air temperature : 100 ^oC (value for 2-S)
- LT charge air temperature : 40 ^oC (value for 2-S)
- Condensation temperature : 30 ^oC

  (sea water cooling of condenser; $T_{cond} \approx T_{sea} + 5\ ^oC$)

Currently existing marine ORC applications – OPCON MARINE

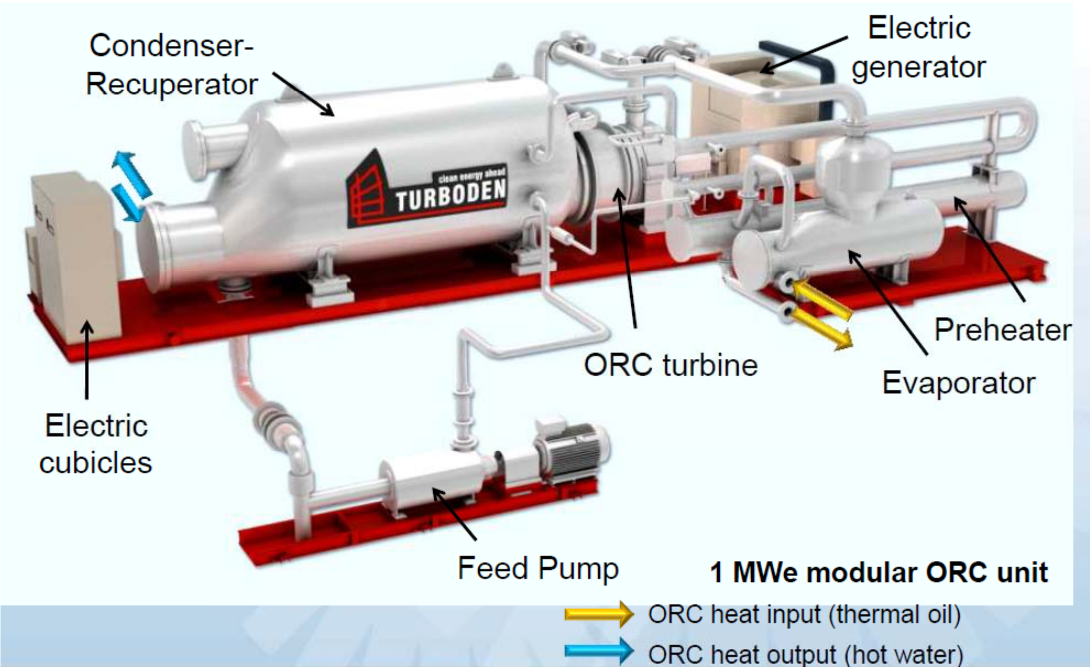
- ORC Powerbox from OPCON MARINE for medium-sized and large ships
  - Useable heat sources: scavenging air coolers (FW-cooling water), waste steam, jacket cooling (HT-system), thermal oil system
  - Installed in a 75,000 gross tonnage MV
    - Main engine: 2-S MAN B&W 8S60ME-C8, constant-pressure turbocharging system, 19,040 kW @ 105 rpm
    - Useable heat source: jacket cooling water
    - Up to 500 kW additional power



Source: OPCON

Currently available (not yet applied) marine ORC applications – Turboden-Wärtsilä

- Wärtsilä Marine ENGINE COMBINED CYCLE (ECC) from Turboden-Wärtsilä JV
  - Heat source: exhaust heat (300 < T (^oC) < 500)
  - Up to 10% additional power



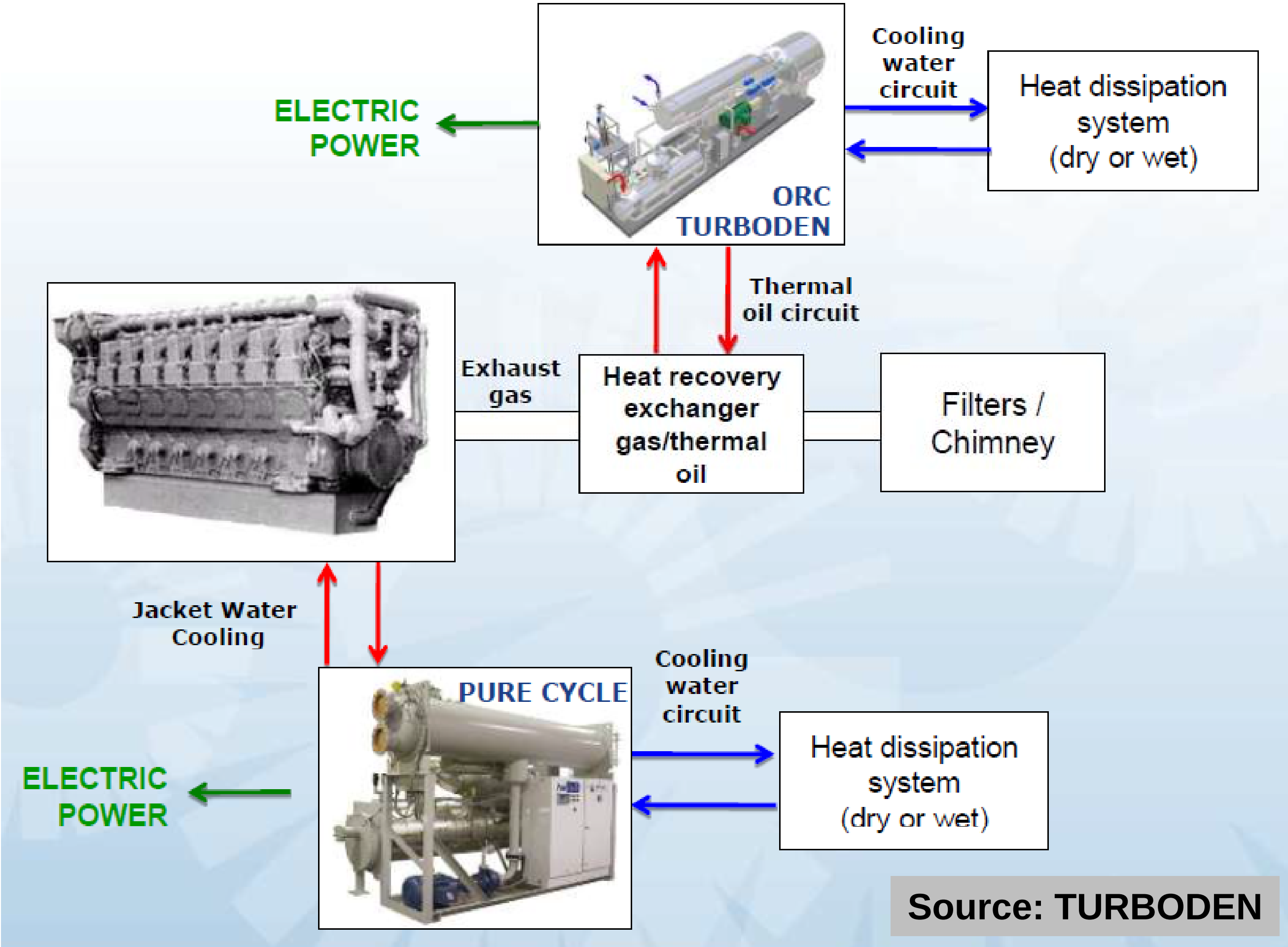
Source: TURBODEN

- PURECYCLE power system from Turboden
  - Heat source: jacket cooling water (91 < T (^oC) < 149)
  - Up to 3% additional power

Source: TURBODEN

Currently available (not yet applied) marine ORC applications – Turboden-Wärtsilä (cont'd)

- Possibility for combined operation of ECC and POWERCYCLE
  - Minimum thermal power input 2.5 MWth for Turboden ORC system application



Source: TURBODEN

General criteria for working fluid selection

- Typical fluids that can be used in ORC applications:
  - Halocarbons
    - CFC (Chloro-Fluoro-Carbon)
    - HCFC (Hydro-Chloro-Fluoro-Carbon)
    - HFC (Hydro-Fluoro-Carbon)
  - Hydrocarbons (e.g. ethane, propane, butane, ethylene, propylene, toluene)
  - Alcohols (e.g. methanol, ethanol)
  - Inorganic fluids (e.g. ammonia, water, carbon dioxide)
- No optimal working fluid exists specifically for ORC applications
- Criteria can be divided into 4 general categories:
  - Usage requirements
  - Thermodynamic requirements
  - Legislative requirements
  - Safety requirements

Usage requirements for working fluid selection

Parameter	Target	Reason
Freezing point	T_freeze < -50 °C	Avoid freezing at very low ambient temperatures
Evaporation temperature	T_evap > T_ext_max ≈ 50 °C	Avoid evaporation at very high ambient temperatures
Condensation temperature	@ p_cond, 60 °C < T_cond < 90 °C	At very high ambient temperatures, avoid heat transfer from ambient to working fluid
Exhaust gas temperature	T_exh_min > 150 °C	Avoid sulphur acid condensation
Evaporation pressure	P_evap < 30 bar P_evap < P_crit	Avoid exceeding strength limit of materials Avoid working fluid degradation
Condensation pressure	P_cond ≥ 1.2 bar	Avoid ait infiltration in condenser
Slope of saturation vapor curve	Positive or isentropic curve	Avoid droplets creation in expander
Vapor density	High vapor density	Avoid high volume rates, leading in high pressure losses in HXs and increased expander sizes
Viscosity	Low viscosity	Achieve high heat transfer coefficients and low pressure losses
Thermal conductivity	High thermal conductivity	Achieve high heat transfer rates in HXs

Thermodynamic requirements for working fluid selection

Process	Target in therm. properties	Characteristic on T-s diagram
Preheating - Evaporation - Superheating	c_p as low as possible L_{evap} as low as possible	**Isoenthalpy** curves as **far** as possible **Saturation** curves as **close** as possible
Expansion		**Isoenthalpy** curves as **close** & **orizontal** as possible
Vapor cooling - Condensation	c_p as low as possible L_{evap} as low as possible	**Isoenthalpy** curves as **far** as possible **Saturation** curves as **close** as possible

Legislative requirements for working fluid selection

RICARDO

Environmental issue	Working fluids affected	Legislation
Ozone Depletion Potential (ODP)	- CFCs banned since 2010 - HCFC to be banned gradually until 2020 (99.5% of reference amount)	Montreal Protocol
Global Warming Potential (GWP)	- HFCs are listed (not banned) - GHG emissions reduced to 8% of 1990 value until 2012	Kyoto Protocol Regulation No. 842/2006 of EU

Industrial designation or common name	Chemical formula	GWP for 100-year time horizon	
		Second assessment report (SAR)	4th assessment report (AR4)
HFC-23	CHF_3	11,700	14,800
HFC-32	CH_2F_2	650	675
HFC-41	CH_3F_2	150	92
HFC-125	CHF_2CF_3	2,800	3,500
HFC-134	CHF_2CHF_2	1000	1,100
HFC-134a	CH_2FCF_3	1,300	1,430
HFC-143	CH_2FCHF_2	300	353
HFC-143a	CH_3CF_3	3,800	4,470
HFC-152	CH_2FCH_2F		53
HFC-152a	CH_3CHF_2	140	124
HFC-161	CH_3CH_2F		12
HFC-227ea	CF_3CHFCF_3	2,900	3,220
HFC-236cb	$CH_2FCF_2CF_3$		1,340
HFC-236ea	CHF_2CHFCF_3		1,370
HFC-236fa	$CF_3CH_2CF_3$	6,300	9,810
HFC-245ca	$CH_2FCF_2CHF_2$	560	693

- Next generation low GWP fluorinated fluids:

  HFOs (Hydro-Fluoro-Olefins)

  e.g. HFO-1235yf (2,3,3,3-tetrafluoropropene)

Safety requirements for working fluid selection

- Two main safety issues:
  - Flammability
  - Toxicity
- Applicable standard for working fluid categorization
  - NFPA 704 standard (NFPA = National Fire Protection Association)

