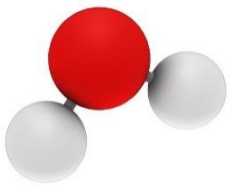
Plenary Session

Panel I : HERCULES Achievements



HERCULES–2

FUEL FLEXIBLE, NEAR-ZERO EMISSIONS, ADAPTIVE PERFORMANCE MARINE ENGINE

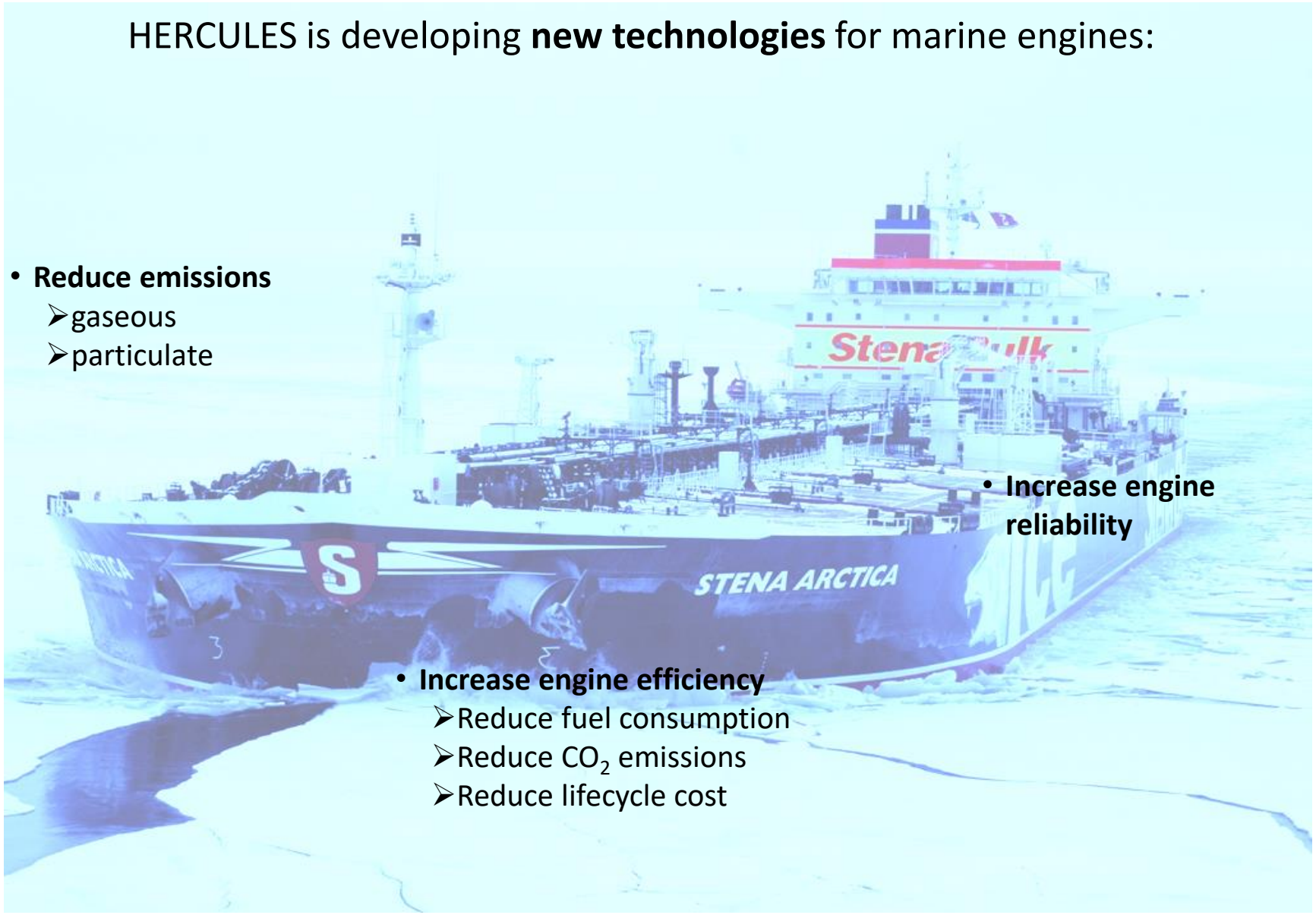
GA 634135

Panel I Members

Panel I: HERCULES Achievements	
Name	**Organization**
Ulf Waldenmaier	MAN ES AUG
Stefan Mayer	MAN ES CPH
Sebastiaan Bleuanus	Wärtsilä NL
Wolfgang Östreicher	WinGD
Dino Imhof	ABB
Nikolaos Kyrtatos (Moderator)	NTUA

The HERCULES (2004-2018) R&D program

HERCULES is developing **new technologies** for marine engines:



- **Reduce emissions**
  - gaseous
  - particulate
- **Increase engine reliability**
- **Increase engine efficiency**
  - Reduce fuel consumption
  - Reduce CO_2 emissions
  - Reduce lifecycle cost

HERCULES Mythology

1998 1999 2000 2001 2002 2003 2004

EC Paper
(...European large Engine Industry...)

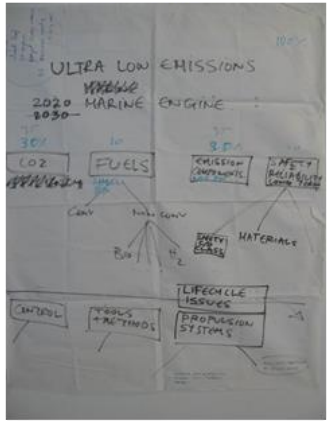
EC FP6 (2002-2006)
...Integrated Projects
(New Concept)

@CIMAC Hamburg
Idea:
Marine Engine Project

Talks MAN + WARTSILA
Talks with EC
100M EUR 10 years

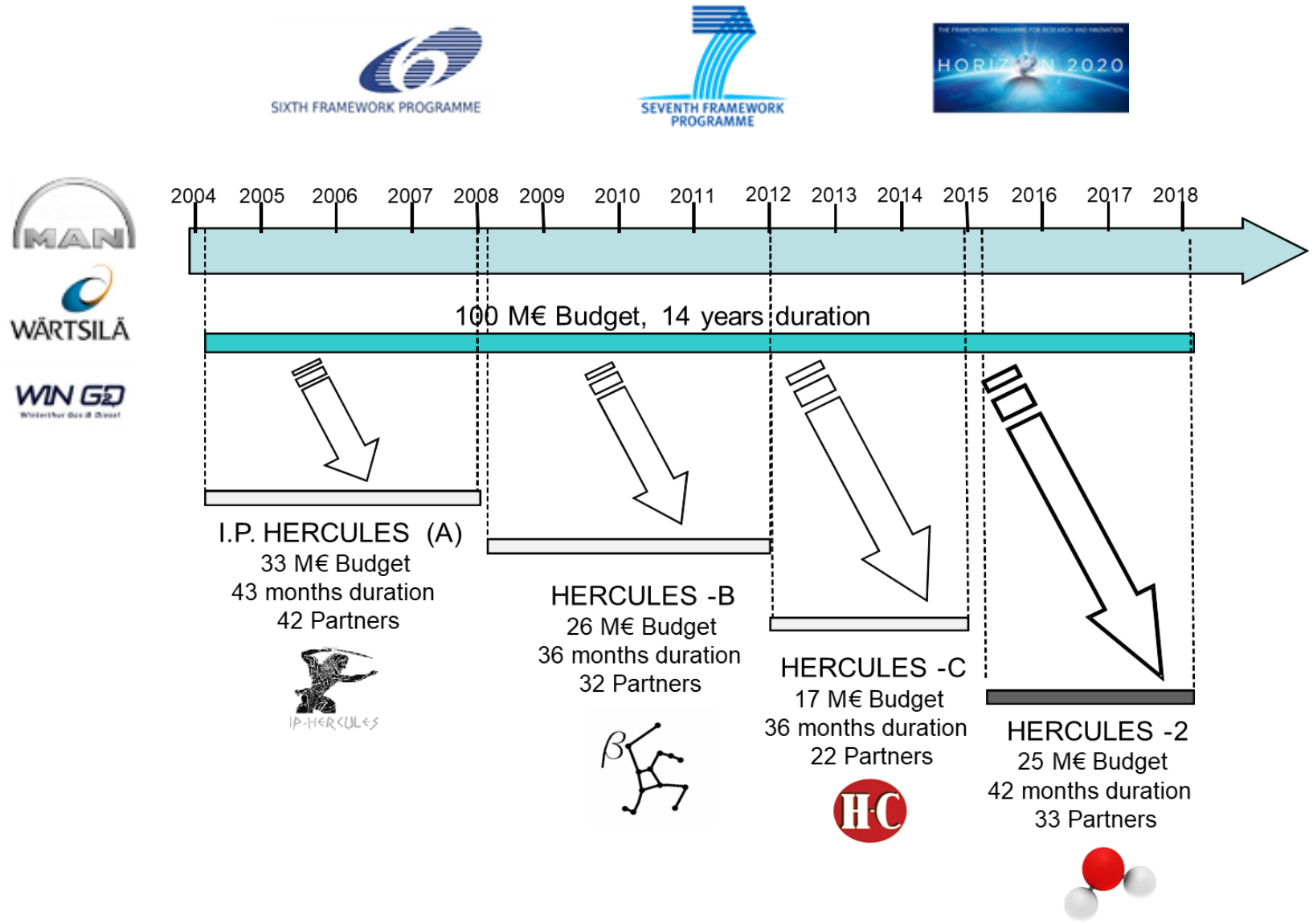
HERCULES proposal
- Efficiency
- Emissions
- Reliability

HERCULES-A starts



Flipchart page
First MAN – WARTSILA joint Meeting: Helsinki, 4th July 2002

The HERCULES Programme Timeline

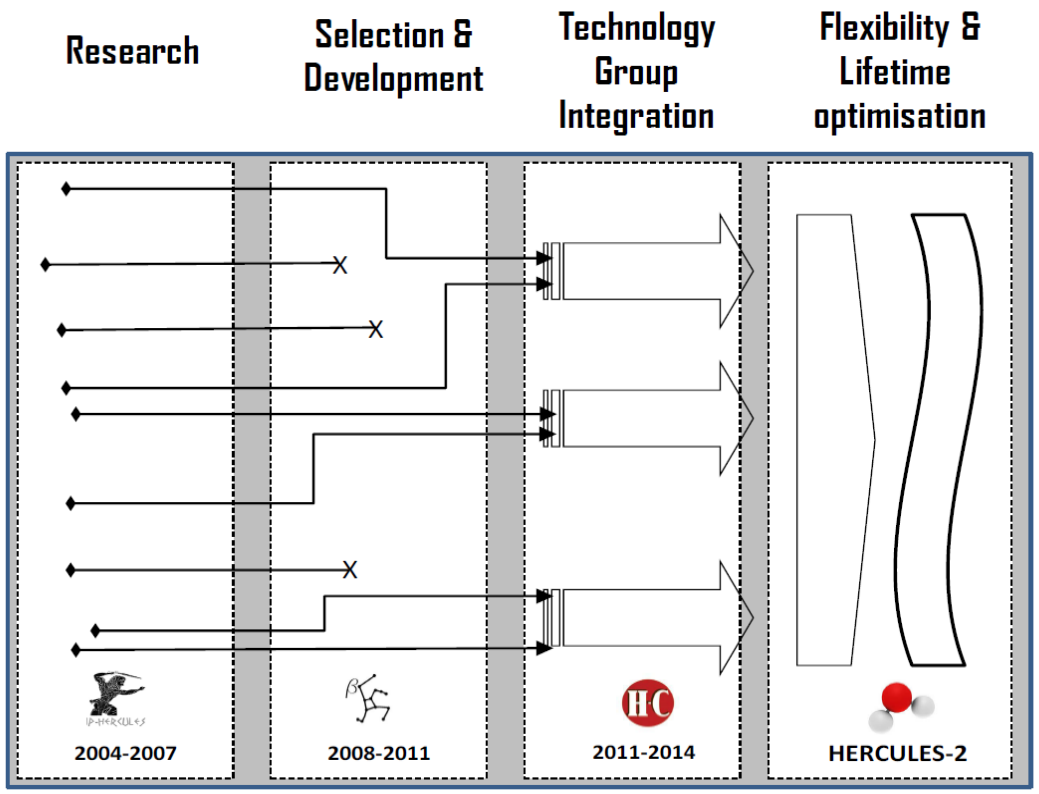


HERCULES Program Partners

SIXTH FRAMEWORK PROGRAMME

SEVENTH FRAMEWORK PROGRAMME

The HERCULES Programme evolution



- HERCULES A

High-Efficiency Engine R&D on Combustion with Ultra Low Emissions for Ships

- HERCULES-B

Higher-efficiency Engine with Ultra-low Emissions for Ships

- HERCULES-C

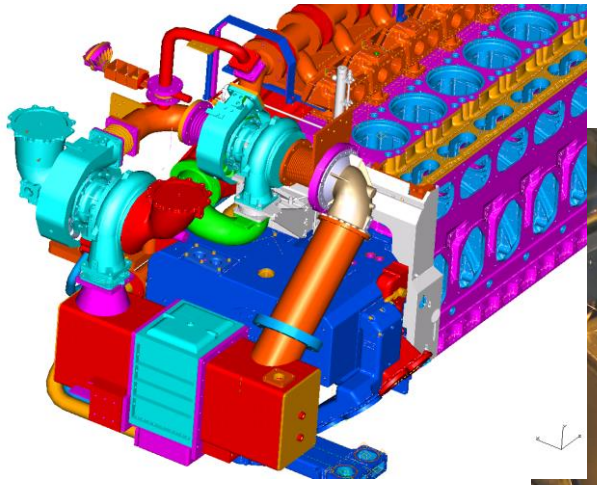
Higher-efficiency, Reduced Emissions, Increased Reliability and Lifetime, Engines for Ships

- HERCULES-2

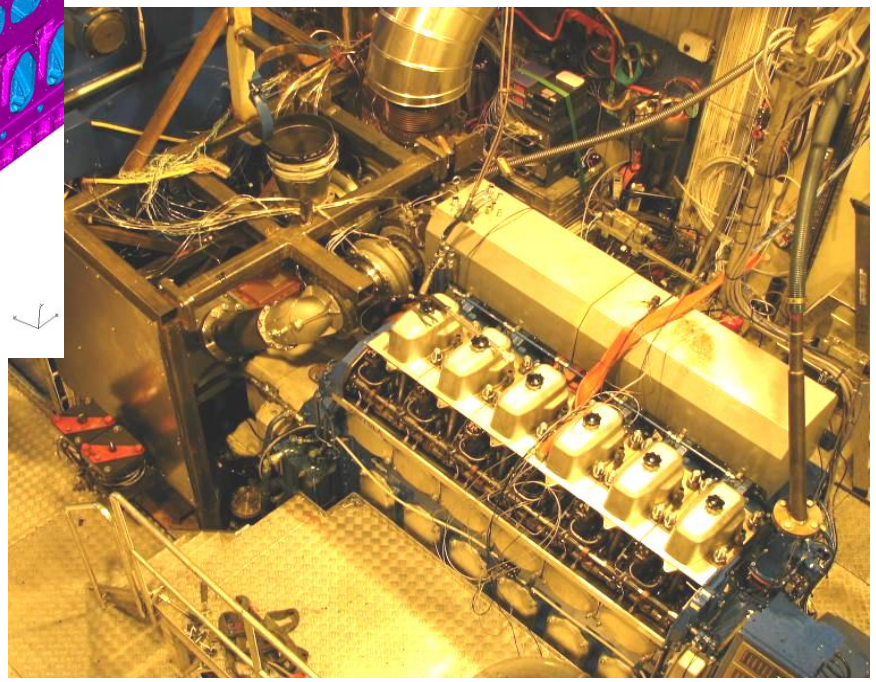
Fuel flexible, near-zero emissions, adaptive performance marine engine