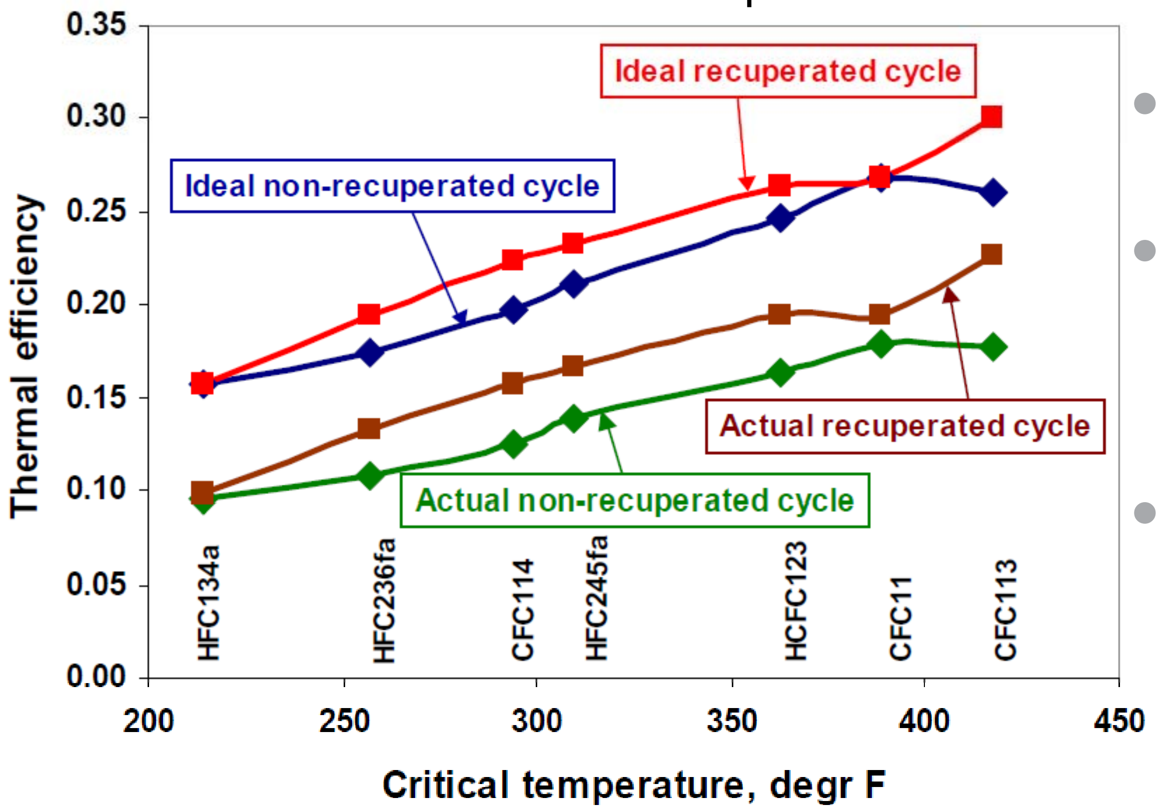
NFPA Rating Explanation Guide

RATING NUMBER	HEALTH HAZARD	FLAMMABILITY HAZARD	INSTABILITY HAZARD
4	Can be lethal	Will vaporize and readily burn at normal temperatures	May explode at normal temperatures and pressures
3	Can cause serious or permanent injury	Can be ignited under almost all ambient temperatures	May explode at high temperature or shock
2	Can cause temporary incapacitation or residual injury	Must be heated or high ambient temperature to burn	Violent chemical change at high temperatures or pressures
1	Can cause significant irritation	Must be preheated before ignition can occur	Normally stable. High temperatures make unstable
0	No hazard	Will not burn	Stable

RATING SYMBOL	SPECIAL HAZARD
ALK	Alkaline
ACID	Acidic
COR	Corrosive
OX	Oxidizing
☢	Radioactive
W̶	Reacts violently or explosively with water
W̶ OX	Reacts violently or explosively with water and oxidizing

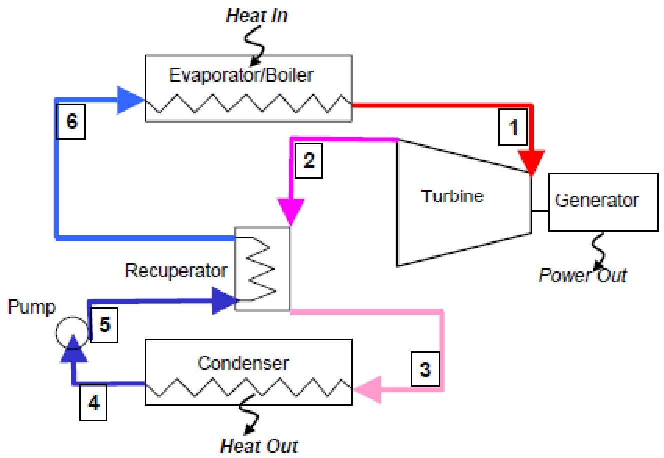
Performance criteria - Approach for working fluid selection

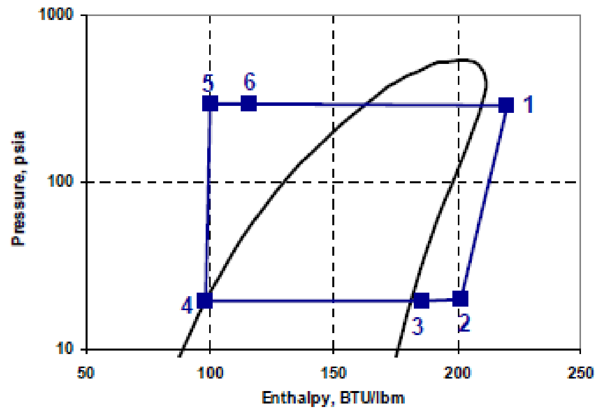
- ORC thermal efficiency for various working mediums
  - Heat source cooled down from 370 °C to 150 °C (exhaust gas case)
  - Evaporator saturation pressure equal to 95% of critical pressure
  - Condenser saturation temperature: 22 °C

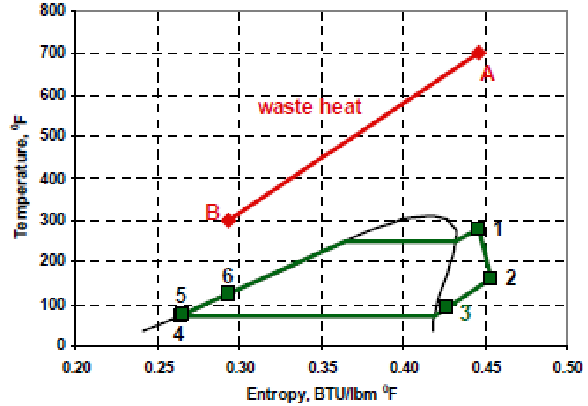


- Both recuperated and non-recuperated cycles
- Both ideal (no component losses) and non-ideal (turbine efficiency: 80%, pump efficiency: 40%, piping pressure losses: 2%) cases
- Selected medium the one that gives the **max. ORC thermal efficiency**

Maximum power output vs maximum efficiency



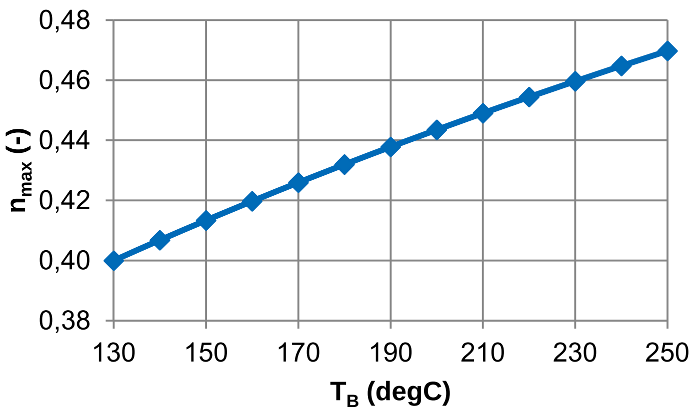




- Max. efficiency of ORC: $\eta_{max} = 1 - \frac{T_L}{T_A - T_B}\ln\left(\frac{T_A}{T_B}\right)$

  T_A : exhaust gas inlet temperature
  T_B : exhaust gas outlet temperature
  T_L : heat rejection temperature

- Max. efficiency increases as T_B increases, i.e. less power output produced



- In ORC applications, **target is max. power output and not max. ORC efficiency**; therefore, exhaust gas outlet temperature should be as low as possible

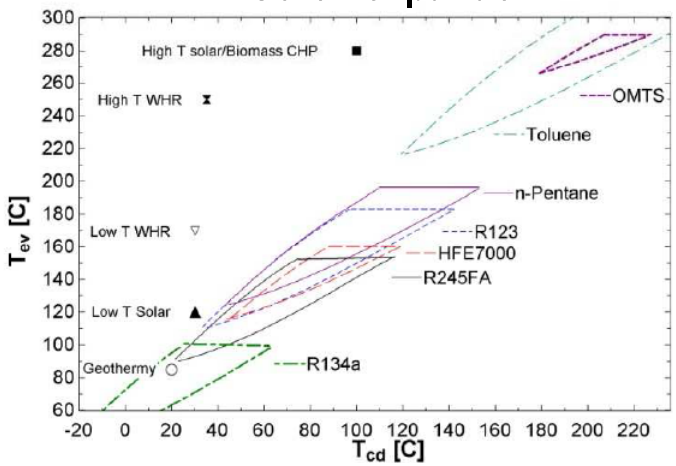
The operating map approach for working fluid selection

- Working medium selection closely linked to operating conditions (ORC application) and expansion machine
- Method based on limitations (boundary conditions) of expansion machines, based on previous experience:
  - Scroll & screw expanders:
    - min. & max. volumetric flow rates
    - max. pressure ratio
    - isentropic efficiency
  - Turboexpanders:
    - max. wheel tip speed
    - min. & max. turbine specific rotational speed
    - max. Mach number at nozzle exit and at rotor exit
    - max. turbine rotational speed

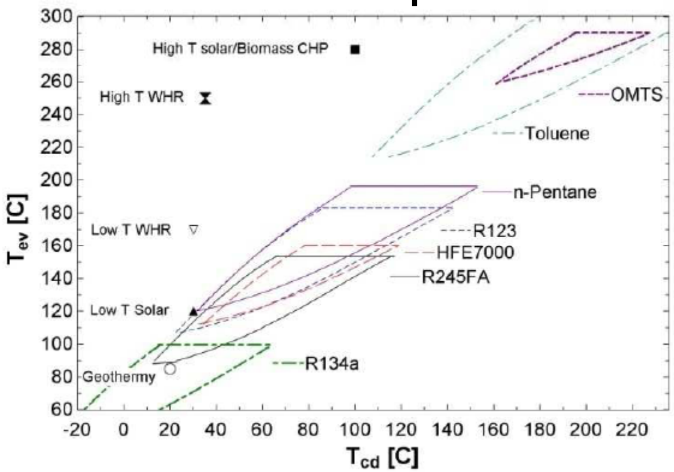
The operating map approach for working fluid selection (cont'd)

- For each expander, its limitations are used to construct an operating map including various organic working fluids on a (evaporating temperature) – (condensing temperature) diagram

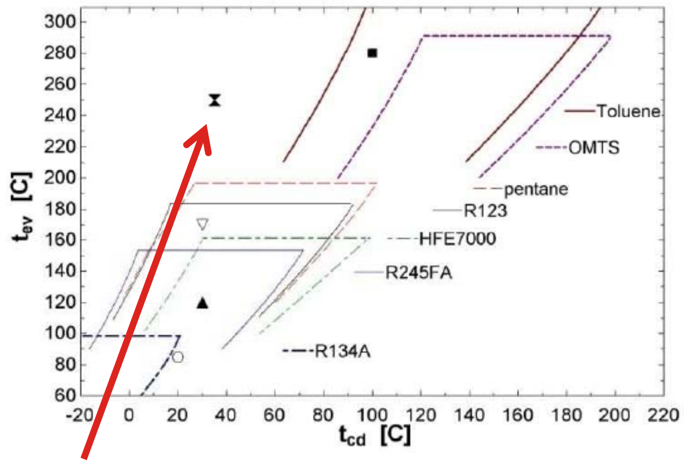
Scroll expander



Screw expander



Radial inflow turbine



- Limits of fluid curves

Turboexpander has wider capabilities compared to the positive displacement expanders since only one application is outside the defined maps

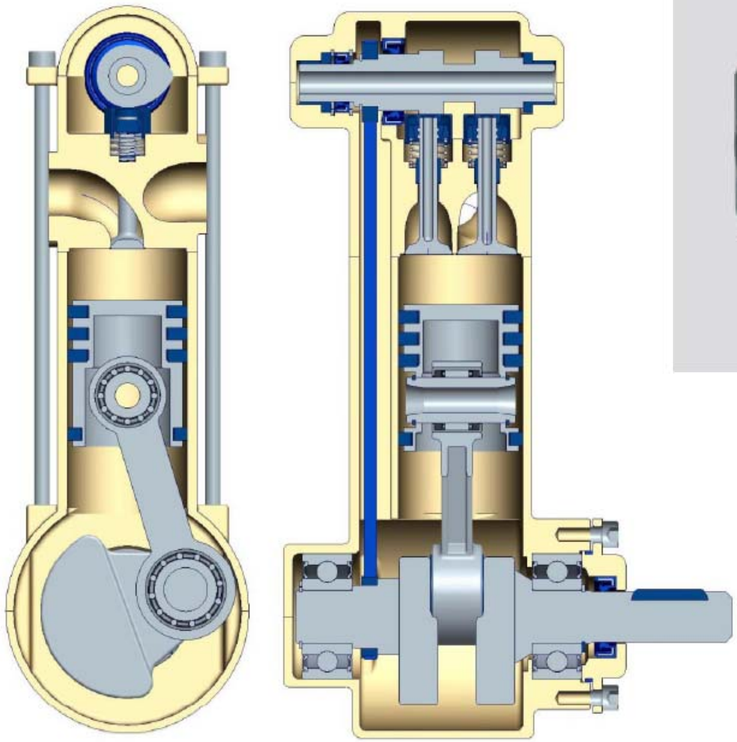
Curve	Limit (scroll-screw expander / turbine expander)
Left	Under-expansion losses / max. Mach number at nozzle exit or min. turbine specific rotational speed
Right	Volume coefficient / max. turbine specific rotational speed
Upper	Critical temperature of fluid / Critical temperature of fluid

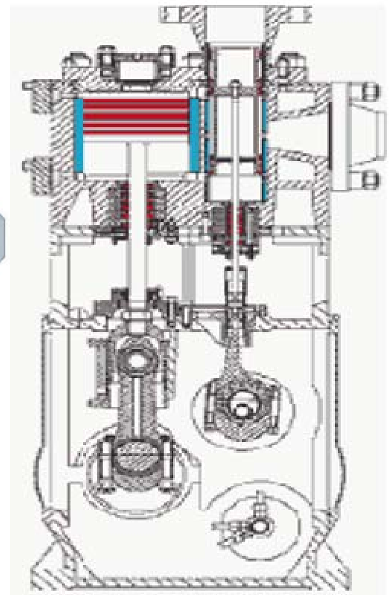
Expander technology

- Choice of expansion machine critical for Rankine cycle based WHR system success
- Two main categories under which a number of basic operating principles can be classified:
  - Positive displacements machines
    - Reciprocating piston machines
      - plunger piston
      - crosshead
    - Rotary ‘piston’ machines
      - vane-type
      - Wankel-type
      - scroll-type
      - screw-type (Lysholm)
  - Continuous flow machines
    - Turbines (reaction or pressure type)
      - radial
      - axial

Expander technology (cont'd)

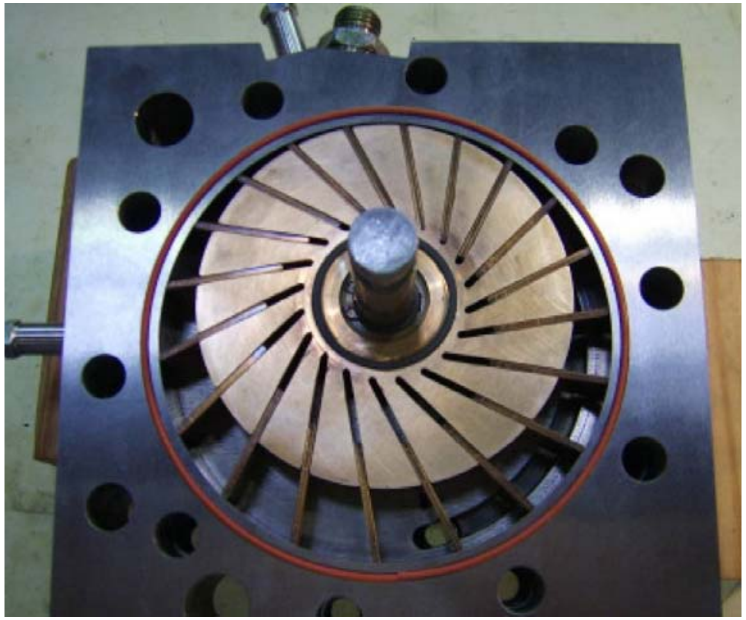
- Reciprocating piston
  - Similar to combustion engine
  - Alternatives:
    - plunger
    - crosshead
    - controlled valves
    - automatic (reed) valves
  - Challenges:
    - package
    - lubrication
    - vibration
    - wear





Expander technology (cont'd)

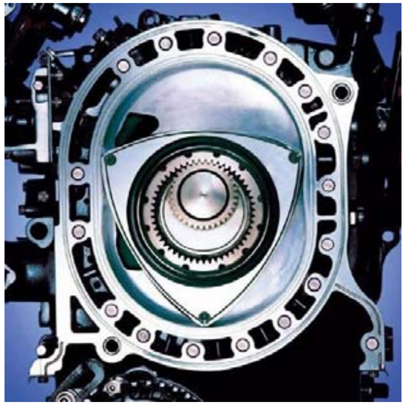
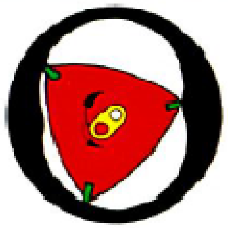
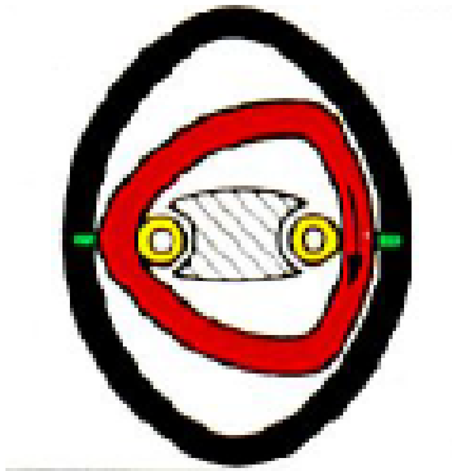
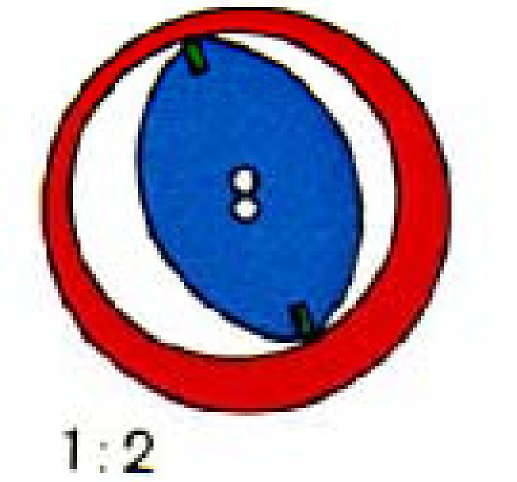
- Rotary 'piston' vane-type
  - Single acting (left) or double acting (right)



  - Main issues:
    - sealing
    - lubrication

Expander technology (cont'd)

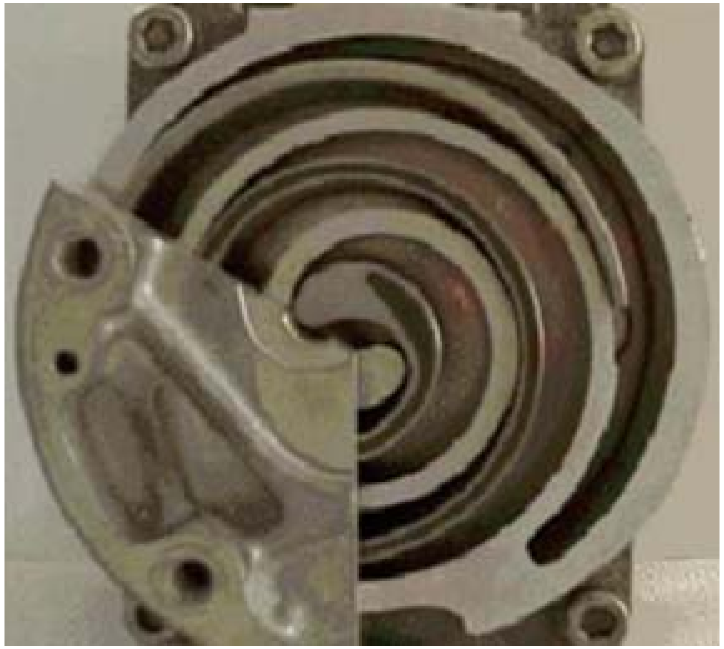
- Rotary 'piston' Wankel-type
  - Implemented both as air compressor and combustion engine
  - Potentially only rotating parts
  - Two-stroke versions (right) preferable

  - Sealing issue

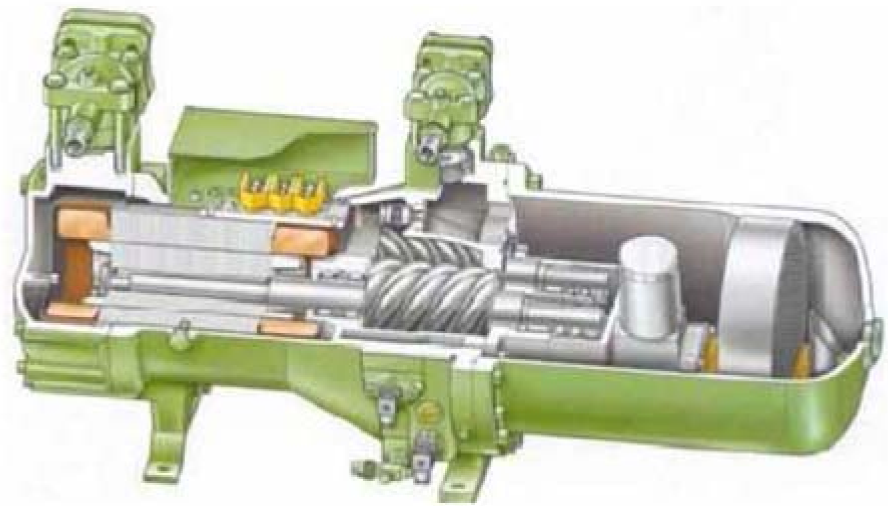
Expander technology (cont'd)

- Rotary 'piston' scroll-type
  - Only low pressure ratio possible - hence, low temperature ratio
  - Low efficiency



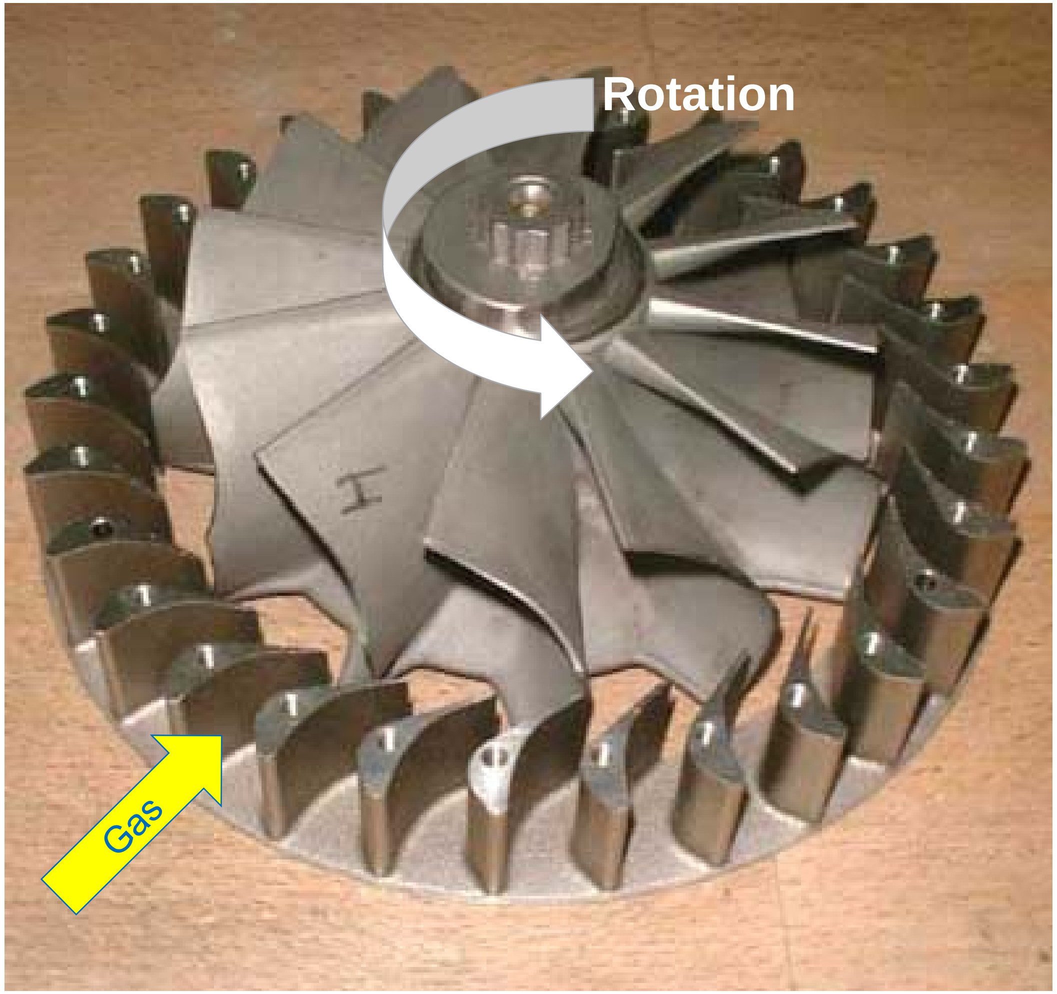
Expander technology (cont'd)