H - A: Variable turbocharging

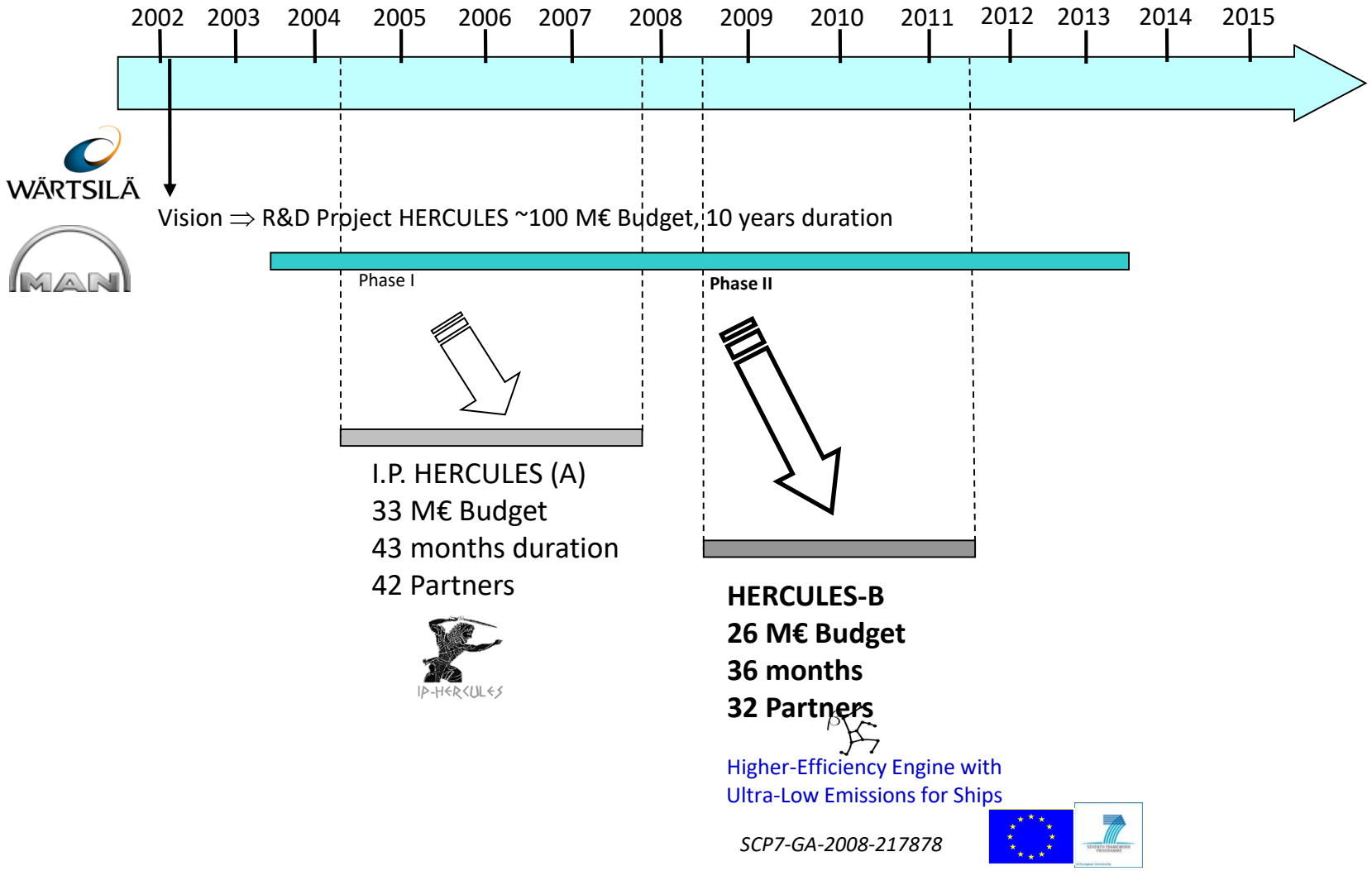
Two-stage turbocharged 4-stroke engine



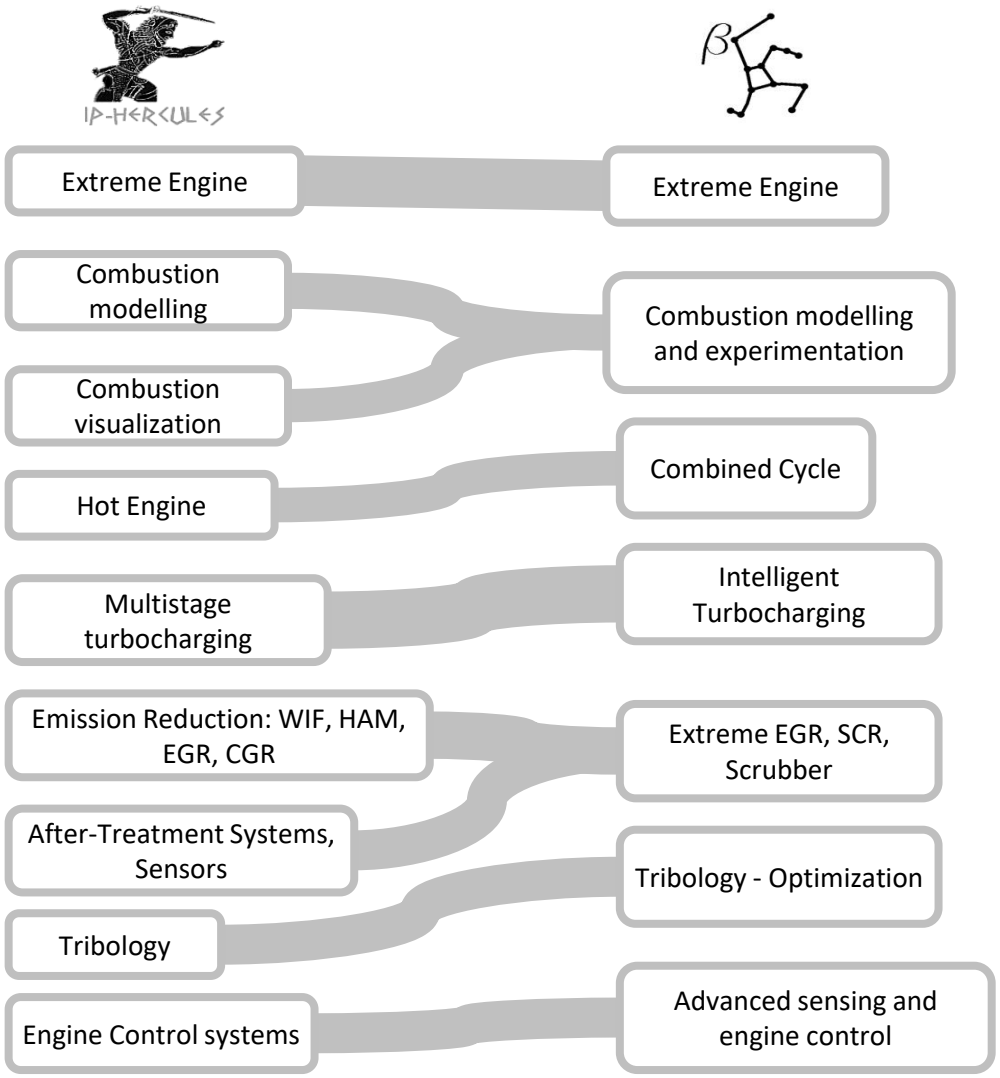
CIMAC 2007 Congress: Best paper award !



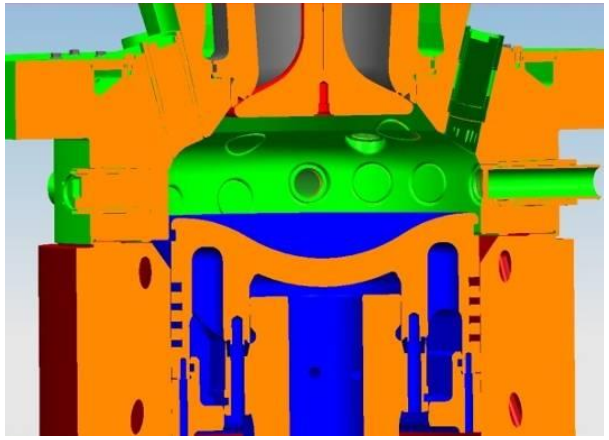
HERCULES Timeline



HERCULES Evolution

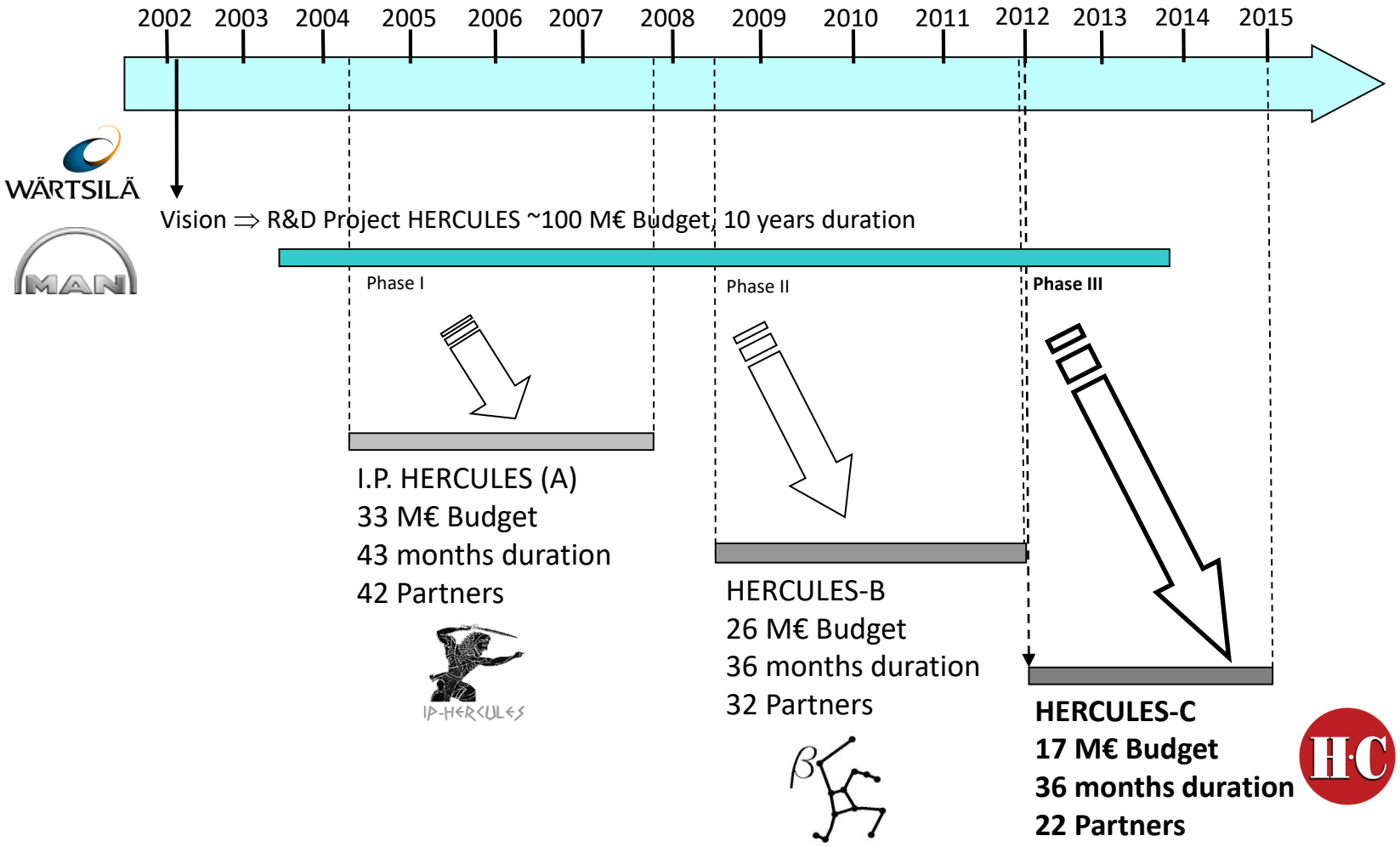


H-B: Combustion process visualization development



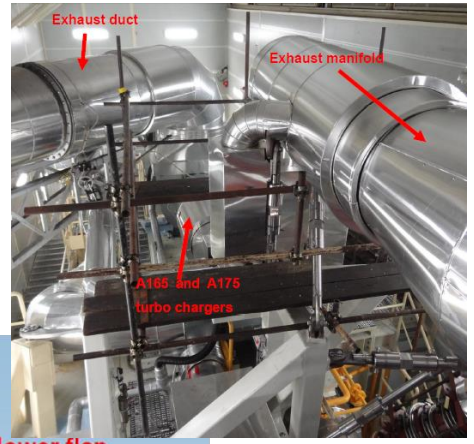
Optical cylinder covers for
2-stroke

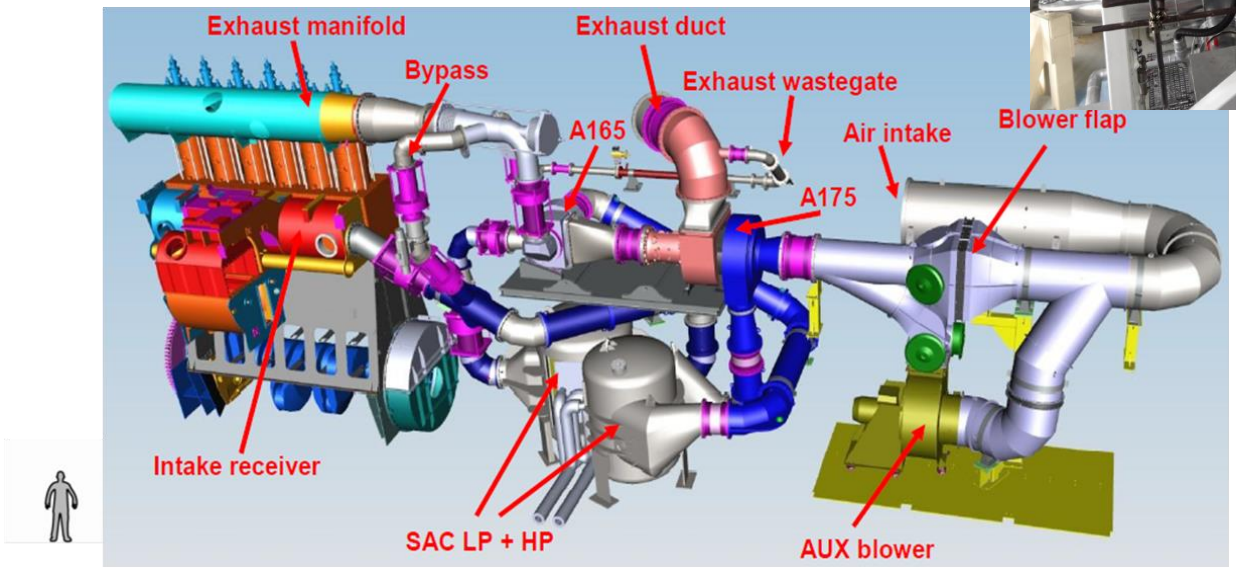
HERCULES Timeline



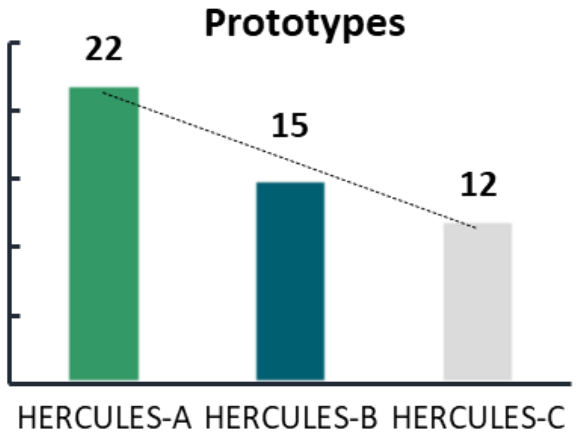
H-C: Full scale experimental setup

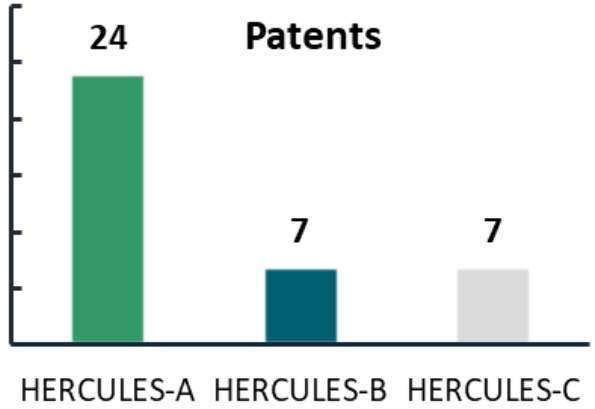
Complete variability of turbocharging system combined with EGR

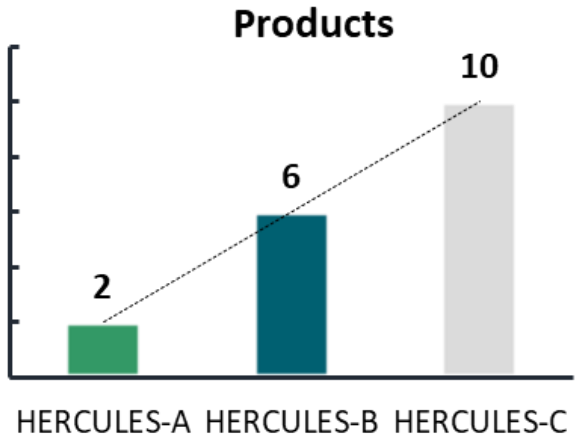


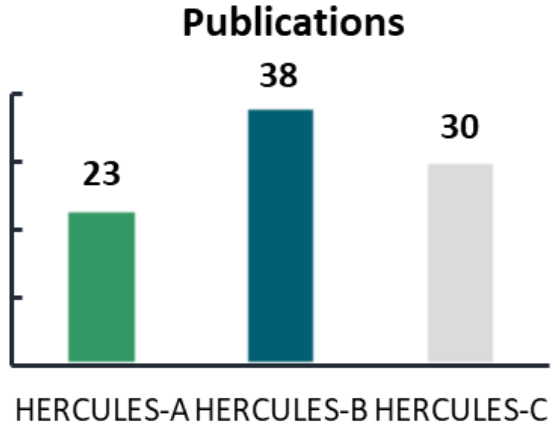


Metrics of HERCULES

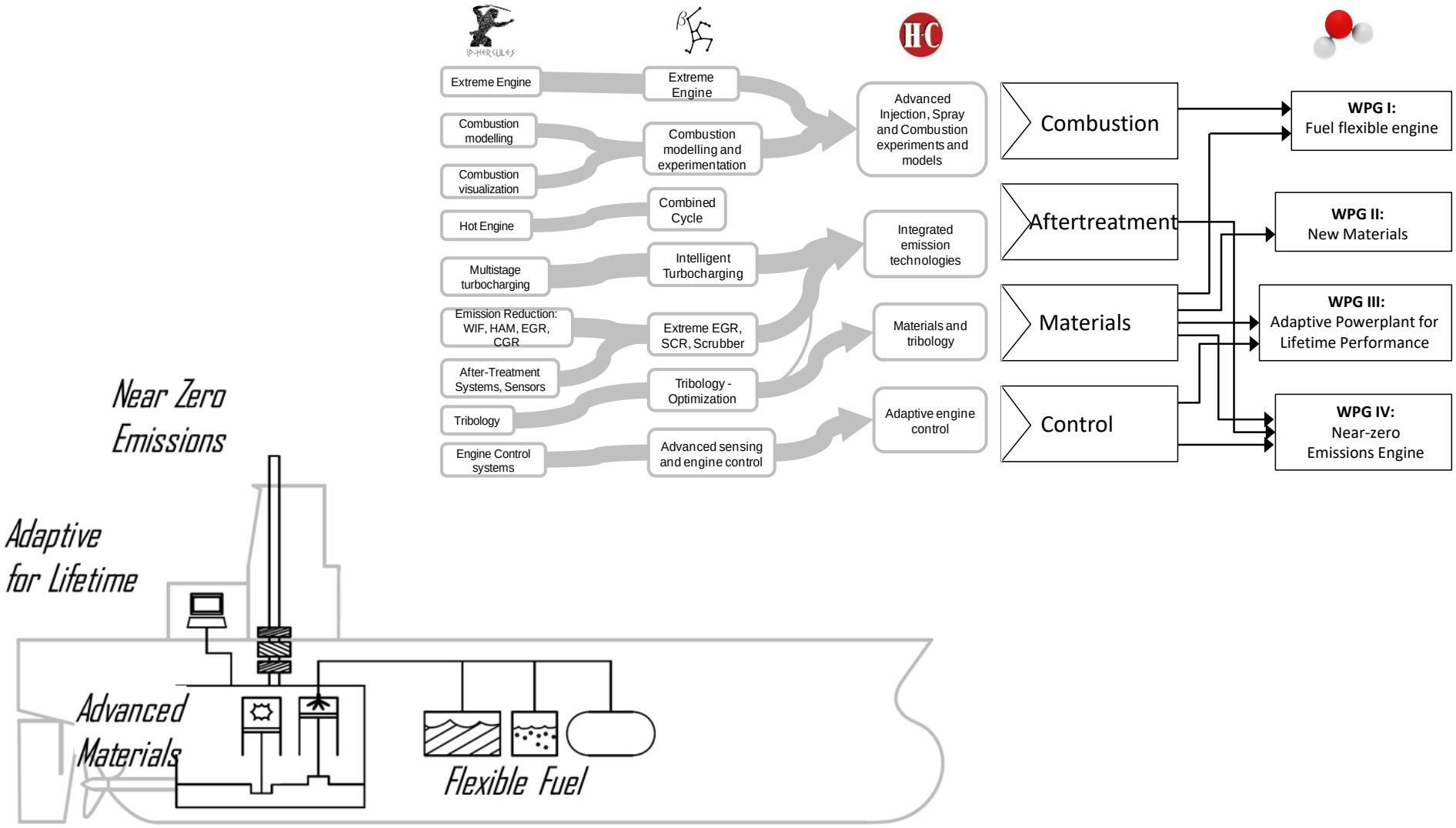




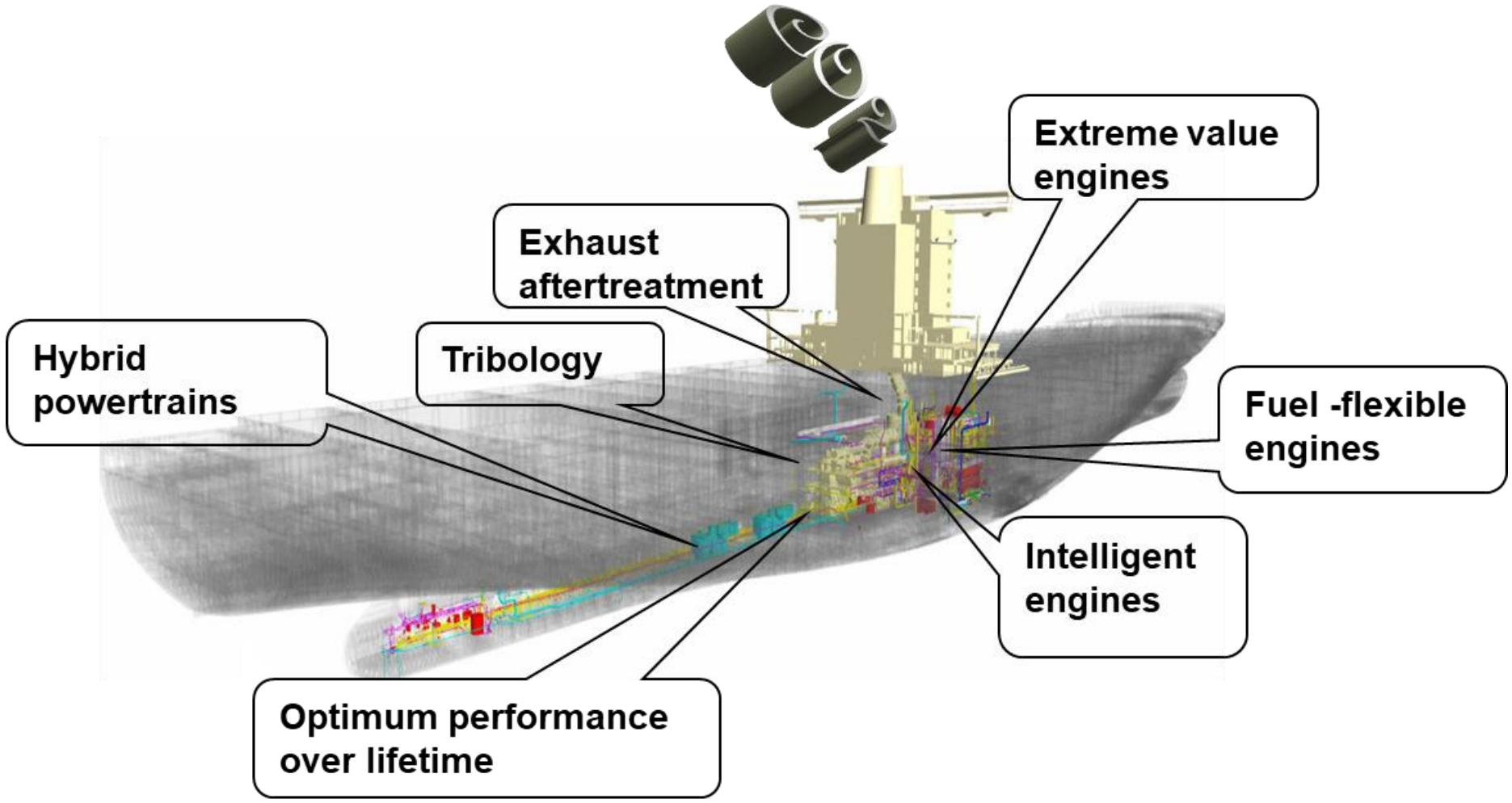




Links among HERCULES Projects



HERCULES and the future in ship propulsion engines



Comments

- The longevity of alliances is often used as proxy of their performance.
- The HERCULES alliance of 14 years has been demonstrably successful.
- Many results of R&D already matured into products.

Panel Members Presentations

Panel I: HERCULES Achievements	
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MAN Energy Solutions
Future in the making

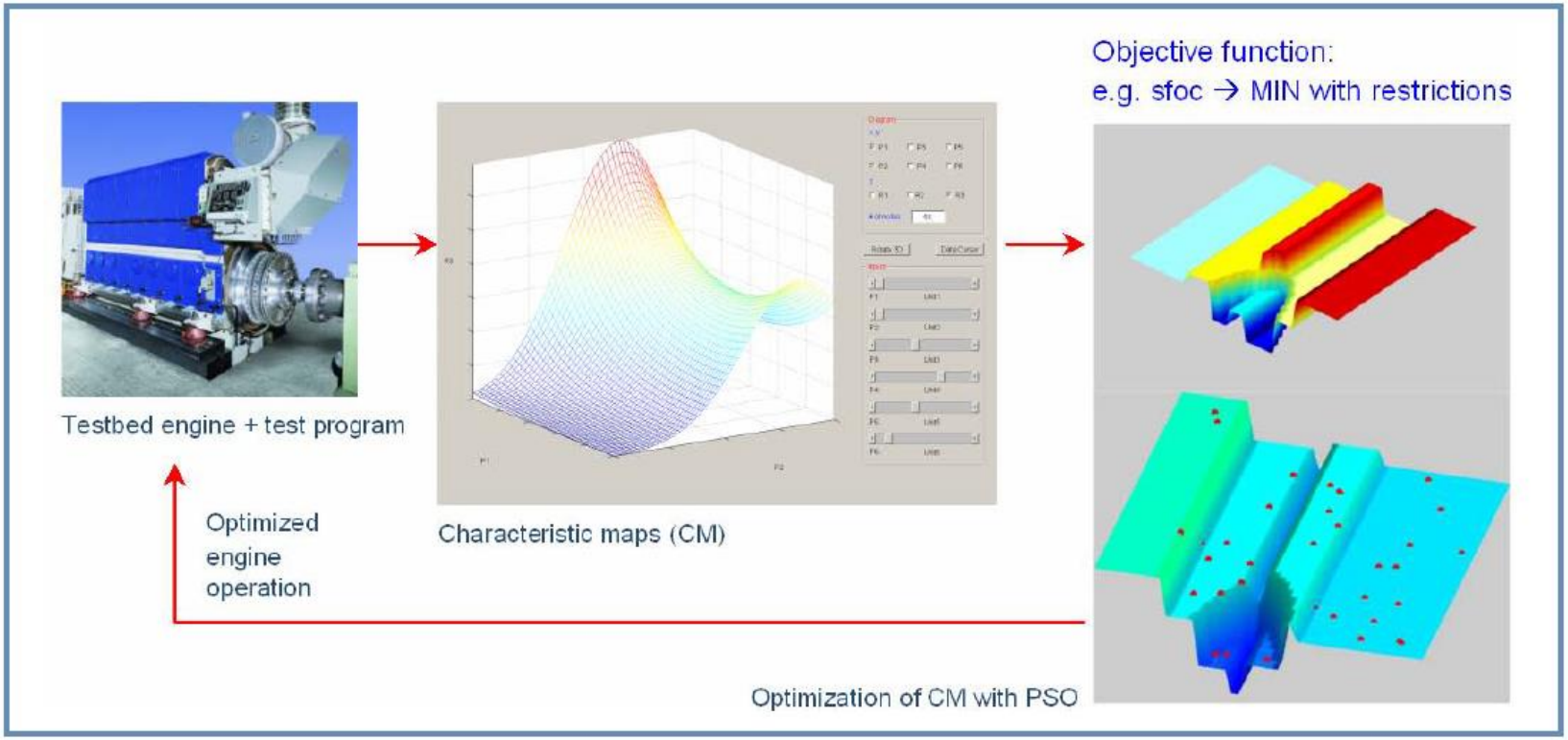
Hercules Achievements

- Intelligent Engine Control
- Exhaust Aftertreatment

Intelligent Engine Control

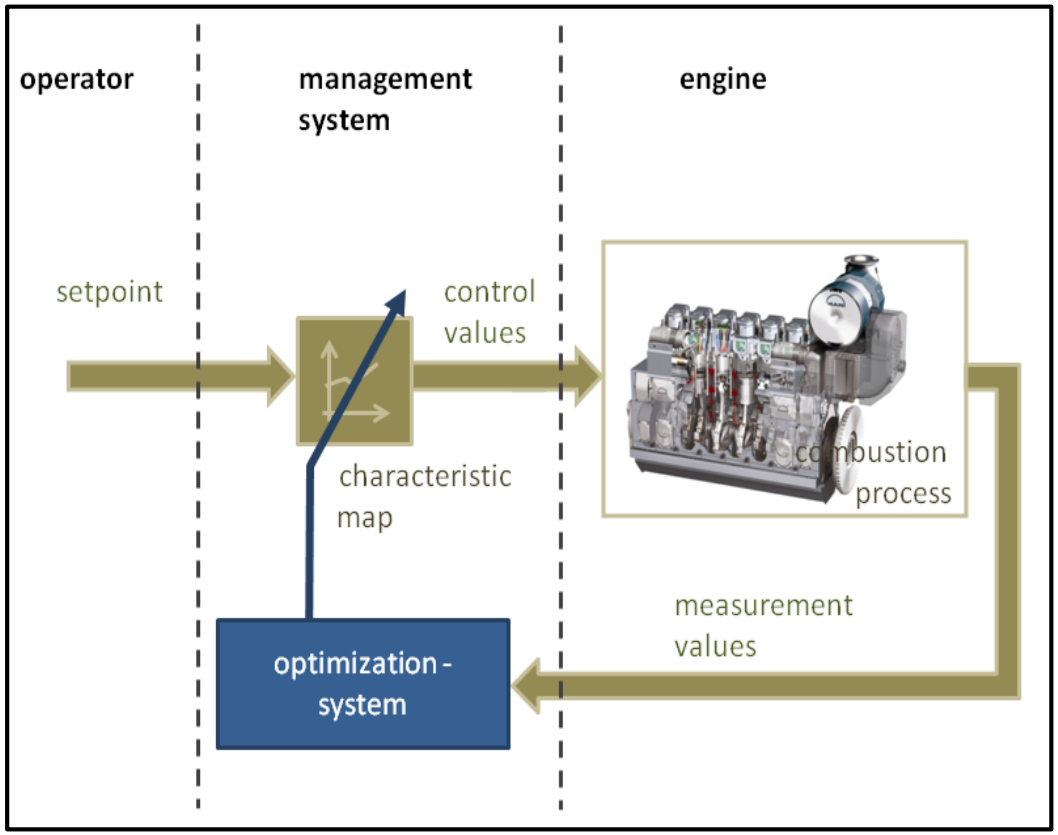
Hercules-A

Offline optimization of engine control based on DoE and neuronal network for reduced emissions and fuel consumption



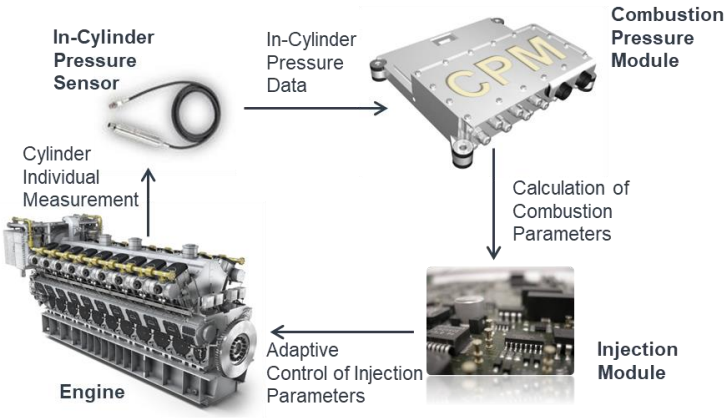
Hercules-B

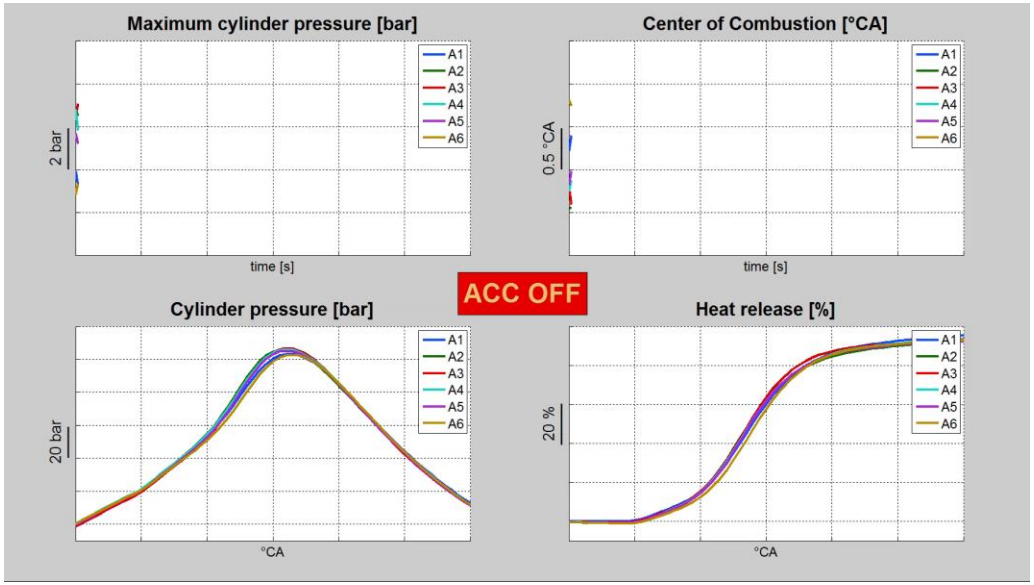
Adaptive Engine Control (AEC) and management system with self-learning and adaptive capabilities for diesel engines



Hercules-C

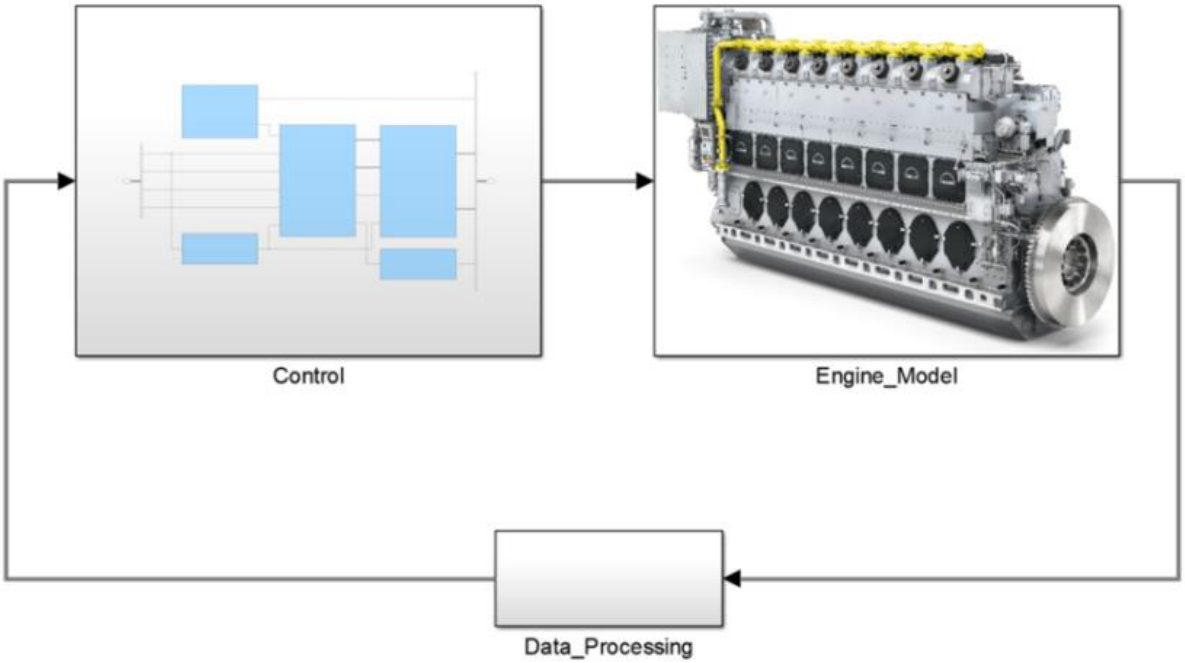
Adaptive Combustion Control (ACC) with cylinder individual control algorithms applicable for multi-fuel engine