- Rotary 'piston' screw-type (Lysholm)
  - Implemented mainly as (silent) air compressor
  - Sealing oil issue



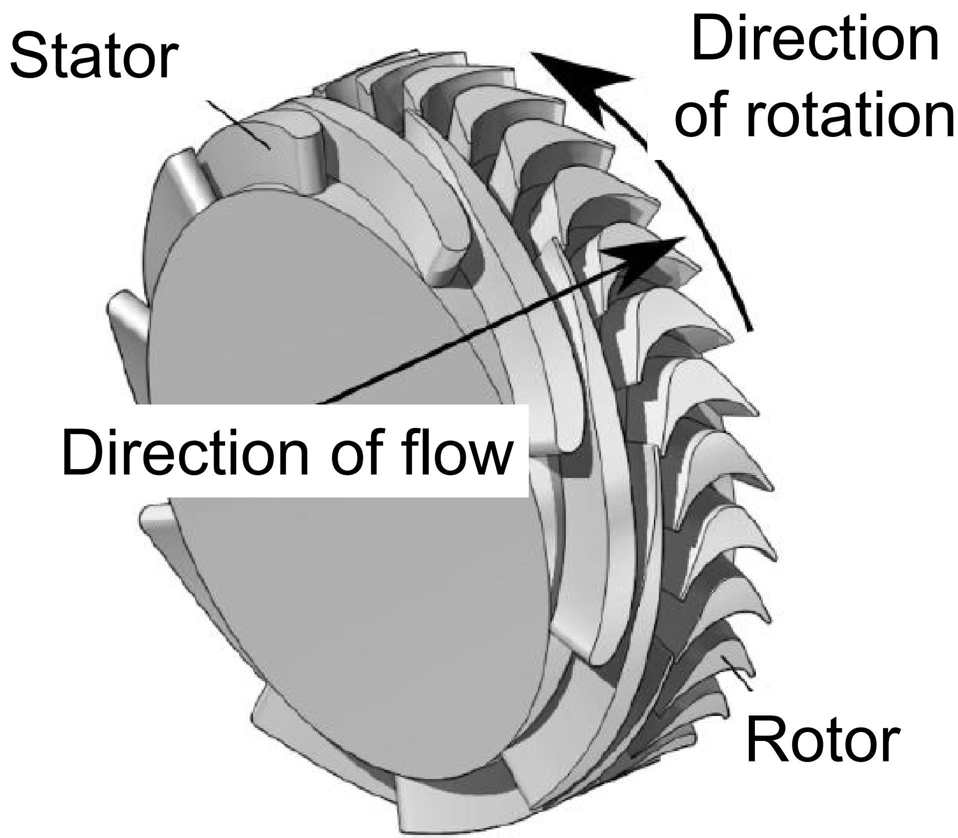
Expander technology (cont'd)

- Radial turbine
  - Back-pressure (non-condensing)
  - Single stage



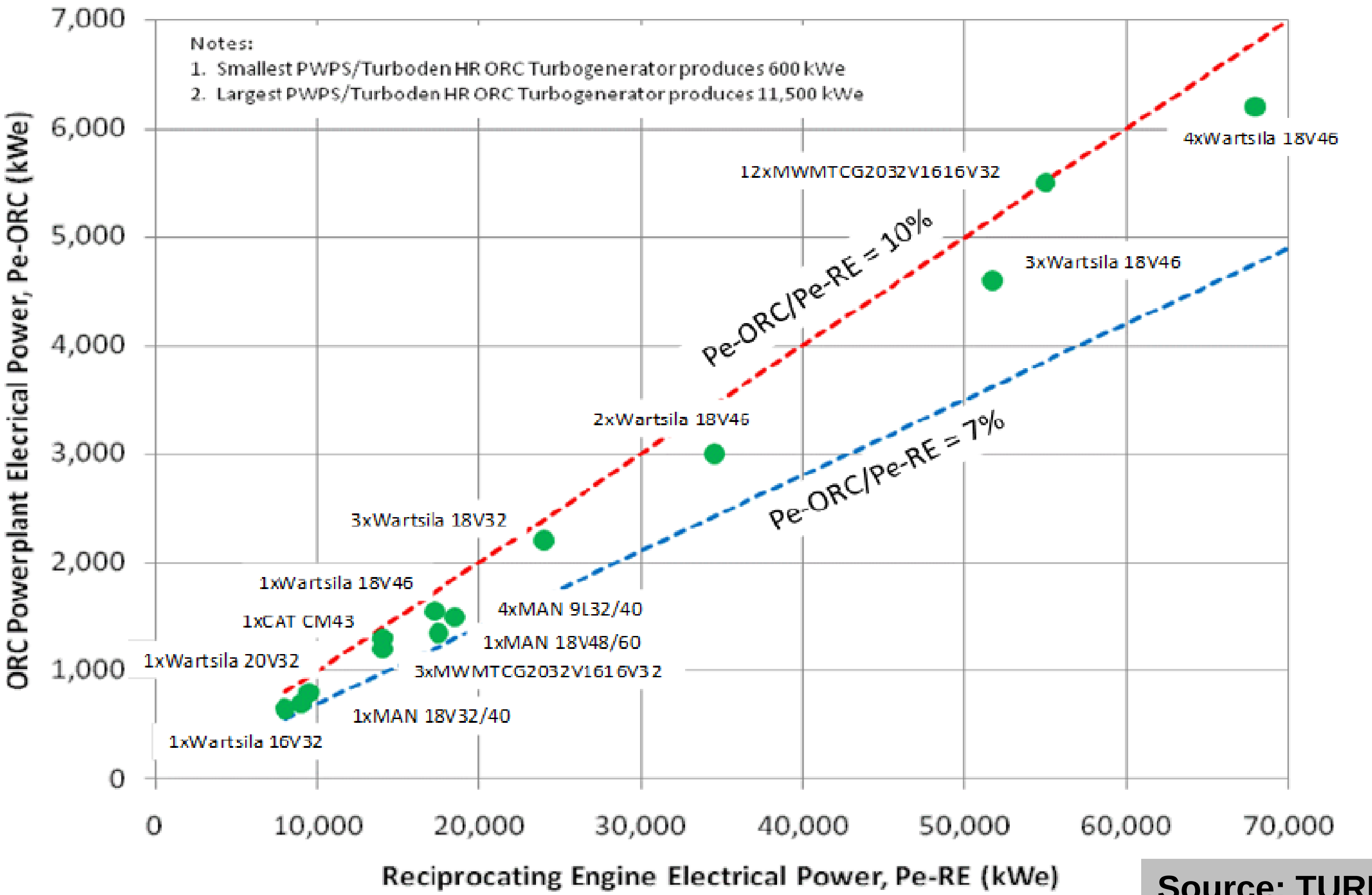
Expander technology (cont'd)

- Axial turbine
  - Reaction type (Laval, p = const.)
  - Single stage



Turboden's experience in ORC projects with various engine manufacturers

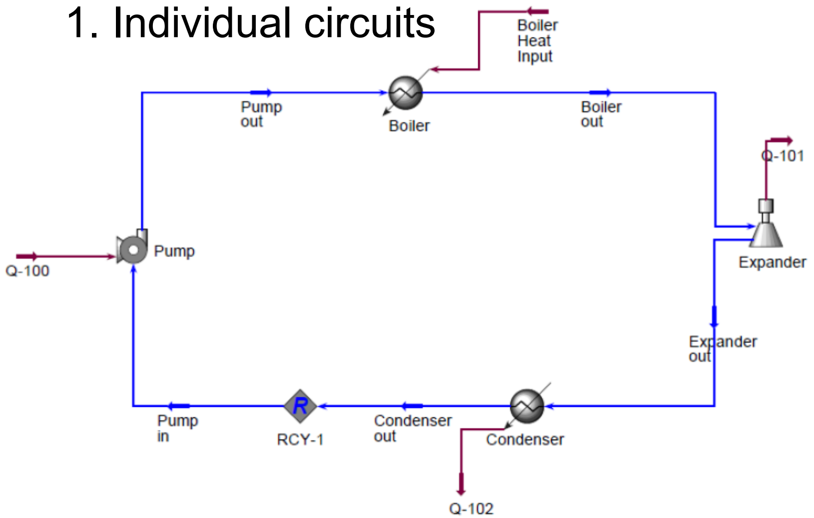
- Non-marine applications



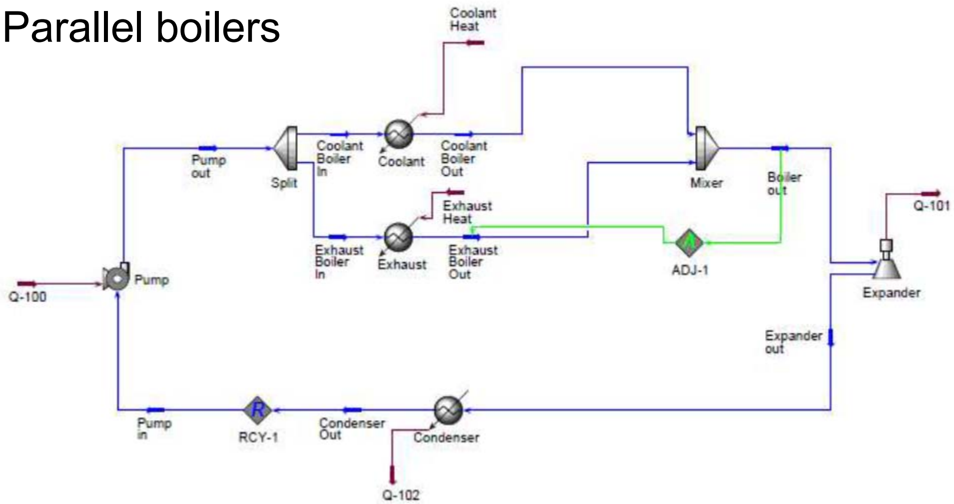
Source: TURBODEN

A case study - Assessment for a 1.5 MW marine engine - Exhaust gas and engine coolant as heat sources

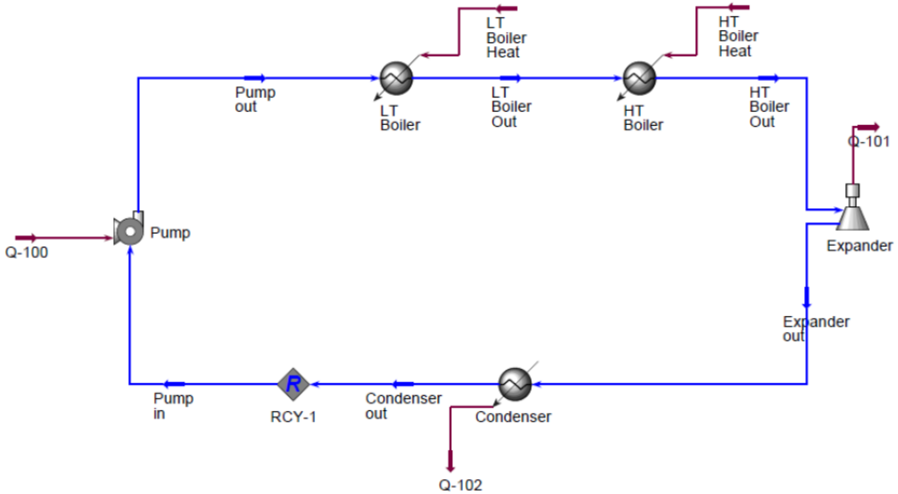
1. Individual circuits



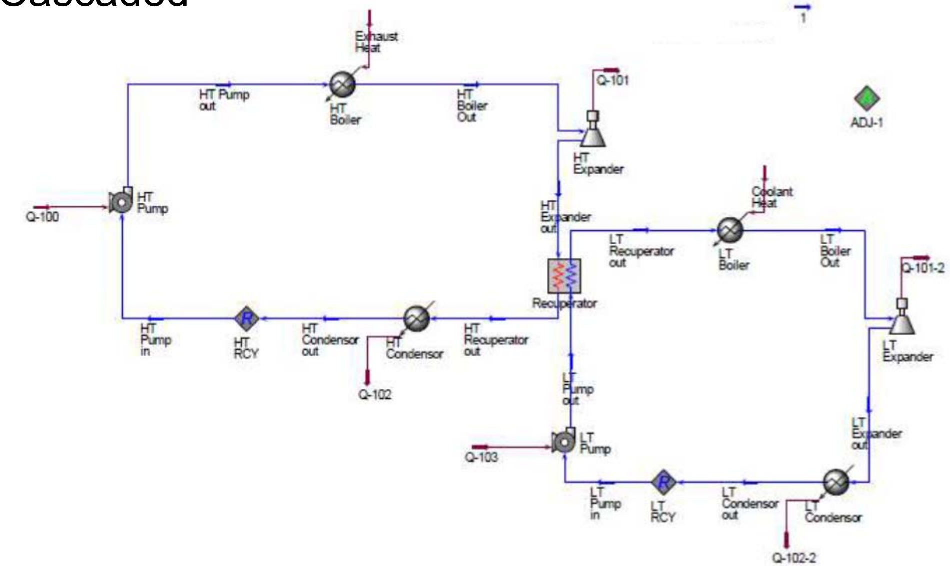
2. Parallel boilers



3. Series boilers



4. Cascaded



A case study - Assessment for a 1.5 MW marine engine - Exhaust gas and engine coolant as heat sources (cont'd)

Architecture	Power savings (%)		
	Ammonia	Ethanol	R245fa
1a. Individual Coolant Circuit	6.2	6.9	6.1
1b. Individual Exhaust Circuit	5.2	4.5	5.5
1c. Sum of Individual Circuits	11.4	11.4	11.6
2. Parallel Boilers	9.9	10.8	9.6
3. Series Boilers	10.6	11.3	10.0
4. Cascaded	11.4	11.4	12.0

Exhaust gas potential from 2-S and 4-S marine diesel engines

Parameter	2-S	4-S
Exhaust gas temp.	250-300 ^{o}C	300-350 ^{o}C
Exhaust gas flow	7.4 kg/kWh	6.2 kg/kWh

- **~ 25% more exhaust gas heat from 4-S engines**
  (assuming an exhaust gas outlet temperature of 180 ^{o}C)

Source: WÄRTSILÄ

Expected efficiency increase from ORC applications

- Expected efficiency increase
  - Exhaust gas as a heat source: mechanical energy 13% @ 150 ^{o}C of input heat
  - Jacket cooling water as a heat source: mechanical energy 7% @ 90 ^{o}C of input heat

Source: WÄRTSILÄ

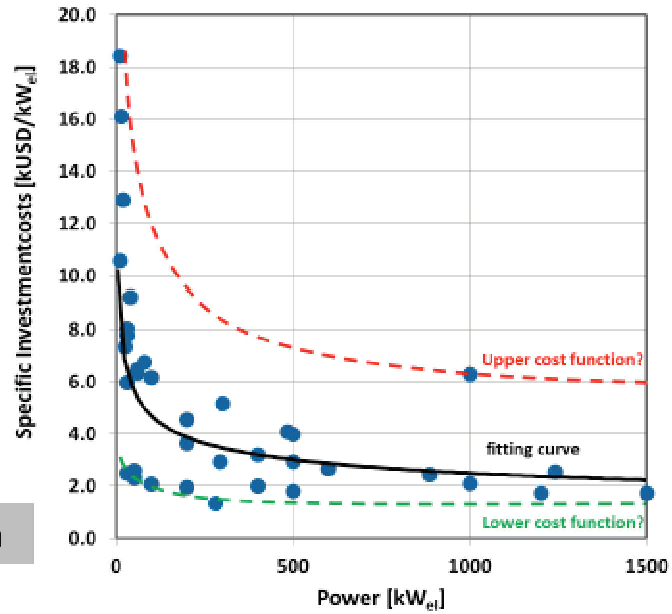
Cost function of ORC systems

- Investment costs by manufacturer (2011)

Source: Economic Implementation…

Manufacturer	Product Line	Size Range (kW)	Min. temp. (°C)	Cost per kW ($)
Infinity	Infinity Turbine ORC Power	10 kW - 280 kW	80	2260
Ormat	Ormat Energy Converter	250 kW - 20 MW	90	1800 - 2000
United Technologies	Pure Cycle	280 kW	75	2857
Electratherm	Green Machine	50 kW	205 (gas) / 90 (water)	2530

- Compiled investment costs by manufacturers as a function of module size (2011)



Source: World Engineers' Convention

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- Thermo-Electric Generator (TEG)
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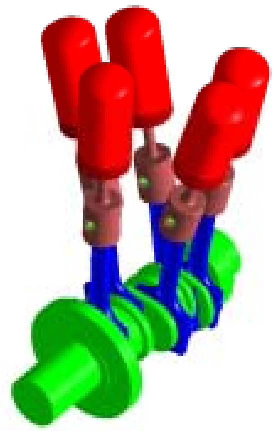
Ricardo has worked on concepts that use Stirling engines to recover waste heat across a range of applications

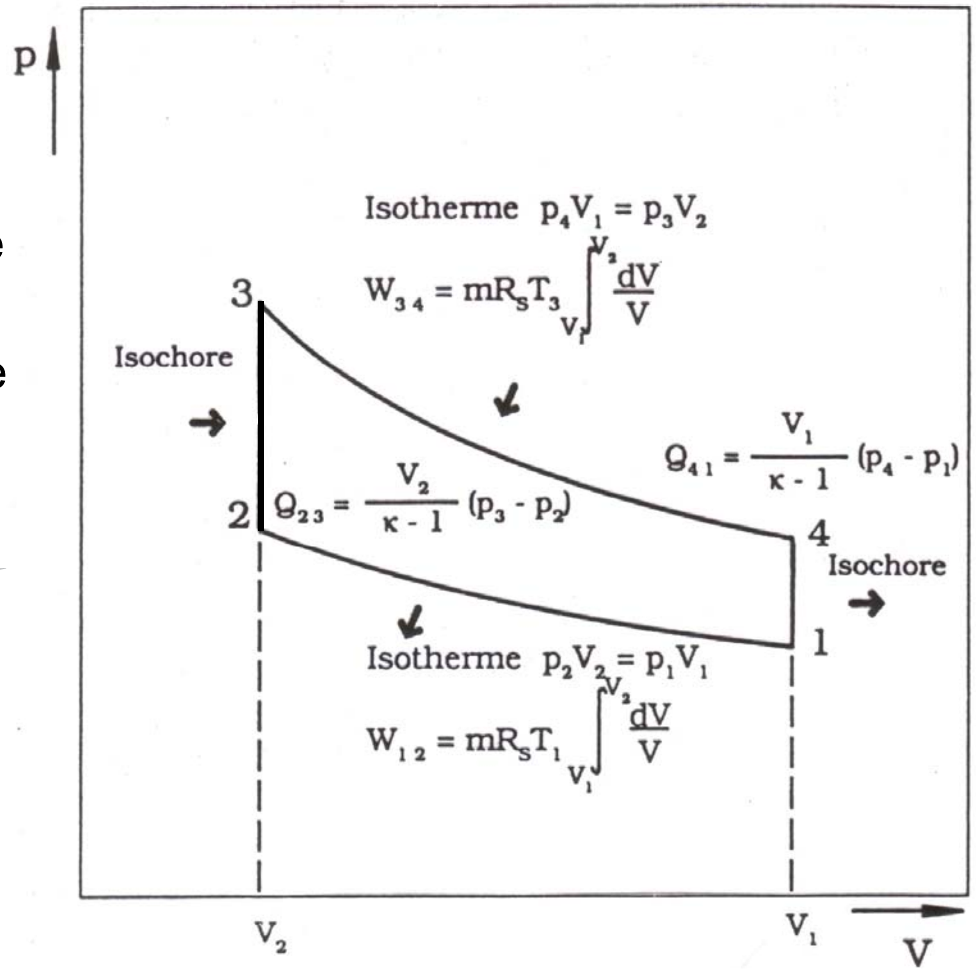
- Ricardo's experience with Stirling engines spans many applications:
  - Micro-CHP: Stirling engines which recover waste heat from domestic boilers to generate electricity and increase the efficiency of the system as a whole
  - Solar Concentrators: Harvesting of solar power using a mirror to focus radiation on the Stirling engine
  - IC engine exhaust heat: Design of a bespoke system for a marine application
  - Industrial waste heat: Investigation of the use of Stirling engines to make better use of waste heat in "clean energy" applications
- Ricardo has 30+ years of experience with Stirling-Engines of all sizes
  - from concept to industrialisation



Thermodynamics

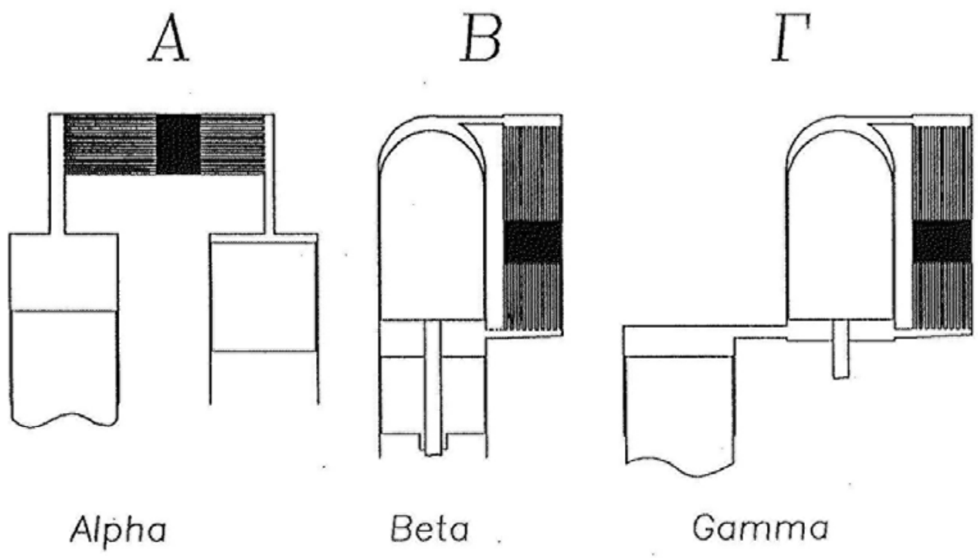
- The Ideal Cycle (Textbook Cycle), as a result of perfect regeneration yields Carnot-Efficiency
- It does however ***not*** reflect the reality inside a machine ***at all***
  - State changes of the working fluid are exercised on the whole of the working fluid
  - Fluid flow and finite heat transfe are not considered
  - Regeneration is just assumed

Hence it becomes clear that the Textbook Cycle is not appropriate as a tool for conceiving engine hardware



Stirling Cycle practical considerations – forming the workspaces

- It is obviously not achieveable to heat and cool the working fluid in one cylinder
- Hence 2 spaces are formed by piston(s) & displacers
- These are connected by the heat exchangers



Work-system aka Gas-circuit

The fluid contained in the two working spaces and the (3) heat exchangers forms one (gaseous) body undergoing the changes of state (of the cycle) and thereby converting heat to work