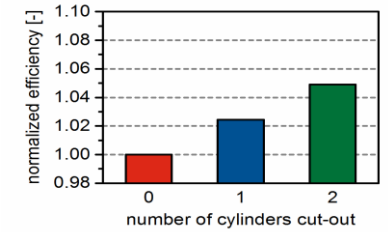


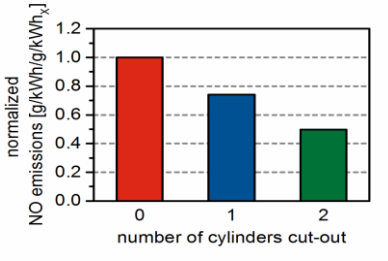


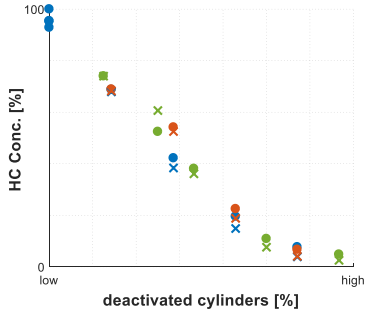
Hercules-2

Predictive model based engine control for improved dynamic behavior and reduced emissions at part load





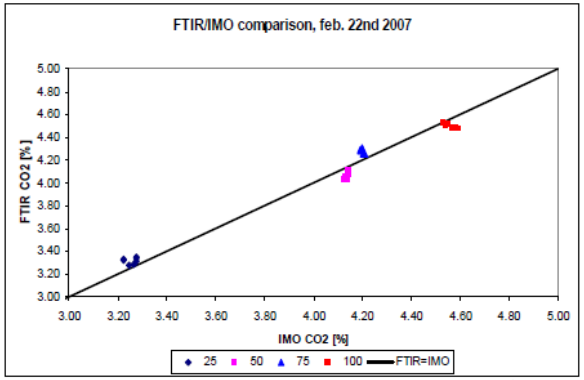




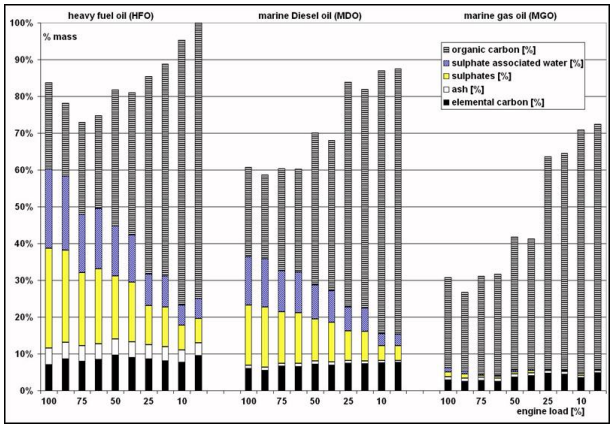
Exhaust Aftertreatment

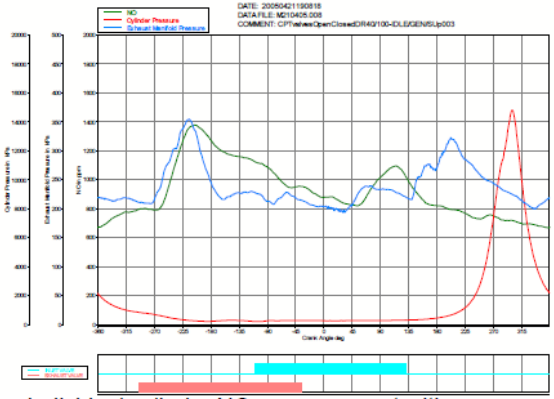
Hercules-A

Development of measurement techniques for on-board emission monitoring as basis for exhaust aftertreatment

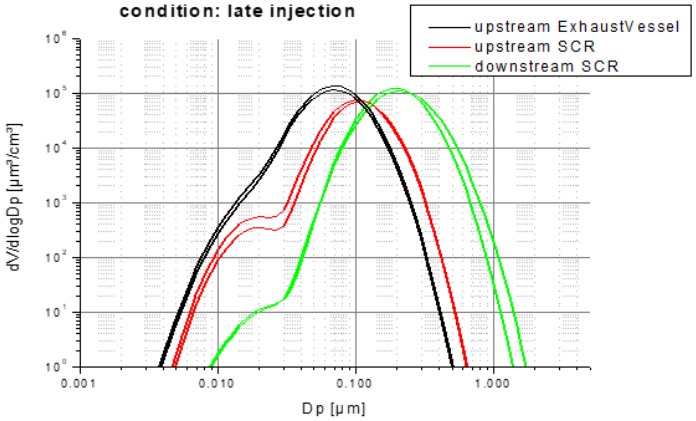


Comparisson between IMO-approved equipment and FTIR multi-component analyser



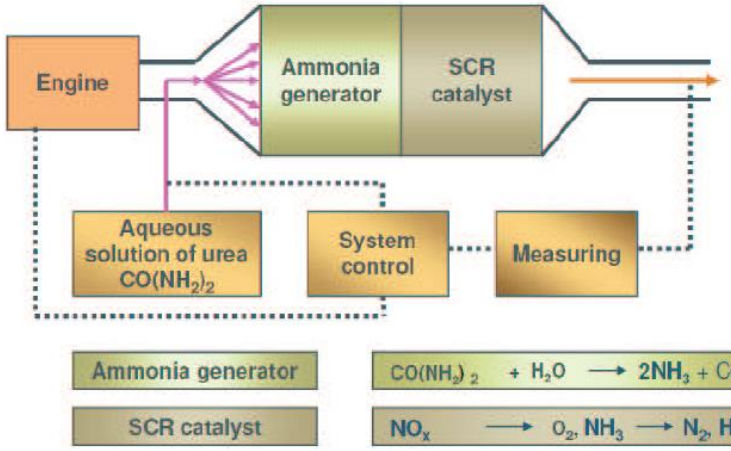


Individual cylinder NO measurement with new designed sample transfer tube



Hercules-B

Investigation and development of Selective Calatytic Reactor Prototype to reduce NO_X emissions towards IMO Tier III



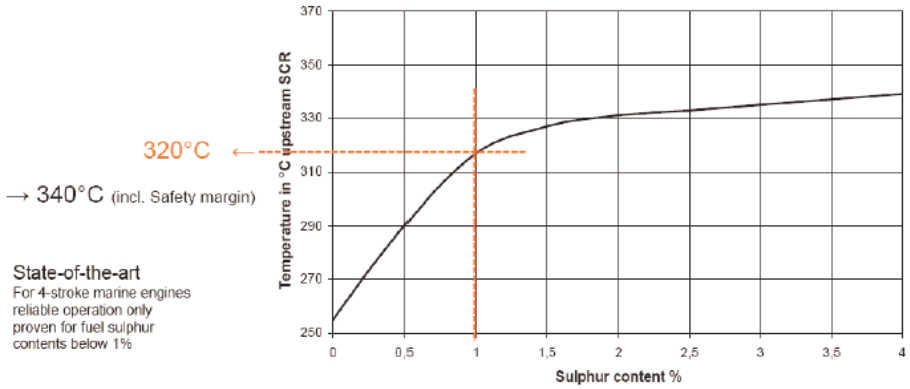
SCR Particulars

NO_x reduction up to 90%

Costs for reducing agent about 10% of fuel costs

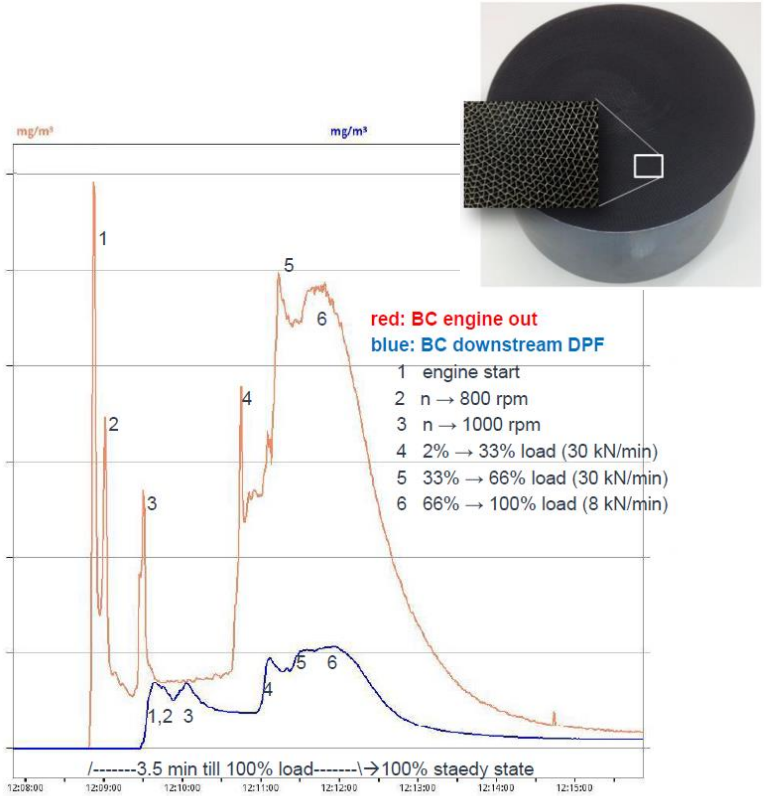
Sensitive on SO_x content in the exhaust gas

Needed minimum temperature at SCR inlet to avoid ammonia sulphate formation



Hercules-C

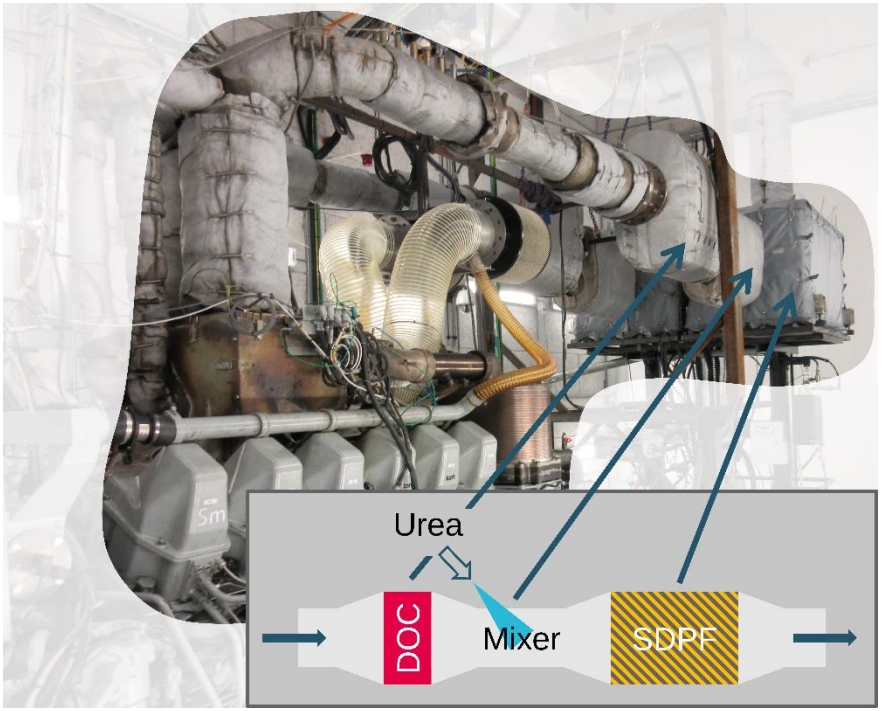
Adaptation & integration of advanced DPF technology for marine diesel engines to achieve US-EPA Tier 4 limit

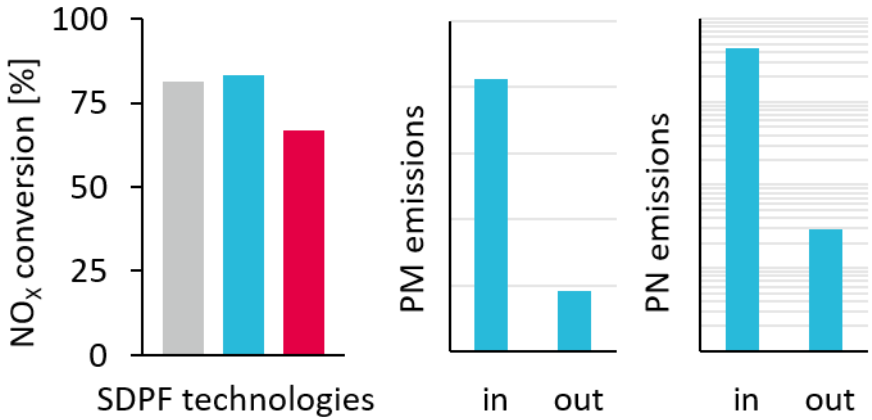


Transient BC emission (not calibrated) up- & downstream of DPF from engine cold start till full load

Hercules-2

Development and prototype test of SCR on DPF on a marine diesel engine to minimize NO_X and PM emissions





MAN Energy Solutions
Future in the making

Thank you!

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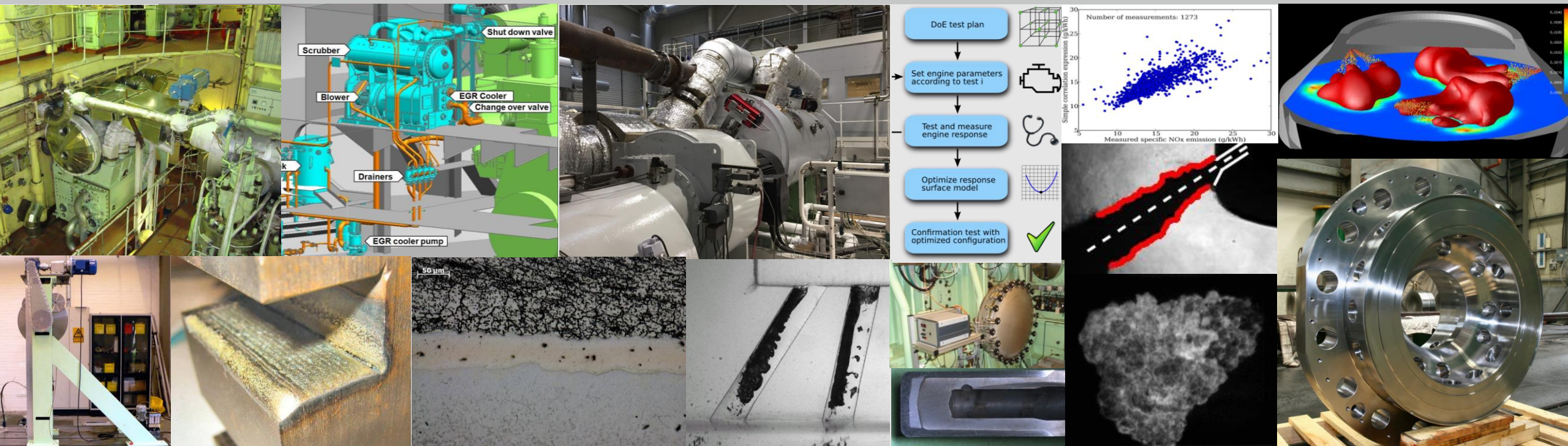
Ulf.Waldenmaier@man-es.com
10.10.2018

MAN Energy Solutions
Future in the making

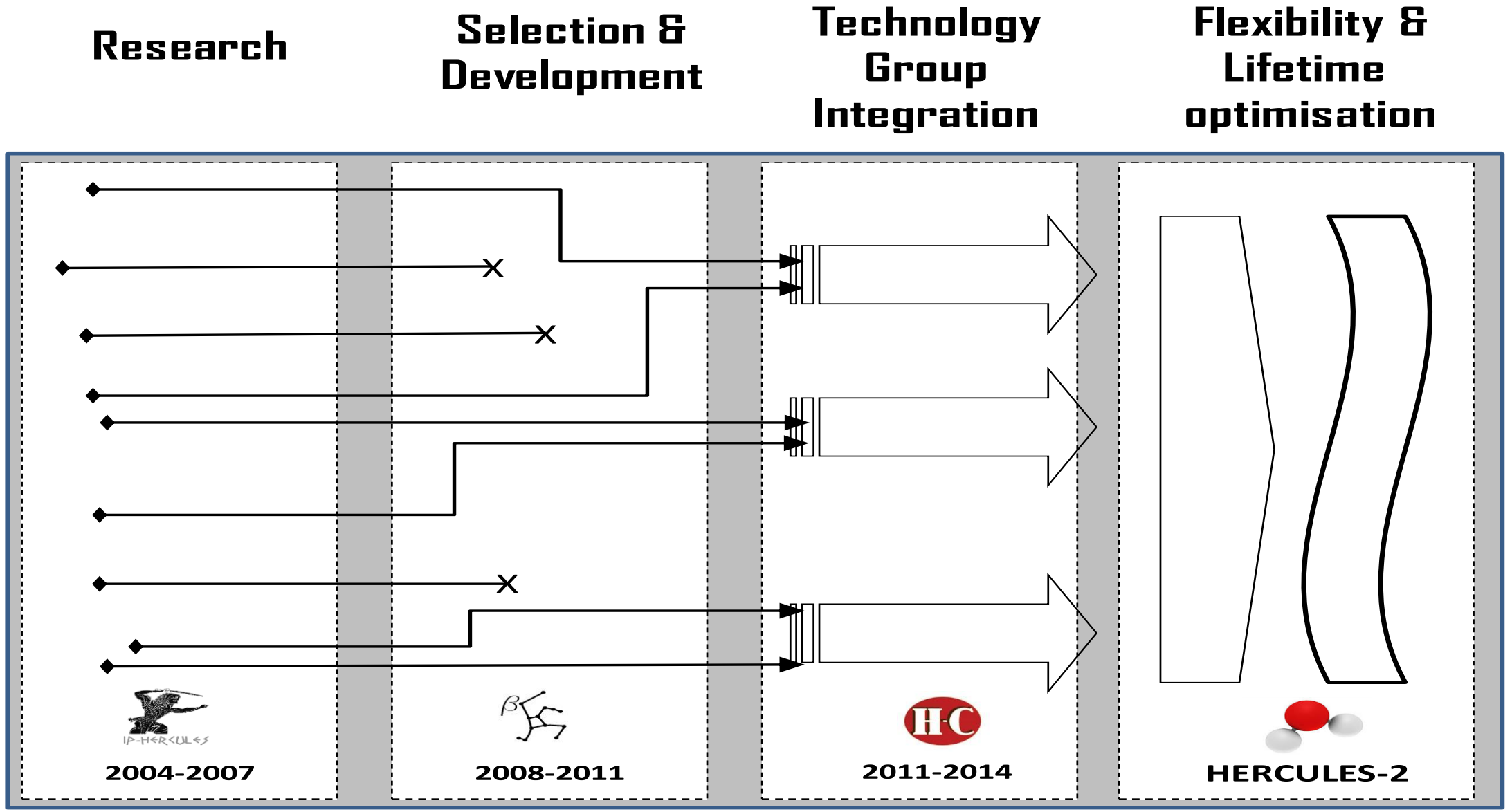
Hercules-ABC2 (2004 – 2018)

The Achievements of the Hercules Programs

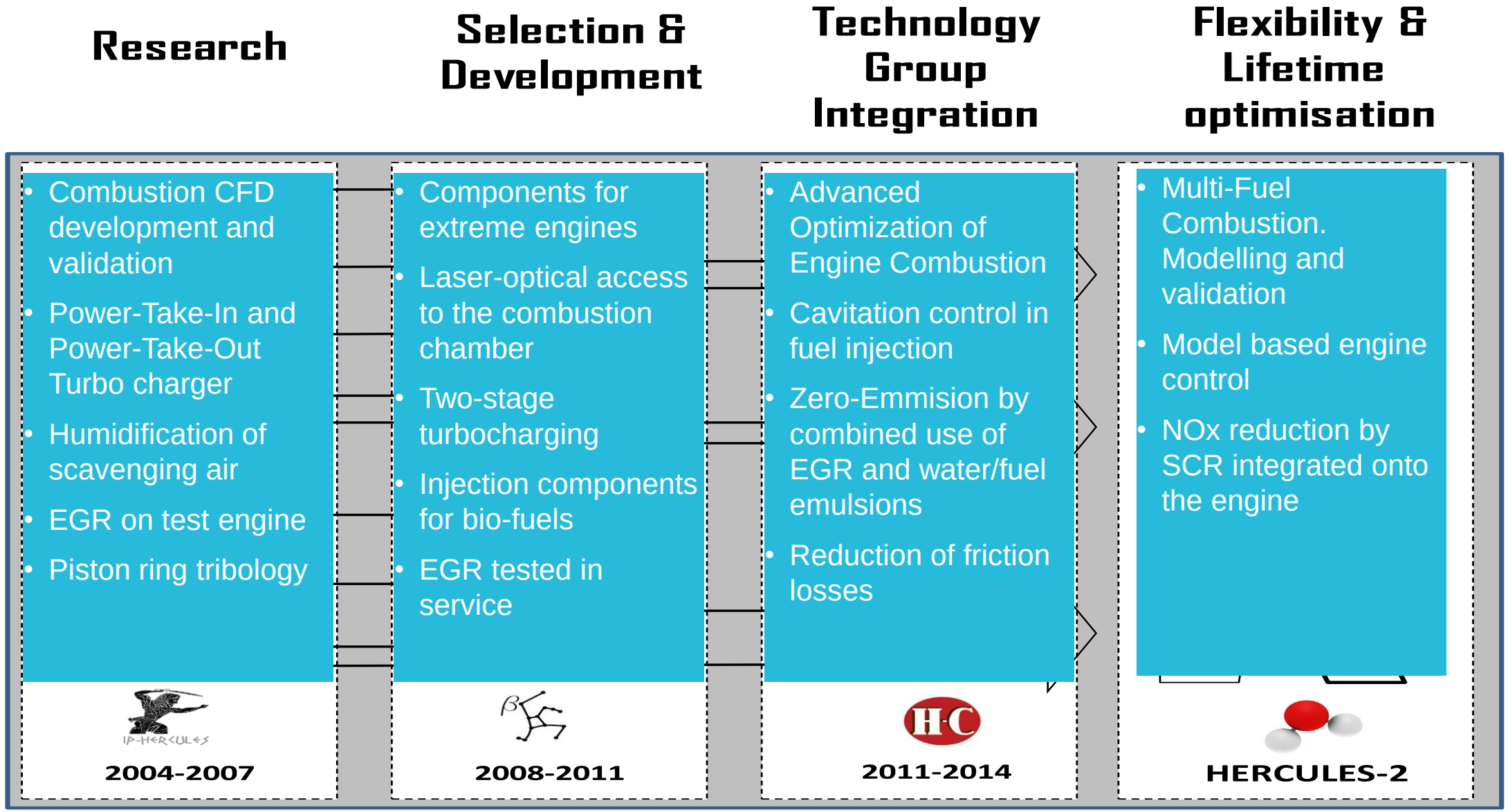
Stefan Mayer
Engine Process Research
2018-10-10



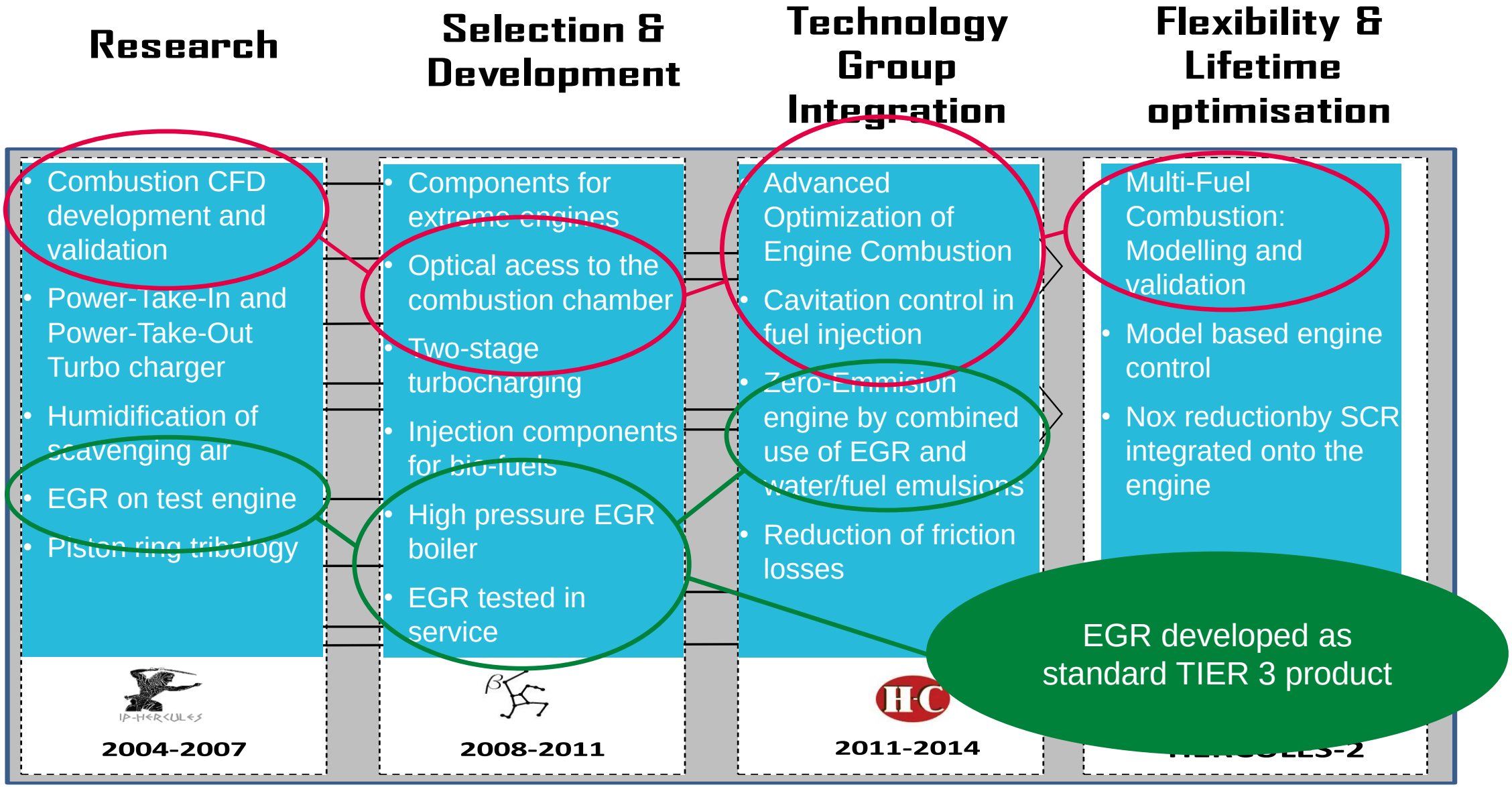
Hercules Programs



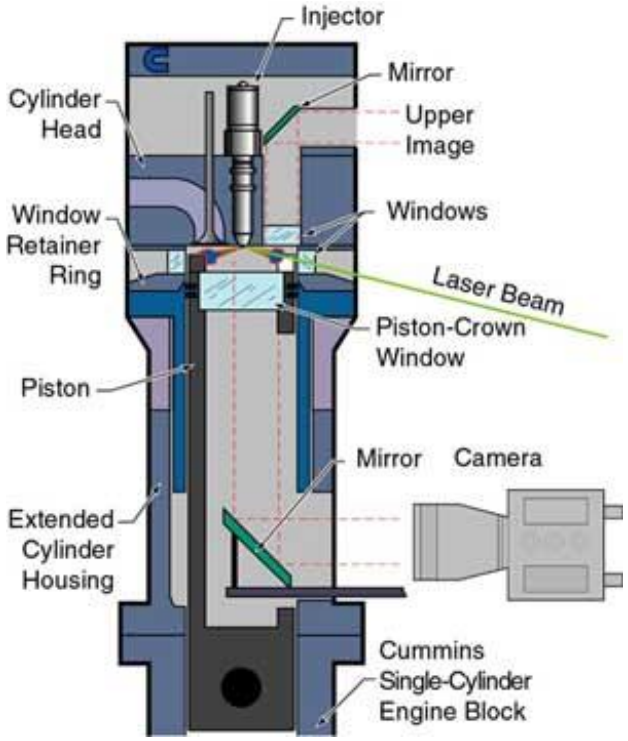
Hercules Programs: MAN – 2 stroke

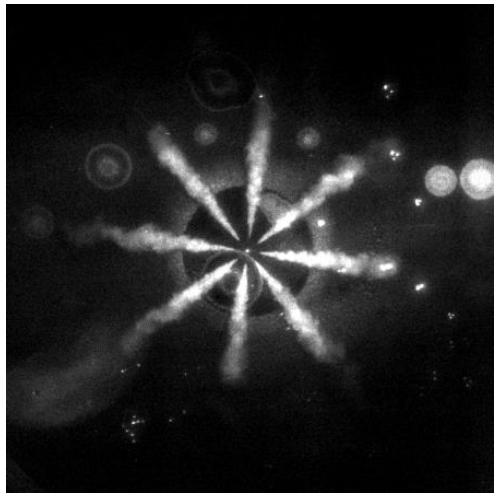


Hercules Programs: MAN – 2 stroke

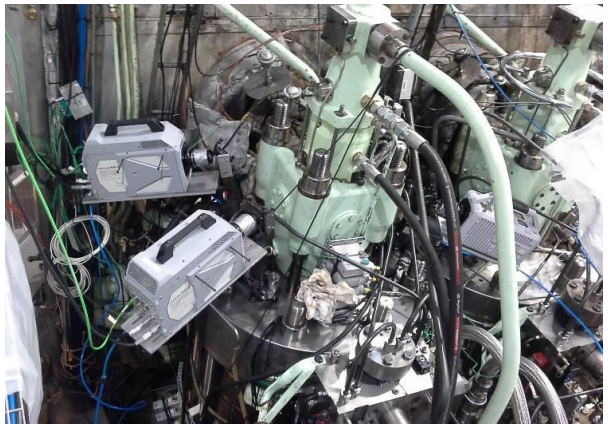


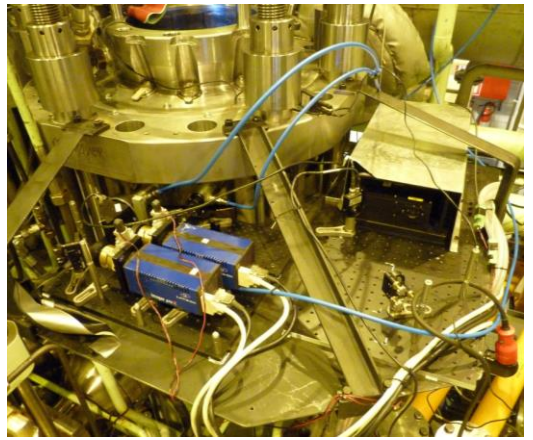
Optical Combustion Diagnostics

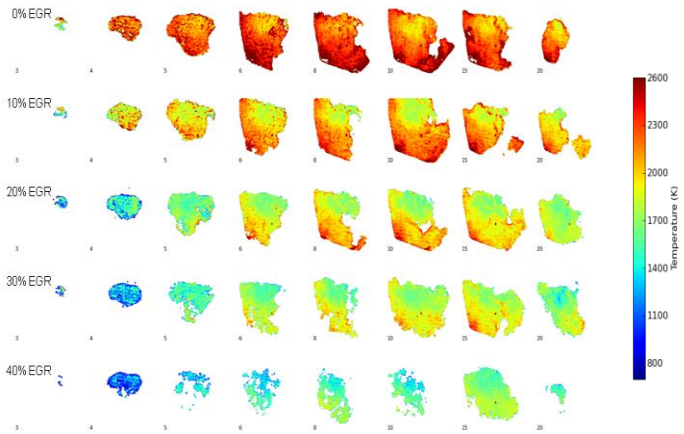


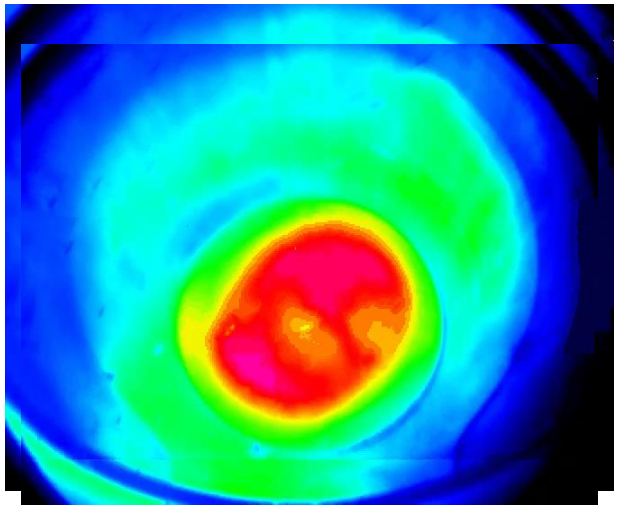


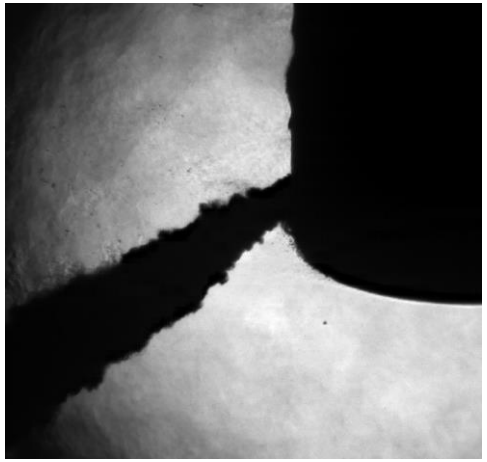
Optical work at the 4T50ME-X test engine

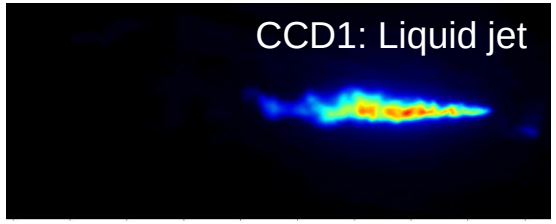


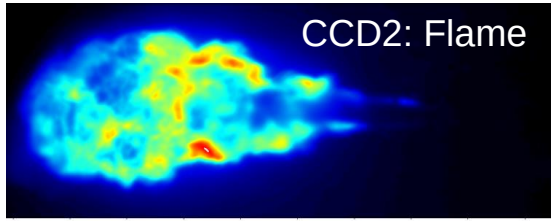












Summary of optical work within Hercules

Hercules has opened for a very large range of new methods now available.

It opened the ‘black box’ combustion chamber

Very high speed flame luminosity imaging

Flame Spectroscopy

2-Color Flame Thermography

Particle Image Velocimetry (PIV)

Mid-Infrared thermography

Mid-Infrared Hot Gas Visualisation

High Speed UV and Mid-Infrared Absorbtion Emisson Measurements in Exhaust Duct

Mie Scattering Imaging of Diesel Spray

High Speed Shadowgraphy of Near Nozzle Spray

Thermographic Phosphors

Cavitation Visualisation

Micro PIV of Cavitating Nozzle Flow

Multi-Camera 3D Reconstruction of Flame

Many of the developed techniques are now used routinely at the engine maker for a multitude of problems and applications.

Scavenging Optimization

Pilot Ignition Optimization

Validation of needed CFD models on
Scavenging Flow, Liquid Spray Penetration Length, Flame Geometry, Near Nozzle Spray, In-Nozzle Cavitation.

Diesel Oil Combustion

Methane Combustion optimization

Ethane Combustion optimization

Methanol Combustion optimization

The established contacts to the relevant European academic environment will continue to bring value to both industry and academia.