Cycle simulation and real engines

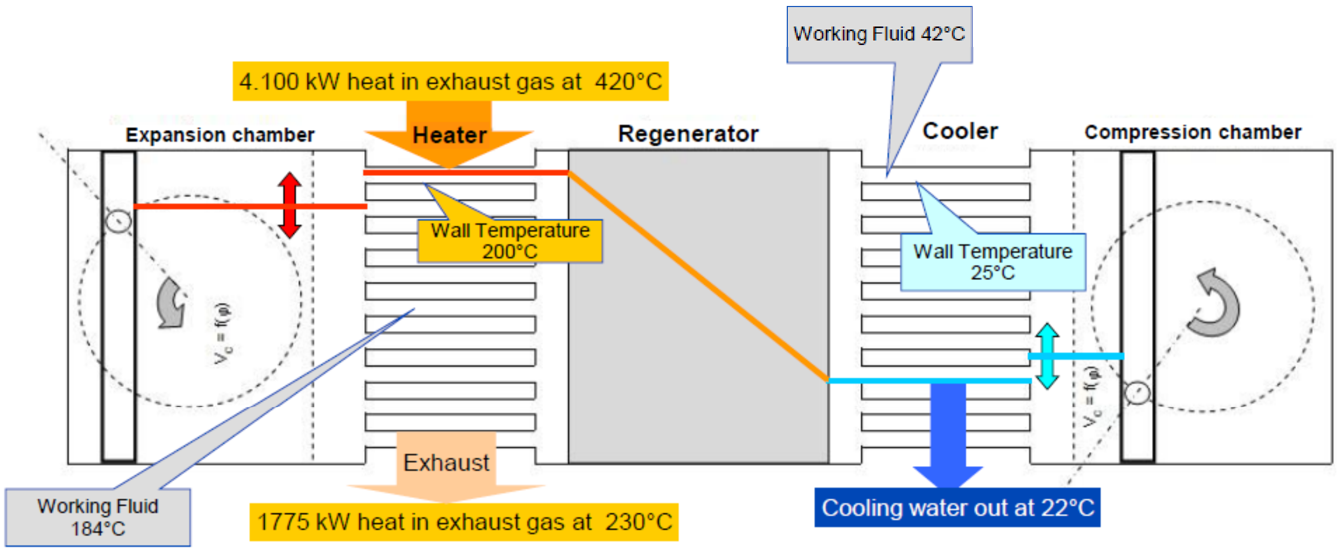
- I propose to stop here and consider for a moment what goes on in a real Engine and how we can measure and/or predict it
  - Compression and Expansion are continuous and happen in all connected volumes simultaneously (save for a little lag due to flow friction)
  - Fluid flow happens continuously and reverses twice per revolution
    - Fluid flow is correlated with heat transfer in all 3 exchangers (e.g. via Nußelt No. correlations)
  - The Heater (source) and Gas-cooler (sink) are not changing their temperature (and its distribution) with cycle frequency (engine operation in steady state) – i.e. the outside flow regime and heat transfer is quite constant while the inside is varying with cycle frequency
  - The regenerator is having a heat transfer rate – in and out at cycle frequency of up to 10 times the shaft power i.e. on a 50 kW engine the regenerator is receiving and emitting ~ 500 kW of heat with a sign change at a frequency of 25 Hz

These considerations might make it sufficiently clear that nothing short of a cycle simulation coupled with steady state calculation of flow and heat transfer on the outside are called for – if a robust design tool is expected – also that intuition and trial and error are treacherous options carrying inacceptable development risks

1-D simulation of Stirling engine

- Cyclic process modelling
- Engine configuration & operating conditions
  - 16 double acting alpha-type pistons
  - piston phase angle 90 ^{o}CA
  - high pressure (~ 200 bar)
- Requirements
  - limitation of exhaust gas back pressure
  - optimization of exhaust gas temp. drop
- Consideration of losses from
  - fluid friction
  - imperfect heat transmission

Exhaust gas heat input to Stirling engine (4100 -1775) kW = 2325 kW

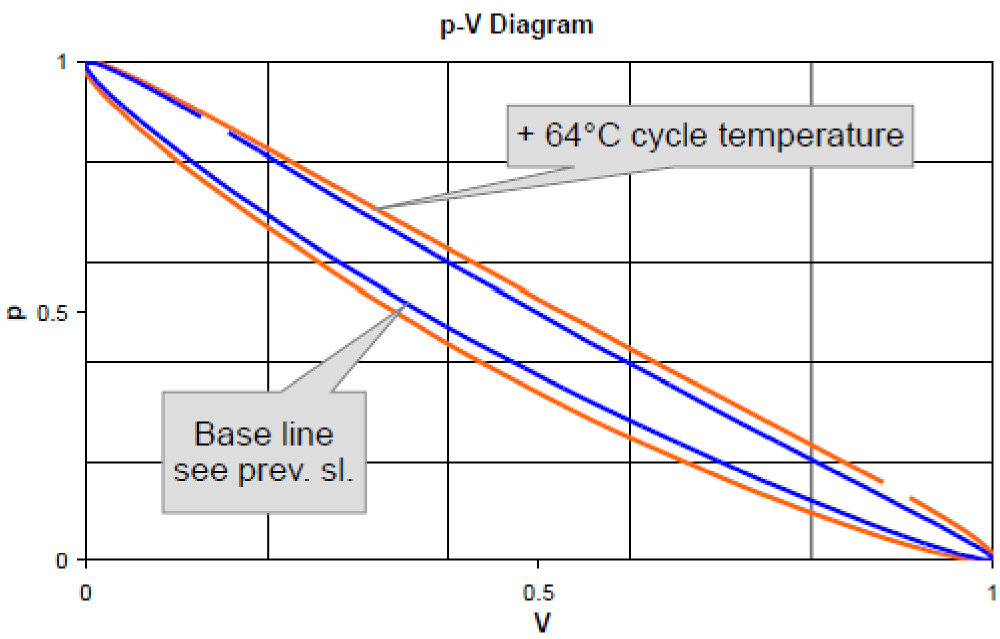


Stirling engine results	
Working fluid high temp.	184 ^{o}C
Working fluid low temp.	42 ^{o}C
Shaft power	440 kW
Speed	600 rpm
Total displacement	72 lt
Overall efficiency	0.18
Mechanical efficiency	0.86
Carnot factor	0.31
Figure of merit	0.68

1-D simulation of Stirling engine (cont'd)

- Option for performance improvement
  - Incorporation of a thermal oil circuit as a heat carrier between exhaust gas and working fluid for temperature difference decrease during heat transfer process
  - Reduction in heat transfer irreversibilities

Stirling engine results	
Working fluid high temp.	248 °C (+64 °C)
Working fluid low temp.	42 °C
Shaft power	740 kW
Speed	600 rpm
Total displacement	72 lt
Overall efficiency	0.27
Mechanical efficiency	0.91
Carnot factor	0.395
Figure of merit	0.77



Pros and Cons

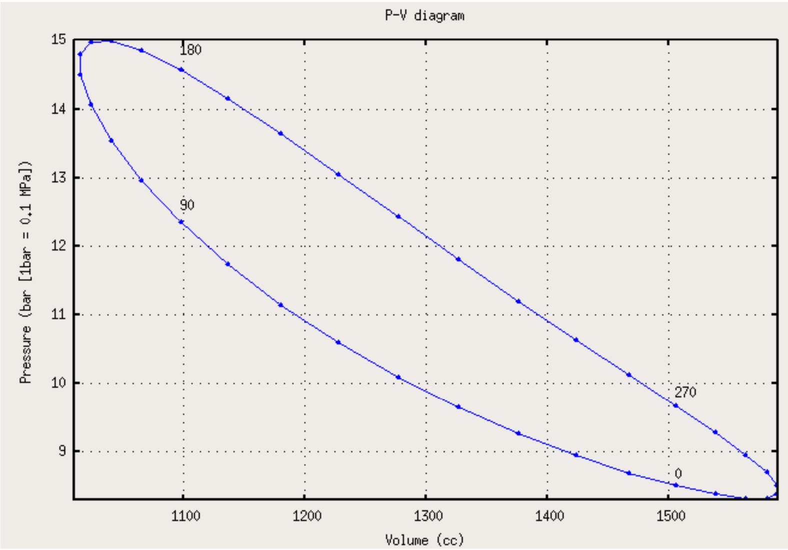
- Pros
  - Higher ideal thermal efficiency than Diesel and Otto engines due to heat transfer under constant temperatures; efficiency ~~same as the Carnot cycle~~
  - Regenerator effect; thermal efficiency increase due to ‘recirculation’ of internal heat that would otherwise pass through the engine irreversibly
  - No pumping losses from gas exchange during the cycle
  - No valves, intake and exhaust pipes; less maintenance
  - Smooth torque delivery
  - Silent operation

Pros and Cons (cont'd)

- Cons
  - Sealing problems due to operation at high in-cylinder pressures
  - High temperature difference needed for high thermal efficiency; high thermal stresses
  - Need for working fluids with high heat conductivity and low molecular mass for fast heat transfer rates, e.g. hydrogen or helium; issues of low availability of 'fuel'
  - Efficient operation only at a narrow range of speed and power; 'thermal lag' associated with increase of heat input for increase of power or speed makes transient operation inefficient
  - High production costs of heat exchangers due to need for very large heat transfer areas
  - High production costs of regenerator due to expensive materials to withstand corrosion and deformation under high heat transfer rates and pressures
  - Regenerator design compromise:
as high as possible heat transfer area .vs. as low as possible volume

Main reasons for non-ideal Stirling cycle (cont'd)

- Sinusoidal (not discontinuous-ideal) power piston motion; non-const. volume regeneration
- Dead space volume existence; volume of gas not taking part in the cycle (in regenerator, in heat exchangers, clearances, interconnecting ducts)
- Pressure drop across regenerator and heat exchangers
- Heat losses; e.g. from displacer to ambient and between hot and cold cylinder spaces for beta-type engines
- Mechanical friction; in bearings, seals and piston rings



A quasi-elliptical shaped cycle is usually measured

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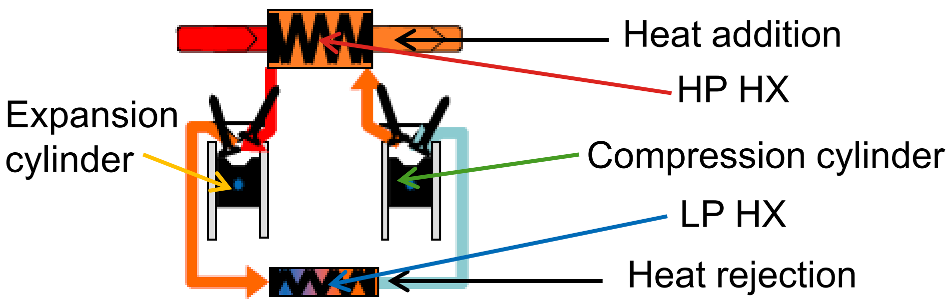
Operating principle

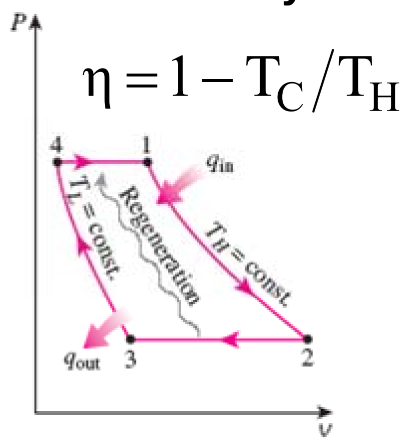
- Thermodynamic cycle can be followed by both **open** and **closed** cycle piston engines
- Ideal cycle made up of two isothermal (compression - expansion) and two isobaric (heat addition - heat rejection) processes; ideal cycle efficiency equal to Carnot efficiency
- Compression & expansion take place in two isolated from each other (through intake and exhaust valves) cylinders
- Heat transfer from heat source and to heat sink takes place outside of the cylinders in dedicated HXs
- Lack of heat exchange surfaces in the cylinders makes isothermal processes impossible; rather isentropic processes occur, therefore Brayton (Joule) cycle more appropriate