Lund Technical University

Technical University of Denmark

University of Hannover

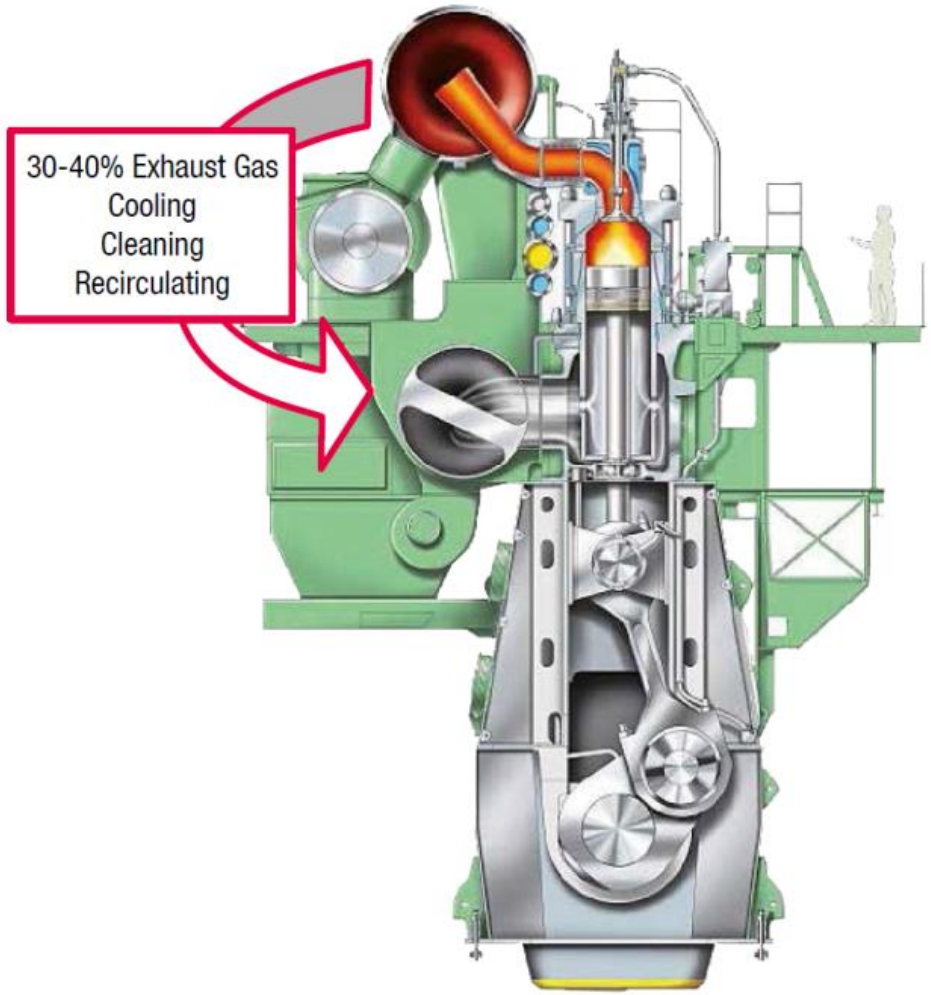
Chalmers University, Gothenburg

Polytechnico Milano

Technical University Munich

University of Karlsruhe

EGR in Large Marine 2-Stroke Engines



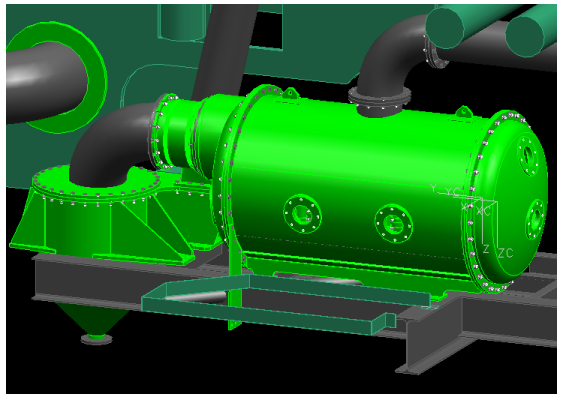
Exhaust gas is recirculated to the scavenge air receiver.

- Lower O_2 content (replaced by CO_2)
- Higher heat capacity of unburned gas
- Reduces peak temperature of the combustion and formation of NO_x

Recirculated exhaust gas is cooled and cleaned in the EGR system, but:

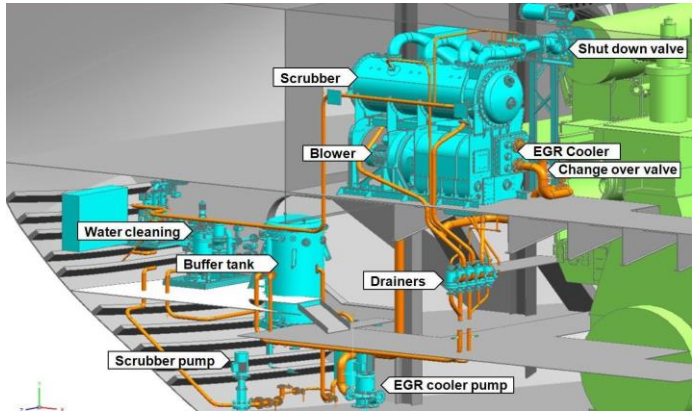
- How to cool and to clean the recirculated exhuast gas
- How to prevent corrosion in the affected engine components
- How to control the system
- How to limit cost of the system to actually secure market acceptance

EGR development

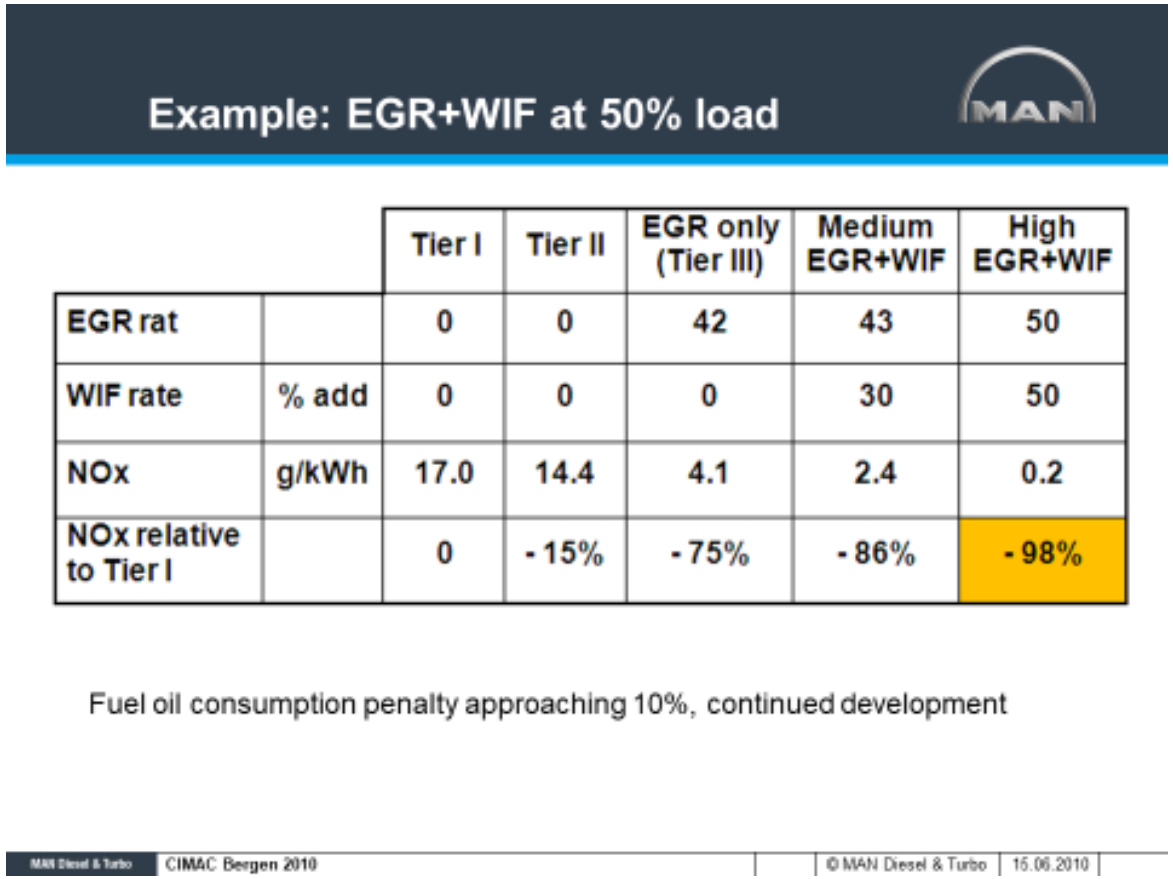


On the test engine 4T50ME-X

On board a ship and in service



The results



Slide from Cimac 2010

No. of engines	Vessel Type	Shipowner
1	Bulker	NYK Line
2	Crude Oil Tanker	Chevron
1	Container	A.P. Moeller-Maersk
12	LNG Tanker	
5	Ethane Gas Carrier	
2	Crude Oil Tan	
1	Tanker	
2	VLCC Tanker	
8	LNG Tanker	
2	Tanker	
2	Container	
2	Container	
4	LNG tanker	
1	Bulker	
1	Tanker	
2	PCTC	
6	Container	
6	Tanker	
1	Bulker	
1		
2	Container	
4	Container	
1	Tanker	Maran Tankers
1	Chemical Carrier	ELCANO
1		Aeolos

No. of engines	Vessel Type	Shipowner
2	Tanker	
2	Car Carrier	
1	Ethane Gas	Jaccar/Evergas
		Maran Tankers
		Shoei Kisen Kaisha
		Shoei Kisen Kaisha
		COSCO Shipping
		COSCO Shipping
		Shoei Kisen Kaisha
		Shoei Kisen Kaisha
		Fednav
		Tsakos
		Wisdom
		Eastern Pacific
		NLNG
		COSCO Shipping
		BW Gas
		yong National University
		Sea Tankers
	Bulk Carrier	
1	Bulk Carrier	

Status October 2018:

- **121 EGR engine in order or delivered**
- **8 EGR engines in service**

Current Reference List

Conclusion

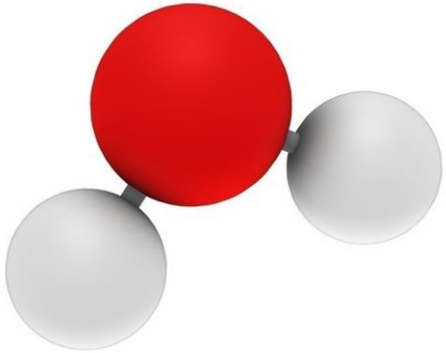
Hercules-ABC2 2004 - 2018

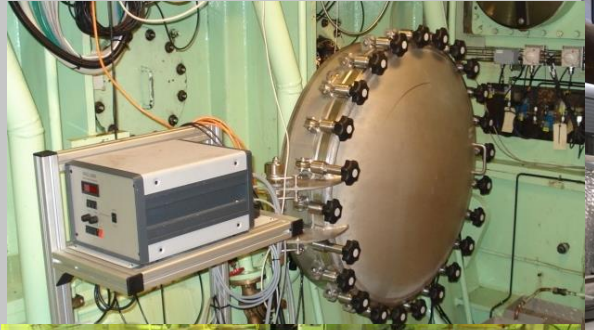
The Hercules programs have ensured that needed fundamental technological knowledge could be built up at the Engine Builder.

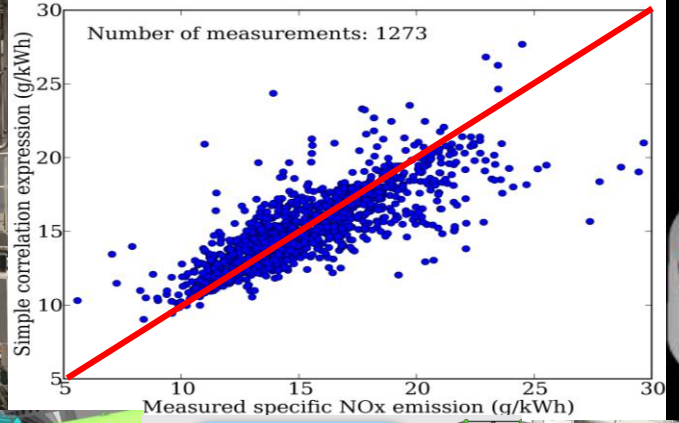
It helped to generated data from real size engines that would otherwise have been impossible to provide.

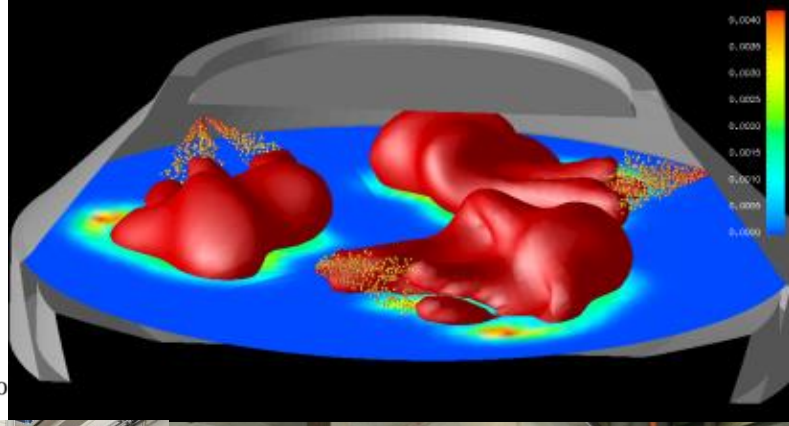
Hercules has secured that high-risk development efforts were brought to successful market introduction.

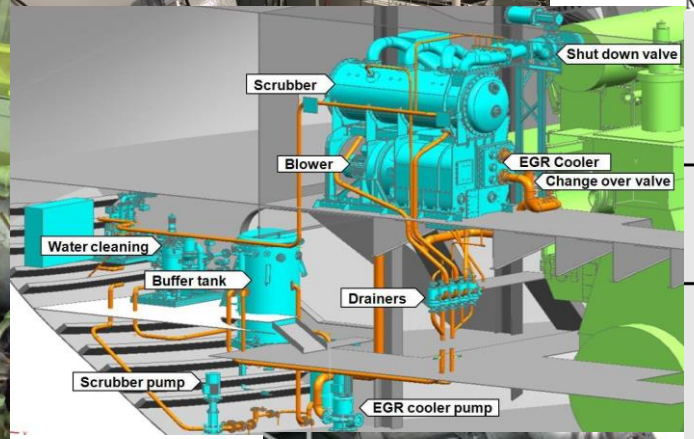
The Hercules programs have supported greatly the built-up of relevant interdisciplinary networks among European industry and academia.

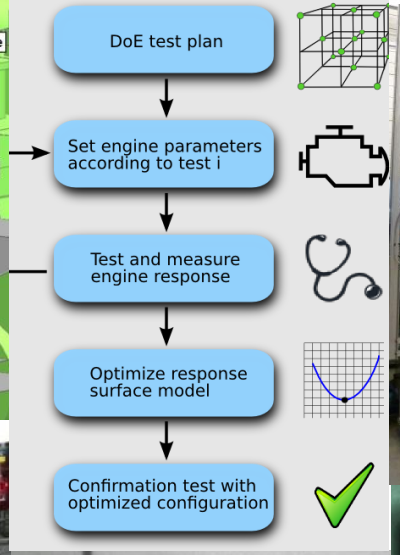


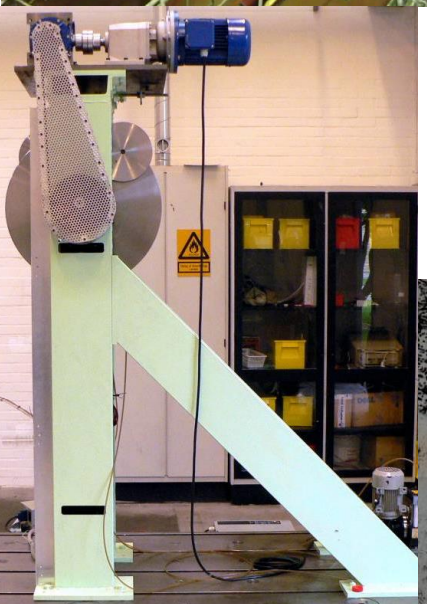


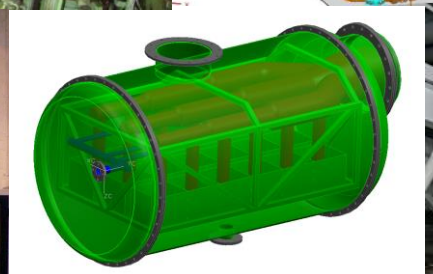

Number of measurements: 1273
Simple correlation expression (g/kWh)
Measured specific NOx emission (g/kWh)
30
25
20
15
10
5
5
10
15
20
25
30

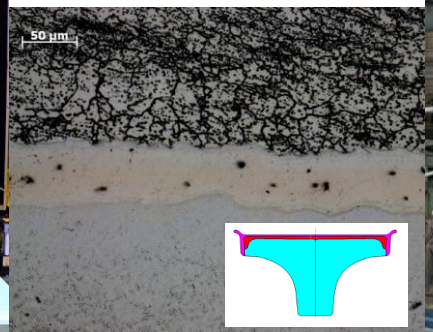


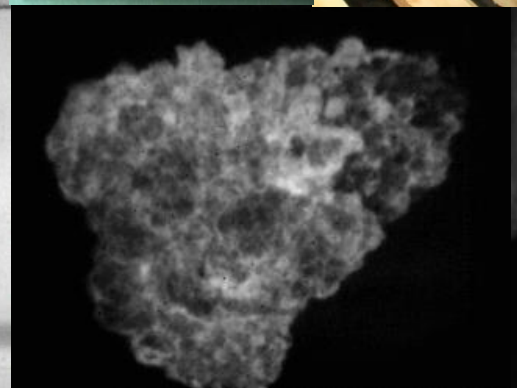

Shut down valve
Scrubber
Blower
EGR Cooler
Change over valve
Water cleaning
Buffer tank
Drainers
Scrubber pump
EGR cooler pump


DoE test plan
Set engine parameters according to test i
Test and measure engine response
Optimize response surface model
Confirmation test with optimized configuration






50 µm



Disclaimer

Strictly confidential

All data provided in this document is non-binding.
This data serves informational purposes only and is especially not guaranteed in any way.
Depending on the subsequent specific individual projects, the relevant data may be subject to changes and will be assessed and determined individually for each project. This will depend on the particular characteristics of each individual project, especially specific site and operational conditions.

MAN Energy Solutions
Future in the making

Strictly confidential

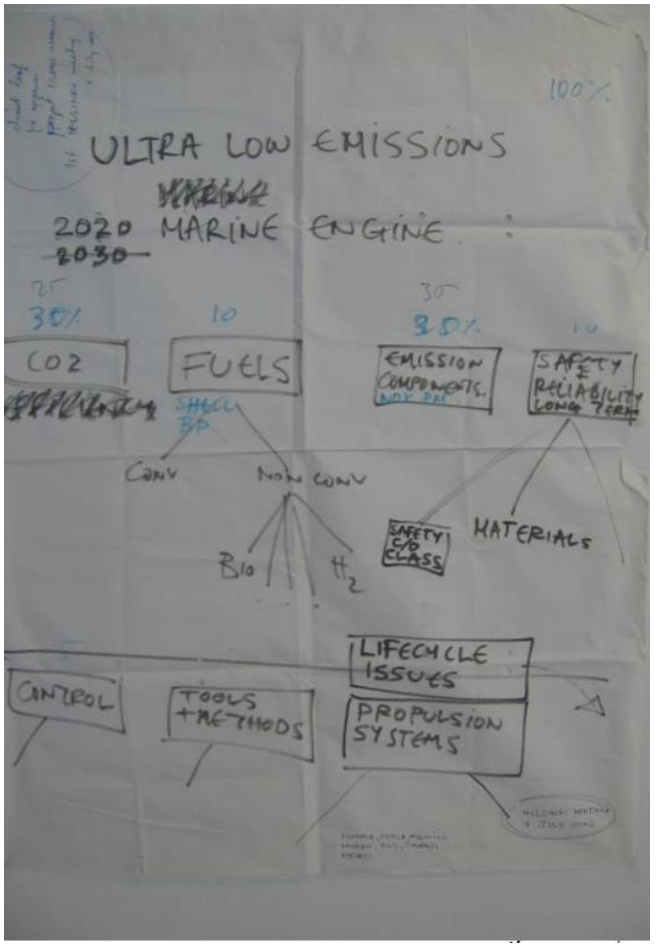
Author
Department
Phone
E-Mail
Day, Month, Year

The rise of gas as a fuel for shipping and the Hercules contribution to that

- From our first discussions in 2002, including fuels, low emissions and GHG reduction

Through many firsts:

- Eidesvik Viking Energy (1st PSV on LNG, 2003)




VIKING ENERGY

The rise of gas as a fuel for shipping and the Hercules contribution to that

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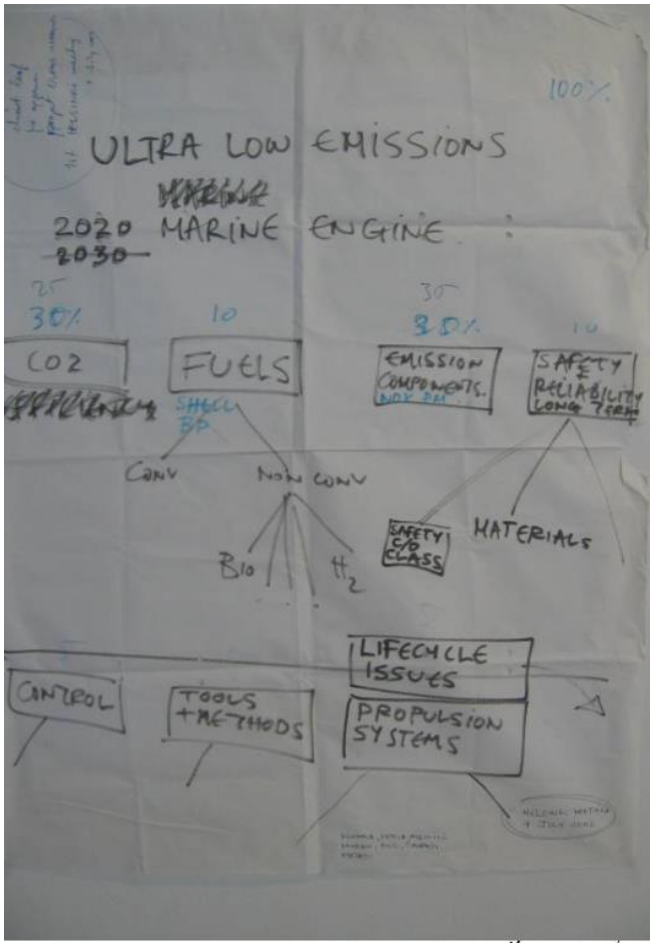
- UASC Barzan (1st LNG-ready container vessel, 2014)




U A S C

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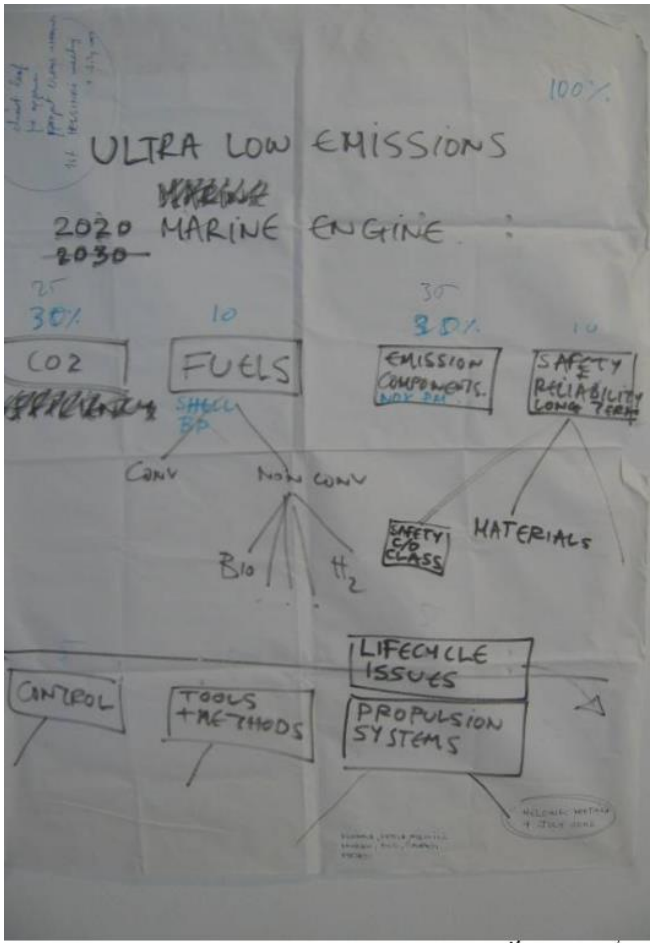

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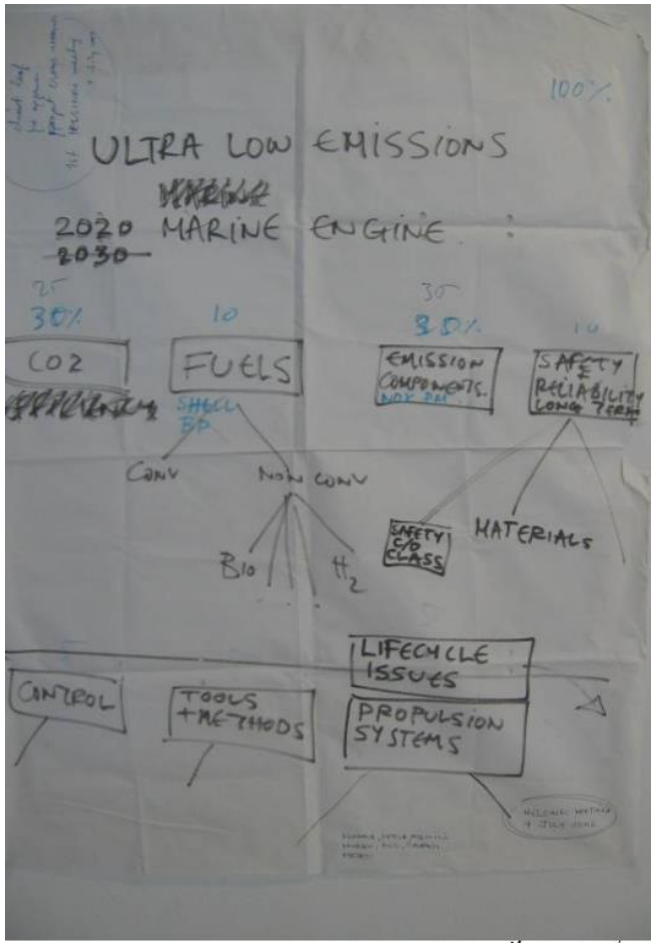
- UASC Barzan (1st LNG-ready container vessel, 2014)
- Francisco (world's fastest ship @ 58knots, 2013)

LNG is now a true alternative to HFO and MDO



Hercules has contributed greatly to this by developing

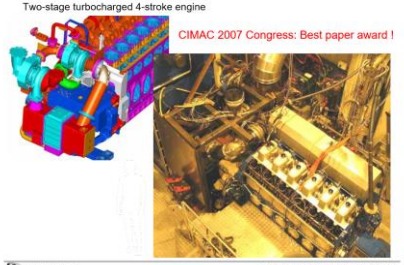
- Advanced realtime combustion controls for fuel composition variation
- Engine efficiency improvements
- Emission reduction

The rise of gas as a fuel for shipping and the Hercules contribution to that

2S-turbocharging

TASK 3.1: Variable turbocharging

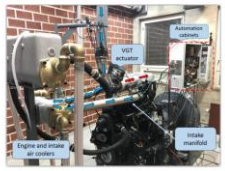
Two-stage turbocharged 4-stroke engine



CIMAC 2007 Congress: Best paper award !

I.P. HERCULES — *Final Meeting & Forum, Brussels 5/9/2007*

Advanced controls



The 4-cylinder AGCO engine was used for the testing of the parameterization tool.

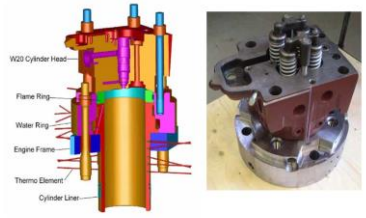
HERCULES-2 — *PTB Meeting, 14th March 2018, Amsterdam*

Near zero emission

Small scale test bench at the roof of engine test cell

High peak pressure

TASK 1.1: Mechanics of engine with extreme design parameters



The EVE cylinder head and liner assembly

I.P. HERCULES — *Final Meeting & Forum, Brussels 5/9/2007*

low friction

TASK 9.1: Adaptive components

Friction loss mapping of W20 – full scale engine test rig

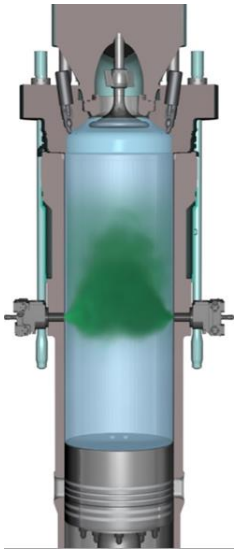
Piston ring / liner friction tester

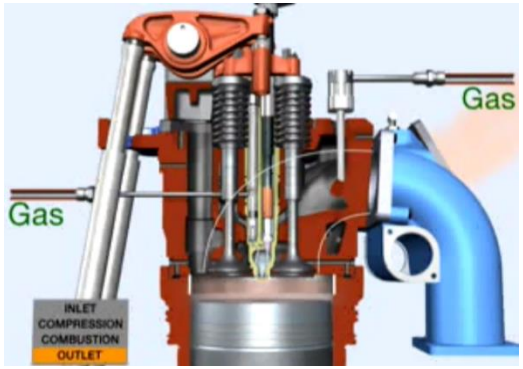
I.P. HERCULES

Advanced materials for reliable engine operation

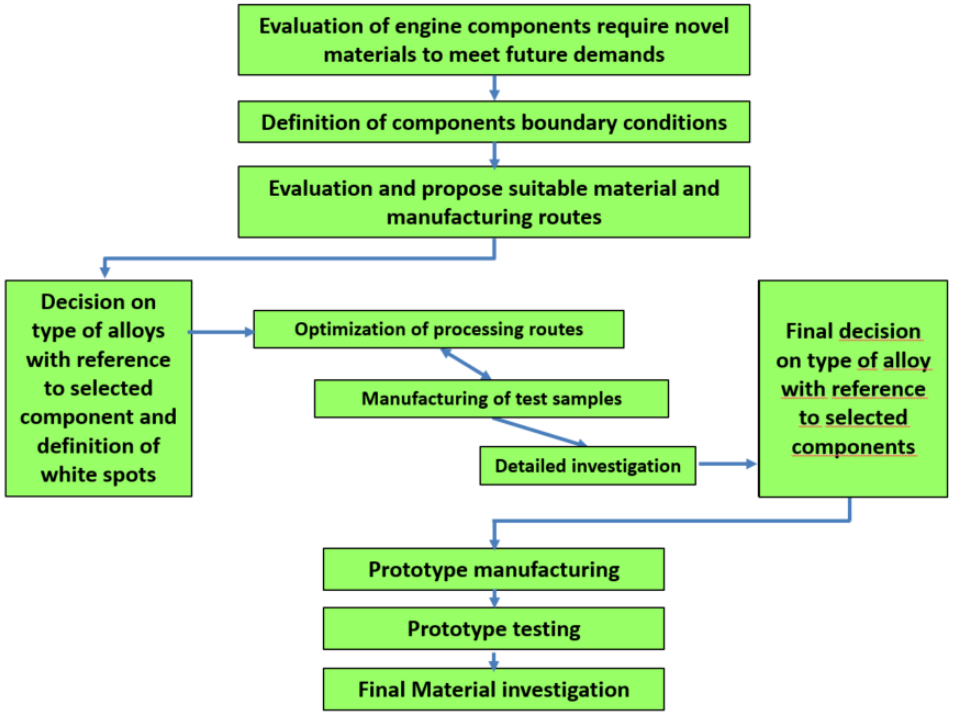
WP3 focus in Hercules-2: Intermetallics and advanced materials for marine engines

- Subproject 3.1: Novel materials for engine applications
  - Examine possibilities of using novel materials in engines to facilitate the development of components that enable higher engine loads, hereby increasing efficiency and lower emissions. Ensure proper lifetime performance and durability.
- Subproject 3.2: Novel materials for turbine casing
  - Material of turbine casing is reviewed in respect of material and design in order to meet requirements needed for higher exhaust gas temperatures.



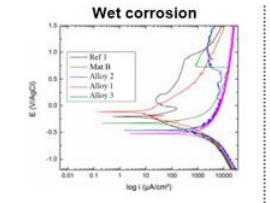


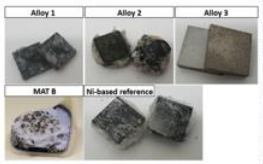
Advanced materials for reliable engine operation – process

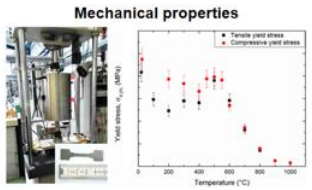


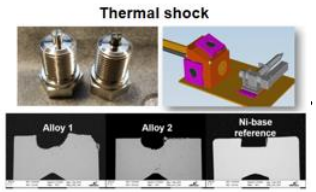
Advanced materials for reliable engine operation – process in practice

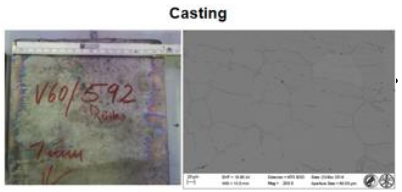
Material Characterisation & Processing Selection

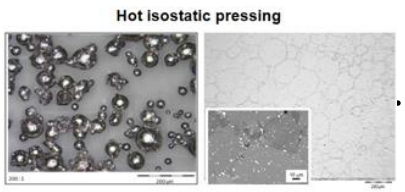




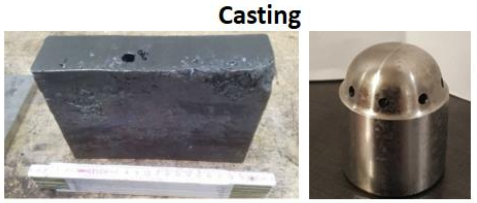


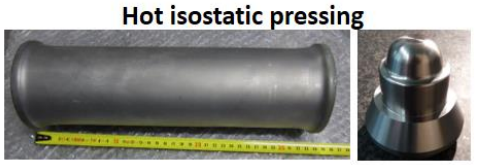




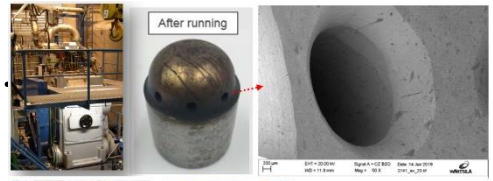


Prototype Manufacturing





Testing



Advanced materials for reliable engine operation – end results

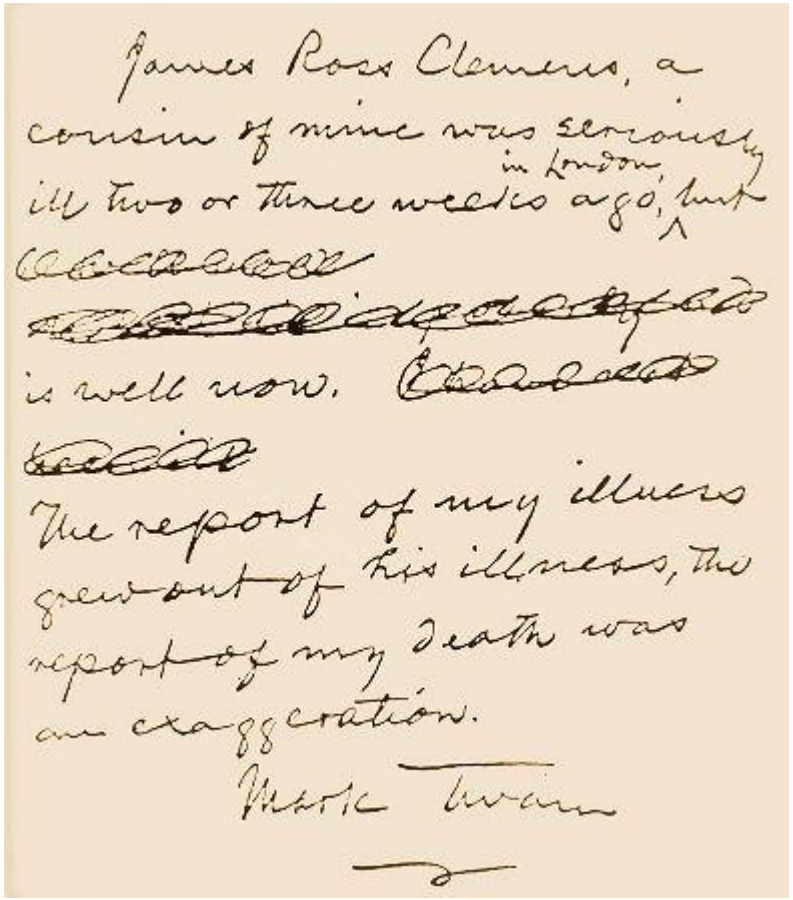
Subproject 3.1 Results & Achievements :