Closed cycle engine

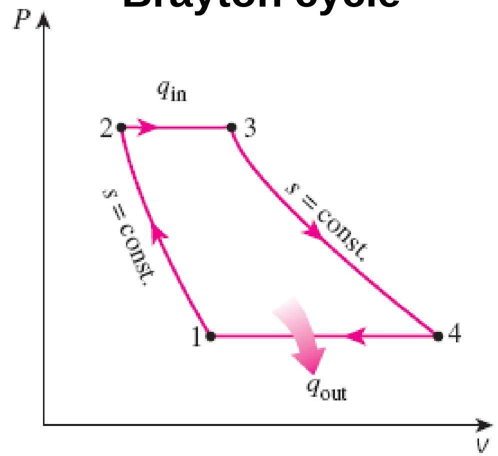


Ericsson cycle

$$\eta = 1 - T_C / T_H$$

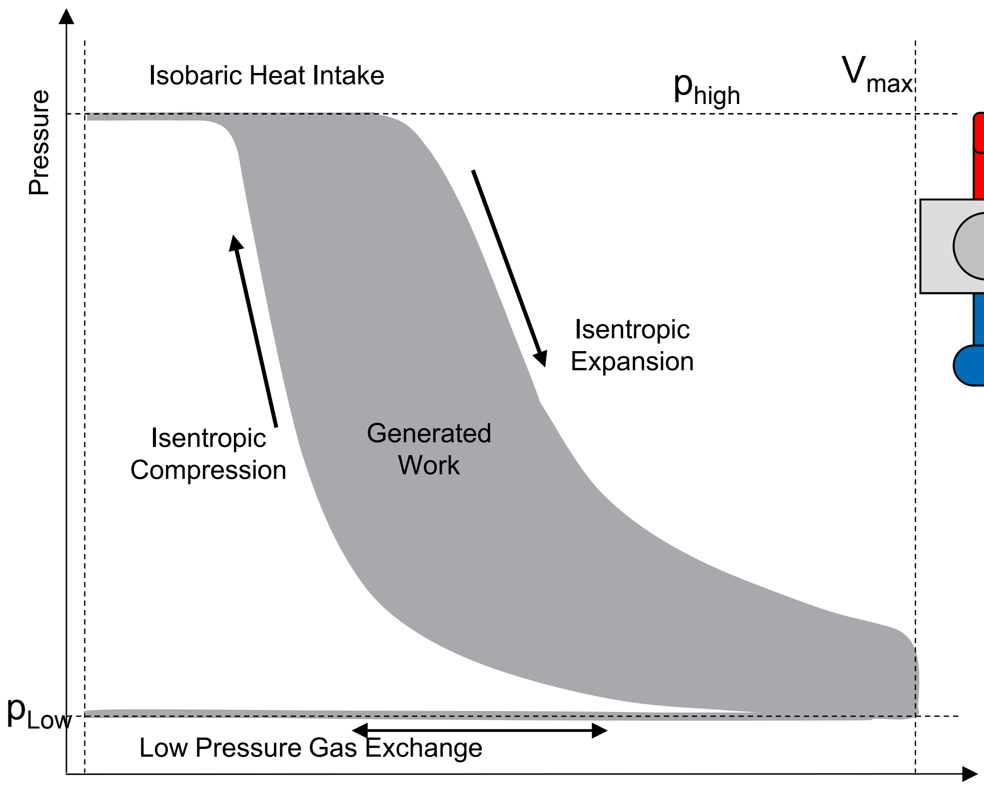


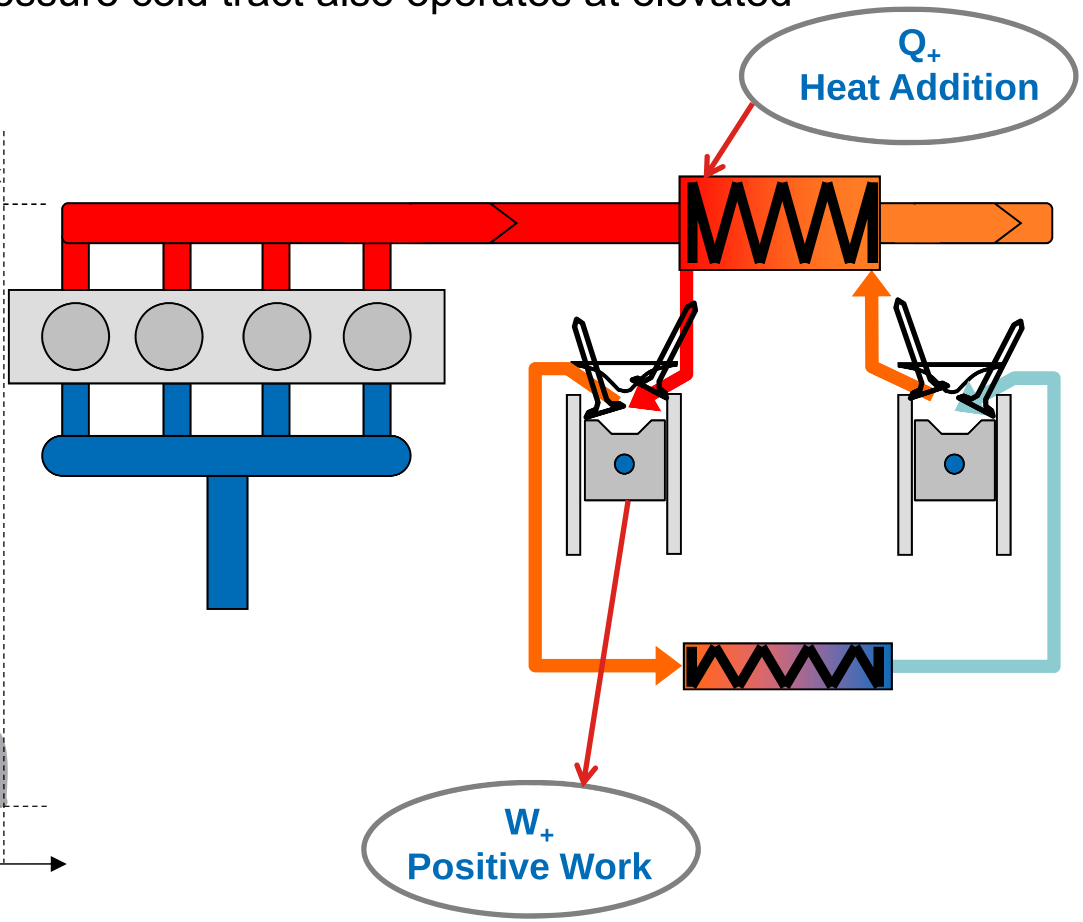
Brayton cycle



Ericsson Heat Recovery Concept

The motivation for trying the Ericsson engine was driven by the consideration, that the Ericsson heater is not dead volume as the Stirling heater. Therefore there is more freedom for dimensioning and design for finding the optimum between exhaust gas back pressure and heat transferred to the bottoming cycle. In the Ericsson cycle, work is done by the expansion of hot air, to which heat is added previously in a heat exchanger at constant high pressure – it was decided to analyse a variant where the low-pressure cold tract also operates at elevated pressure

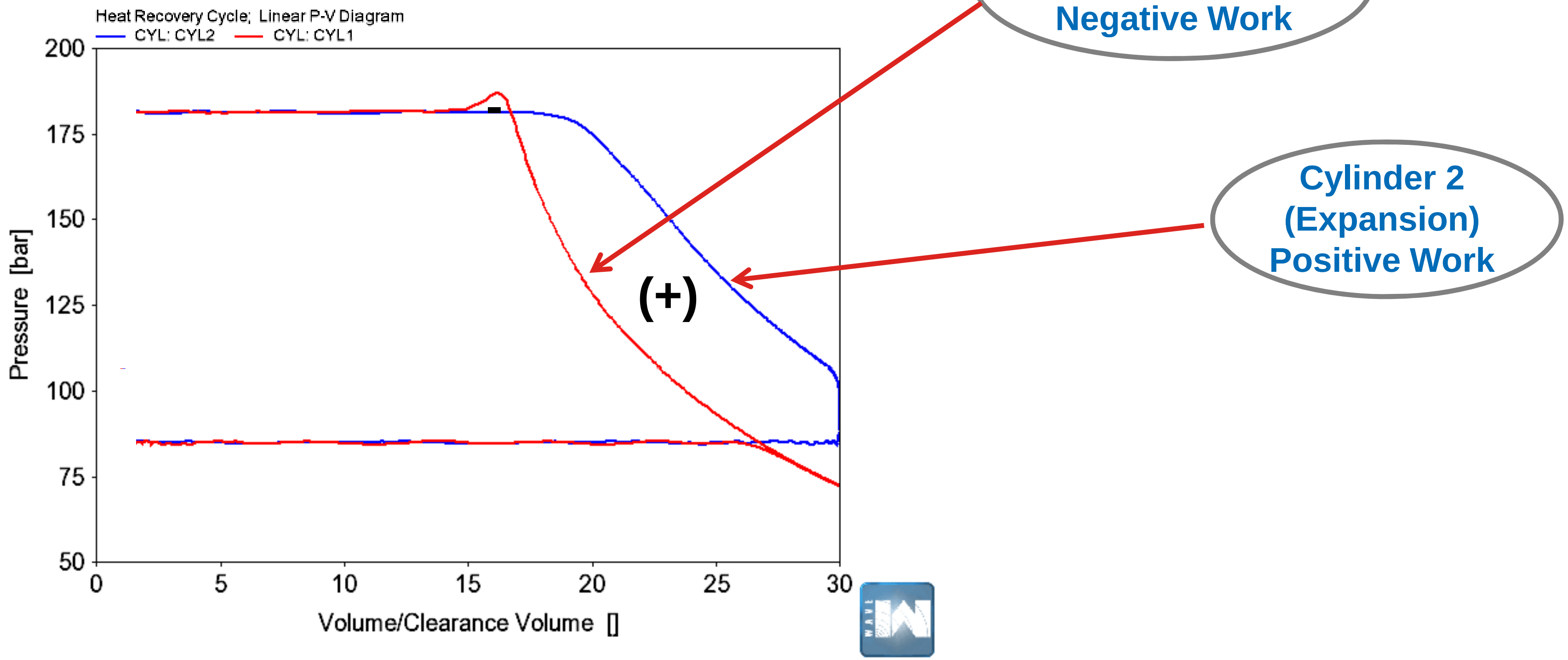




System Characteristic

- The Ericsson Engine in the model utilizes the heat energy in the exhaust gas of the main IC engine and converts it into mechanical energy Work is done in compressing the air in the 1st cylinder and work is produced by the system during the expansion stroke in the 2nd cylinder. Heat is rejected by the system through the Low Pressure Heat Exchanger after expansion .

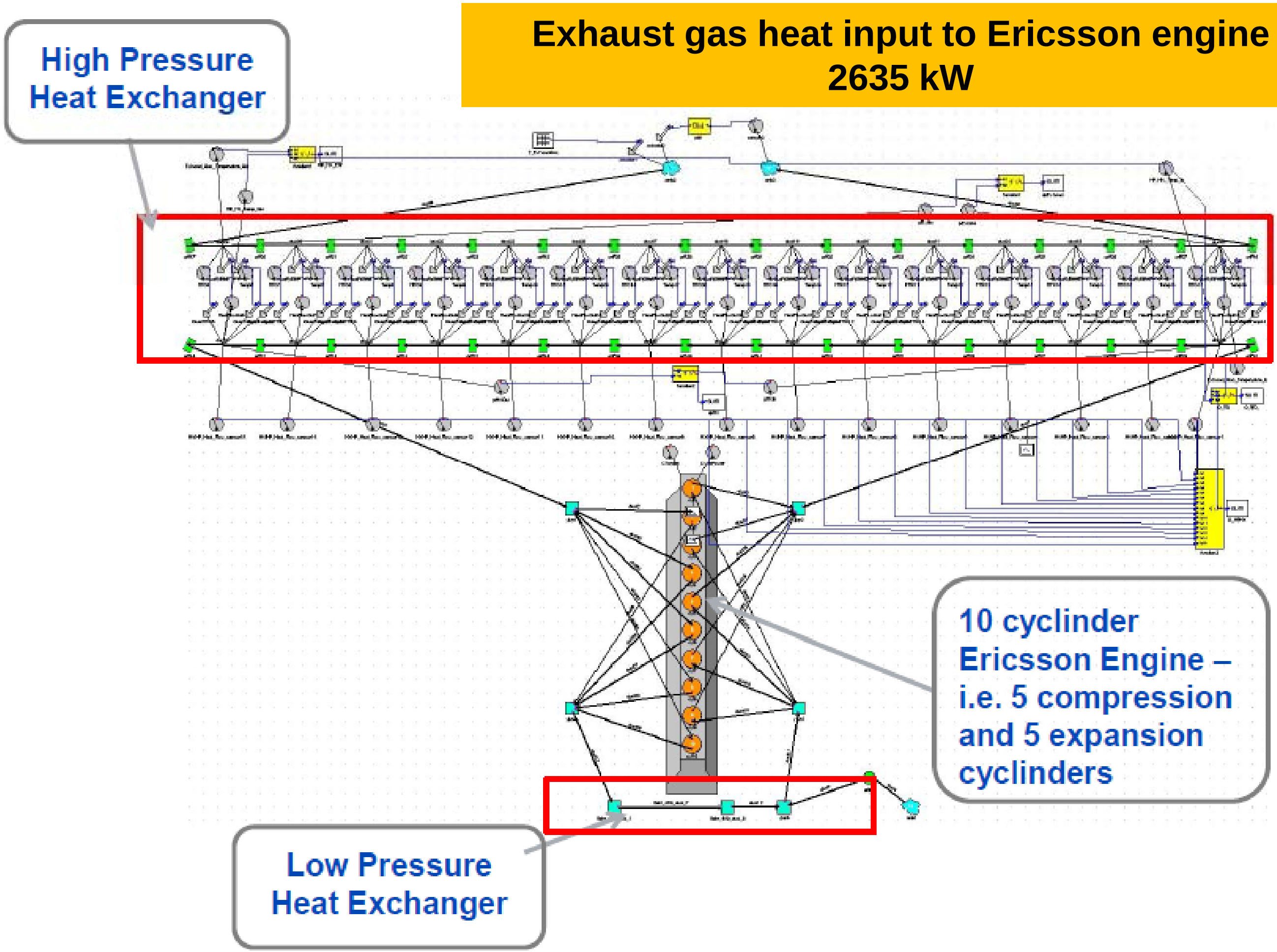
P-V Diagram



1-D simulation of Ericsson engine

- First step: Optimization of most influencing parameters on engine performance (stroke, compression ratio, speed)
- Second step: Performance assessment

Exhaust gas heat input to Ericsson engine 2635 kW



Ericsson engine results	
Working fluid high temp.	280 ^{o}C
Working fluid low temp.	50 ^{o}C
Shaft power	302 kW
Speed	787 rpm
Total displacement	12 lt
Overall efficiency	0.12
Mechanical efficiency	0.79
Carnot factor	0.416
Figure of merit	0.36

Pros and Cons

- Pros
  - HXs not clearance (dead) volumes, like in Stirling engines
  - High cycle temperatures; high Carnot factor
  - Lower operating pressures than in Stirling engines
  - Higher power density than Stirling engines
- Cons
  - High internal cycle losses, e.g. gas exchange losses; low thermal efficiency

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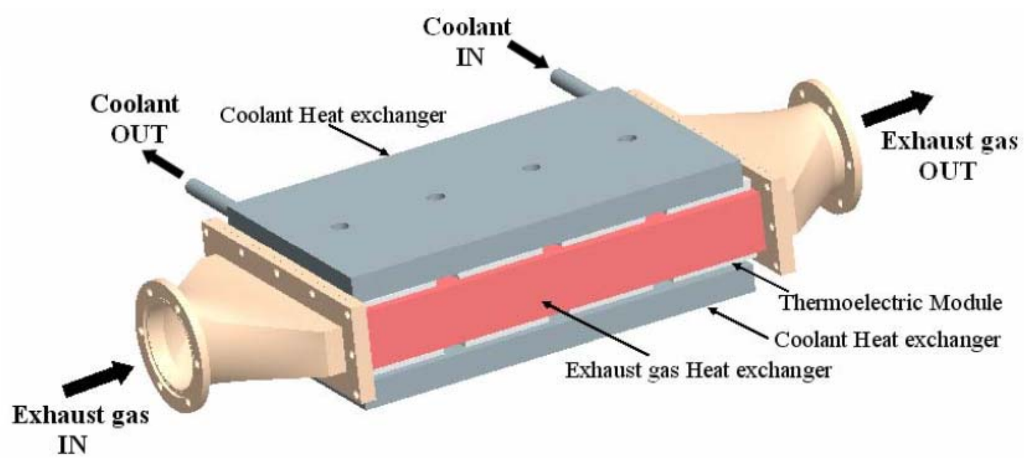
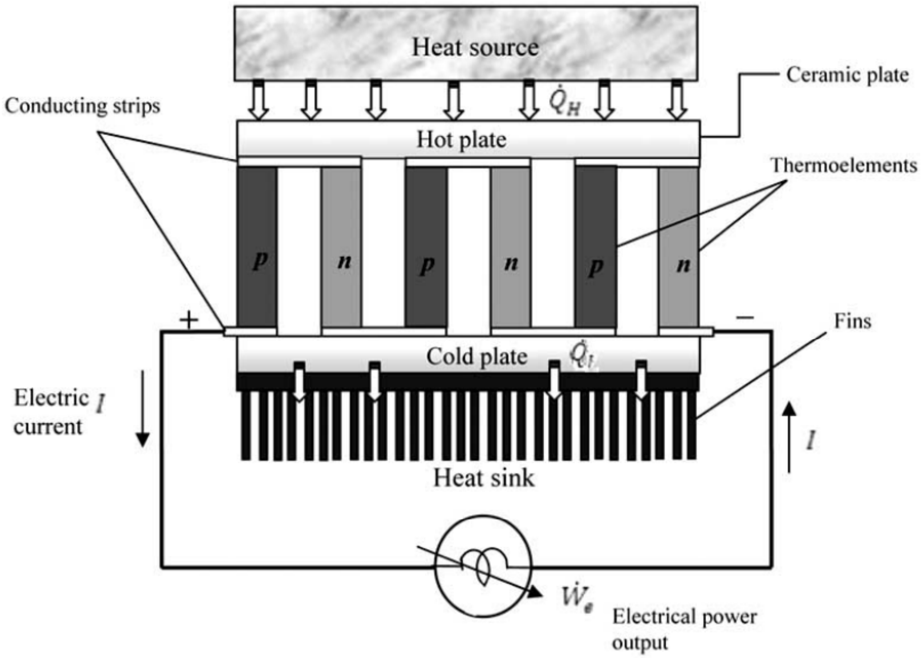
Operating principle

- Temperature difference between heat source and heat sink produces a voltage across the semiconductors – Seebeck effect
- From 1st Law of Thermodynamics, heat provided by heat source minus heat rejected to heat sink equals the electrical power output
- Semiconductors: thermally connected in parallel; electrically connected in series





Efficiency & semiconductors material

- TEG system efficiency: $$\eta = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_C/T_H} \cdot \frac{T_H - T_C}{T_H}$$

  T_H : hot heat stream temperature
  T_C : cold heat stream temperature

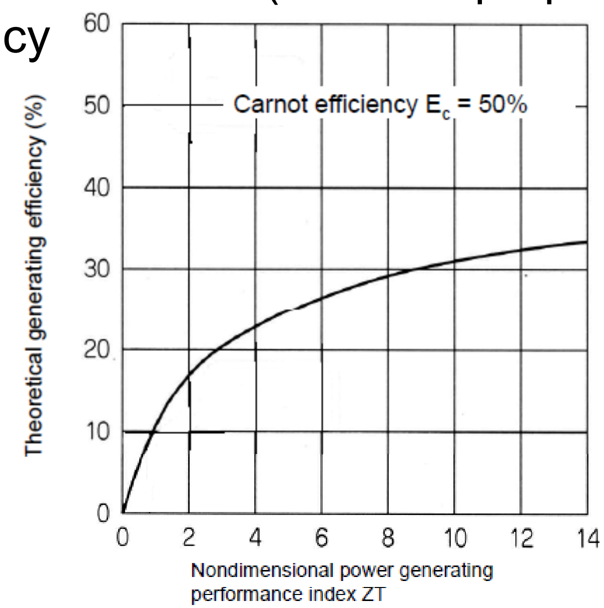
  Carnot efficiency

  material efficiency

- Figure of merit: $$ZT = Z \cdot T = \frac{\alpha^2 \sigma}{\kappa} T$$

  α : Seebeck coefficient
  σ : electrical conductivity
  κ : thermal conductivity
  T : absolute temperature of material

- Impact of figure of merit (material property) on TEG system efficiency for a typical Carnot efficiency

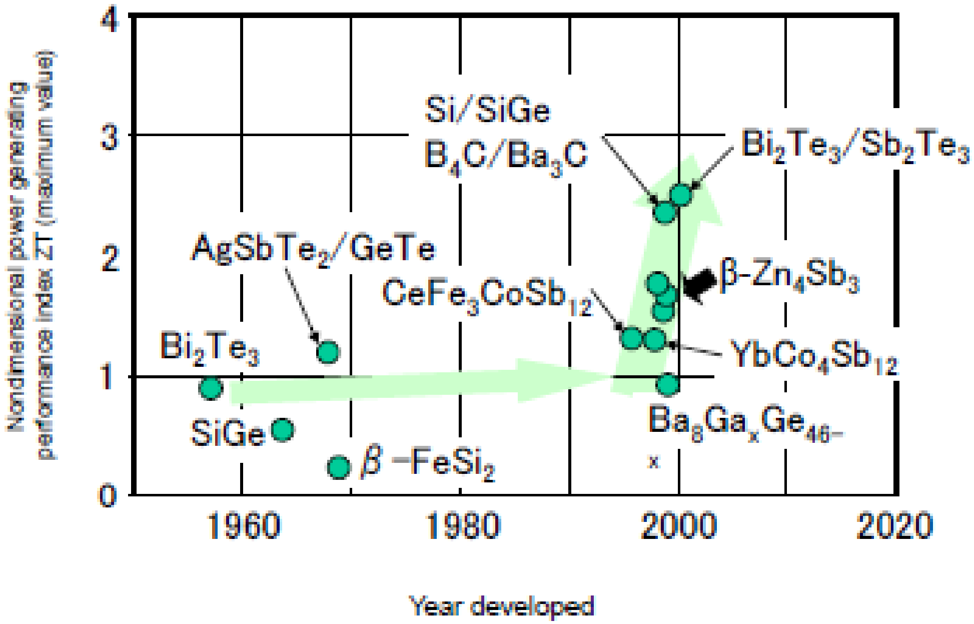


- Penetration of TEG system into market only for η > 15%
- Materials with ZT > 2 are needed

Source: R&D Trends…

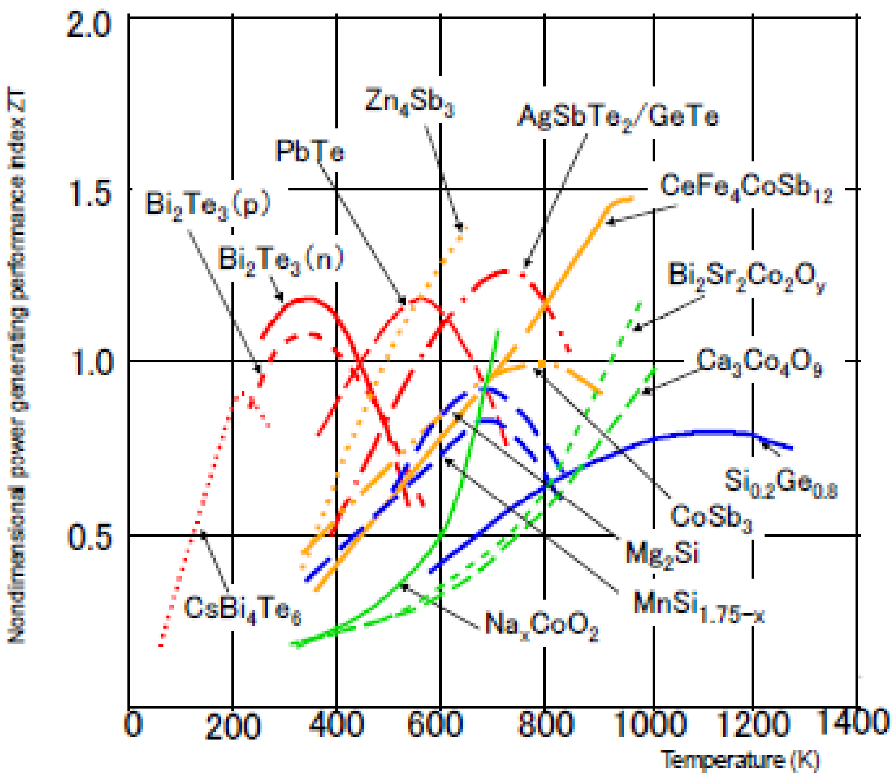
Current status of performance

History of figure of merit development for main semiconductor materials



Source: R&D Trends…

Figure of merit dependence on temperature for main semiconductor materials



Source: R&D Trends…

- Bi-alloys : low-T materials (≤ 450 K)
- Pb-alloys : medium-T materials (≤ 850 K)
- SiGe-alloys : high-T materials (≤ 1300 K)

Characteristics

- Semiconductors weak and prone to mechanical failure due to thermal cycling
- Need for higher robustness at high temperatures; need for higher efficiency across all temperatures
- Different exhaust gas temperature profiles (e.g. automotive vs marine applications) demand use of alternate materials
- Efficiency greatly dependent on semiconductors (e.g. Bi_2Te_3 and SiGe) properties
- High heat source temperatures needed make application **meaningful only for exhaust gas heat utilization**
- Low conversion efficiency: ~ 5%
- Better efficiency achieved using an intermediate oil circuit, due to better heat transfer between exhaust gas and oil than between exhaust gas and TEG – achievement of **favorably constant temperature gradient**

Comparison Ericsson/Rankine/Strling

- There is an overwhelming multitude of options for converting exhaust gas (and coolant) heat to work – if usefull applications for heating and cooling were included this would further expand
- The favourites in the vehicle industry, ORC and thermoelectricity, do not clearly win the thermodynamic stakes when ample low temperature heat sinks are available

	HP Ericsson	Rankine	Stirling
Power	302 kW	332 kW	440 kW
Efficiency	0,130	0,137	0,180

- While the comparatively little researched and understood Ericsson is close behind the Rankine, with water as the working fluid, which is currently a hot subject for the truck industry – the Stirling engine seems to be a potential favourite
- The challenge is to make it or get it made – it can be assumed that the development of an appropriate machine would cost no less than the development of, e.g., the assumed 5 MW main engine

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Comparative features

WHR technology	BSFC improvement
Mech. Turbocompounding	~ 3%
Turbogenerators	~ 7%
E-Turbo	~ 5%
Hybrid System	~ 10%
ORC	~ 7-9%
Stirling Engine	~ 10%
Ericsson Engine	~ 7%
TEG	~ 2.5%

Thank you
for your Attention!