- Investment casting can produce near net shape components
- Alloy 2 exhibits sufficient hot corrosion resistance and for 2-stroke application mechanical properties seems sufficient
- opportunities for enabling higher bearing loads identified

Which means:

- We can further push the envelope on:
  - Efficiency
  - Emissions
  - Reliability

Hercules achievements


James Ross Clemens, a
cousin of mine was seriously
ill two or three weeks ago, but
in London
is well now.
The report of my illness
grew out of his illness, the
report of my death was
an exaggeration.
Mark Twain

"I can understand perfectly how the report of my illness got about, I have even heard on good authority that I was dead. James Ross Clemens, a cousin of mine, was seriously ill two or three weeks ago in London, but is well now. The report of my illness grew out of his illness. ***The report of my death was an exaggeration****."*

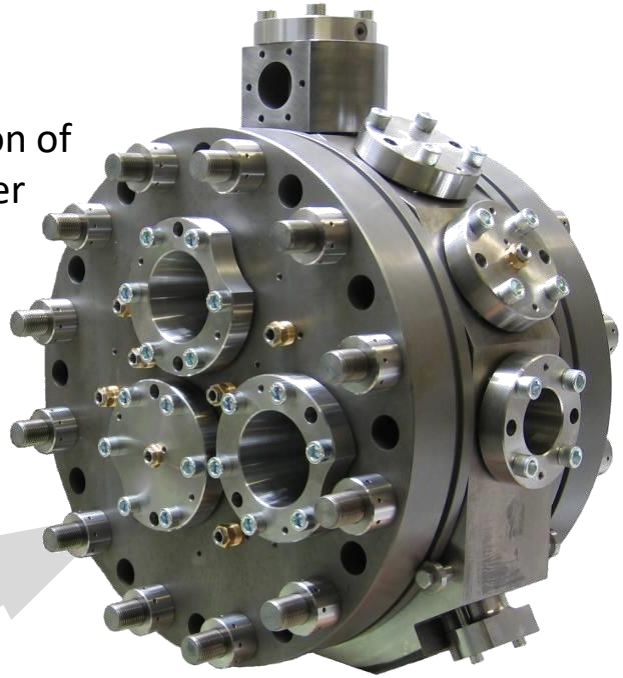
Samuel Clemens, aka. Mark Twain, 31-5-1897

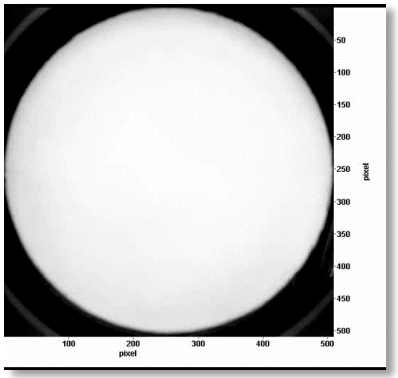

Hercules Program

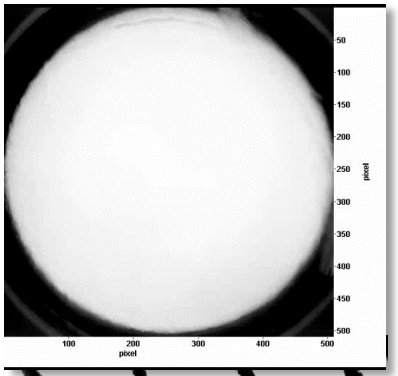
Achievements

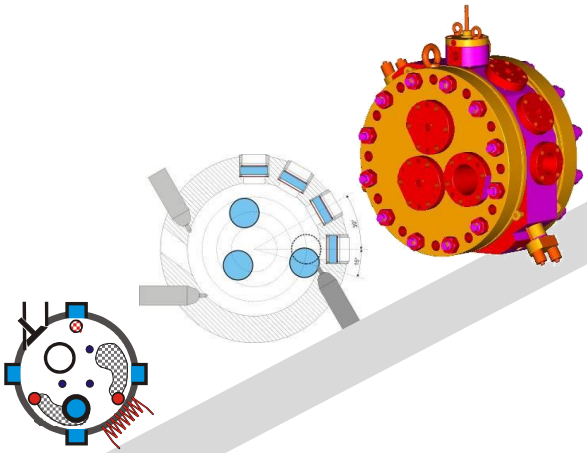
Spray Combustion Chamber – unique tool for 2-stroke marine engines dev.

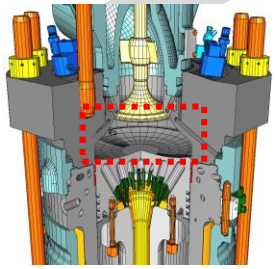
Development, Construction and Commissioning of a worldwide unique experimental setup for the investigation of two-stroke spray and combustion under engine relevant conditions, the **Spray Combustion Chamber (SCC)**



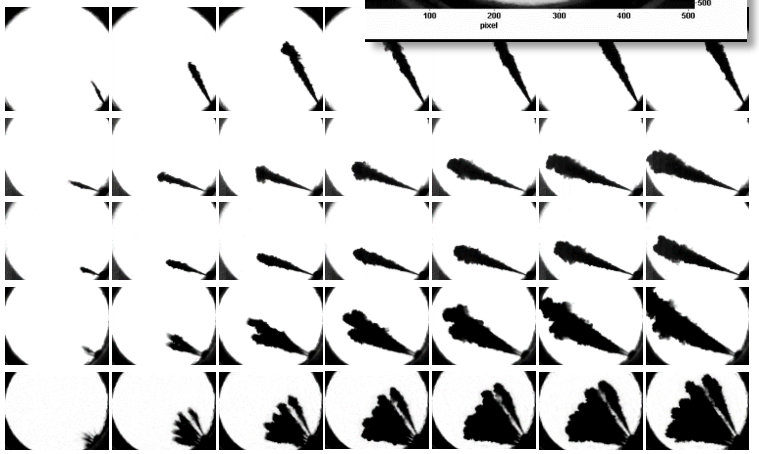




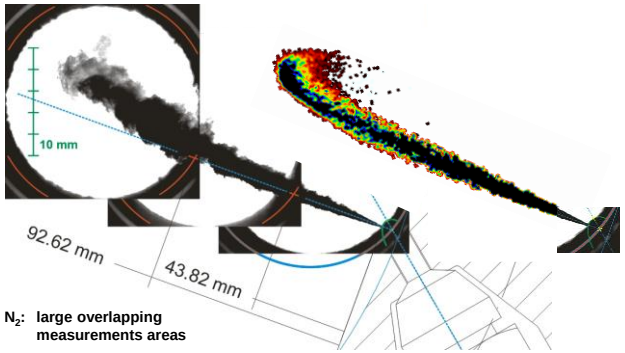




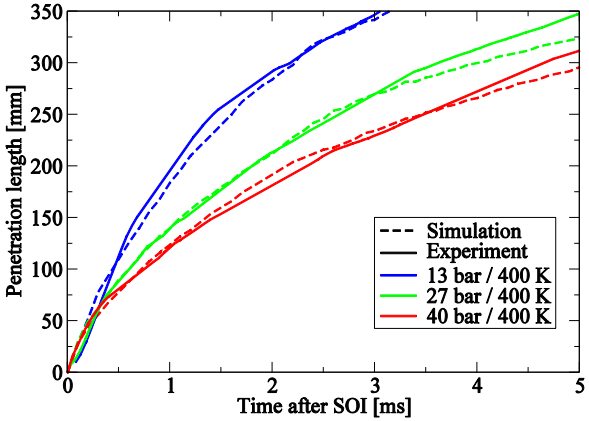
First ever spray and combustion measurements of a two-stroke marine diesel under two-stroke engine conditions.

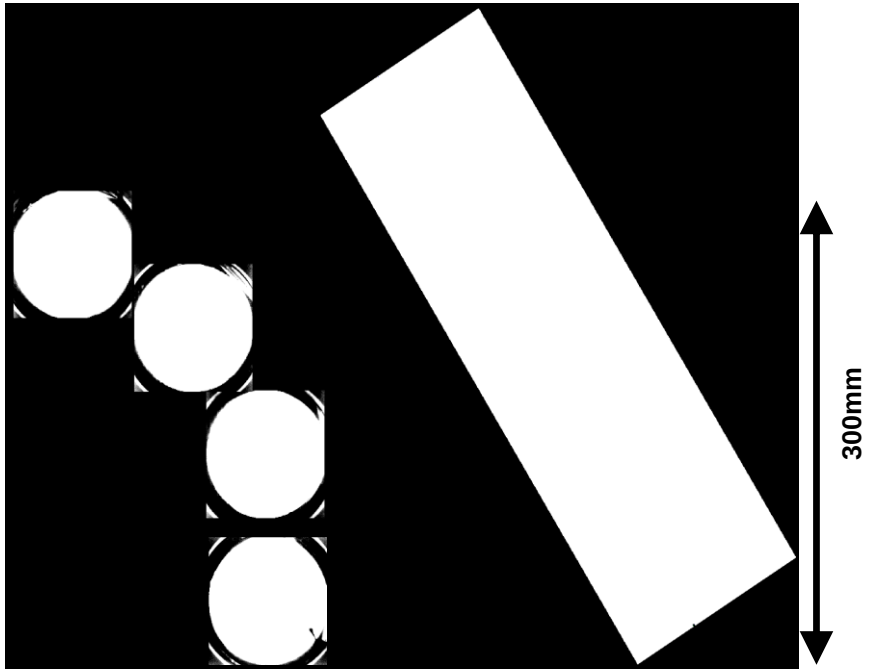


SCC – base for full combustion process modelling and validation



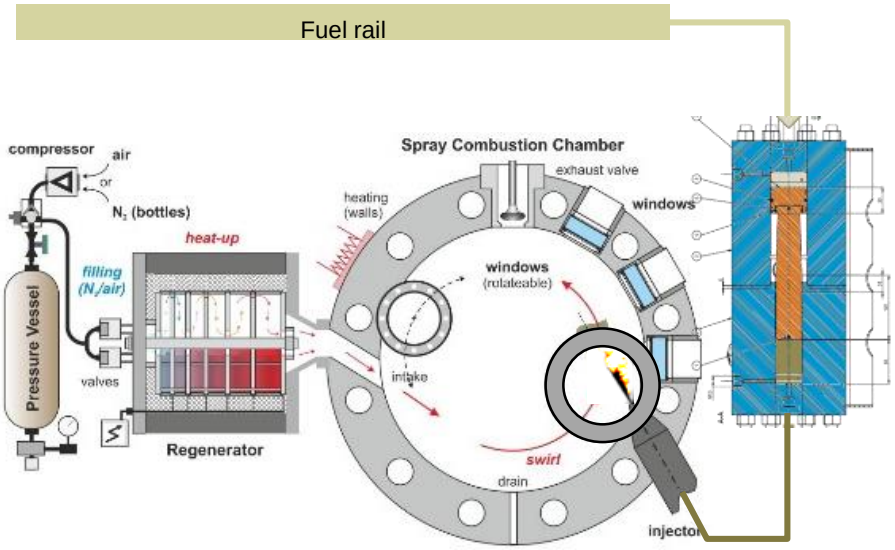
Development and validation of according spray and combustion models to support CFD simulations as well as one-dimensional modelling





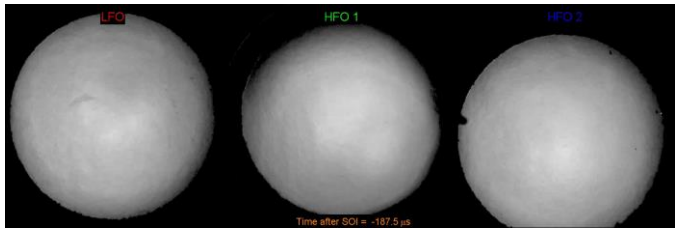
Generating in-depth know how of two-stroke specific phenomena like the interaction with swirl or eccentric sprays

SCC – spray and combustion investigations for todays and future fuels

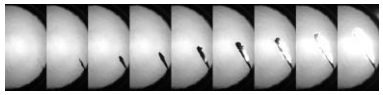


Extension of the SCC setup towards a fuel flexible operation, allowing to investigate a broad spectrum of fuels and supporting the research of new marine fuels.

The SCC can now be used for the evaluation of new marine fuels already at the research or lab level (samples below ten kg) and
can also be used to investigate fuel probes from sailing ships in special cases



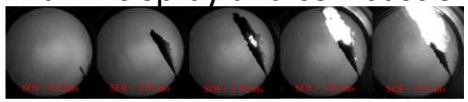
"Classic" fuels for comparison



Bio crude oil spray (reactive conditions)

HORIZON 2020

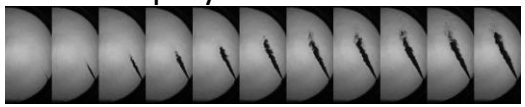
Humins spray and combustion

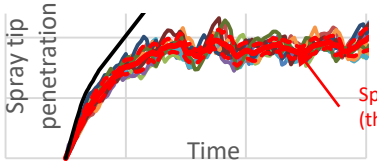


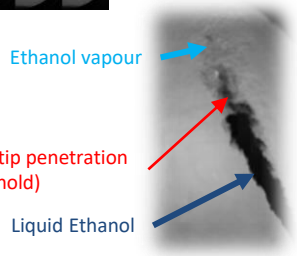
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Bundesamt für Energie BFE
Swiss Federal Office of Energy SFOE

SAE-Paper: Feijen, J., Klink, G., Jong, E., Schmid, A. et al., "Spray Combustion Analysis of Humins," SAE Technical Paper 2017-24-0119, 2017, doi:10.4271/2017-24-0119

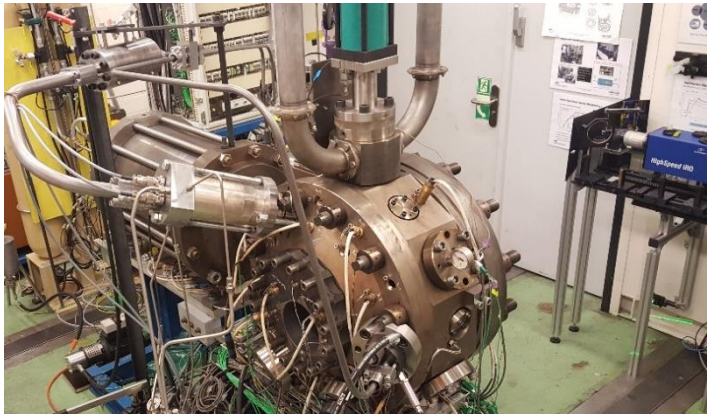
Ethanol spray



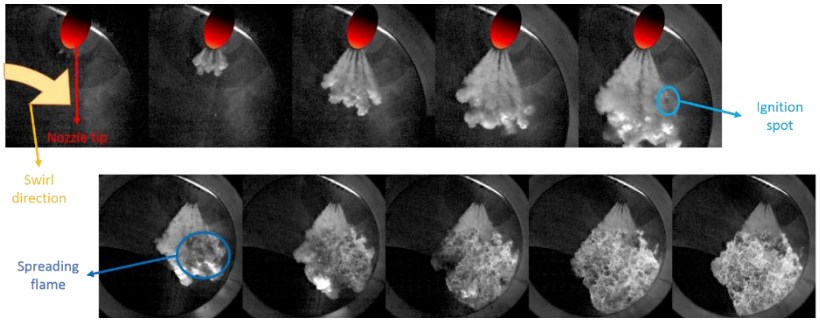




SCC – transfer of results from research to prototype

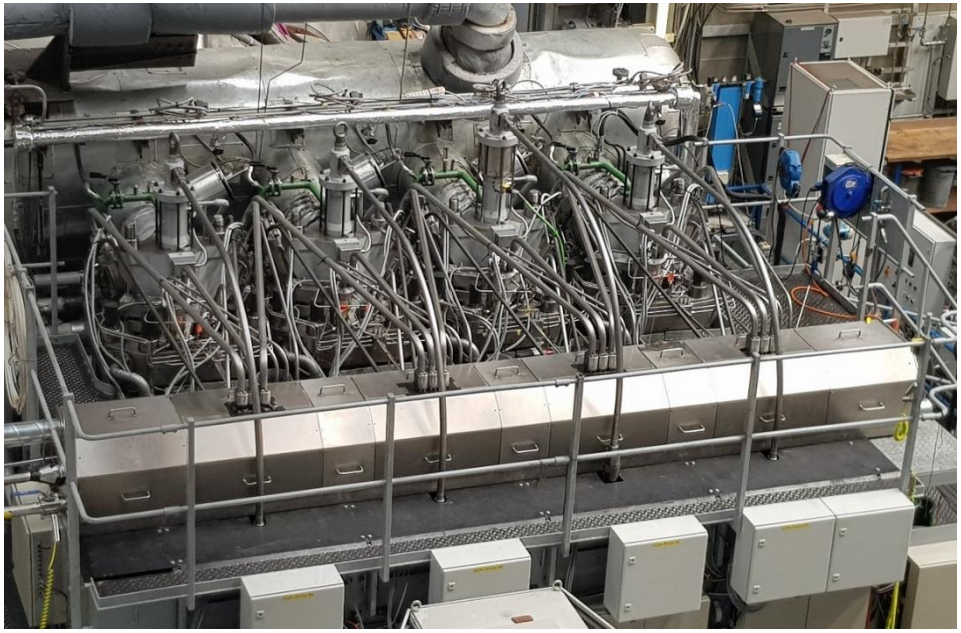


New injection equipment can be investigated regarding its performance under engine relevant conditions, such that the SCC plays an important role in the development process



First “real spray” images

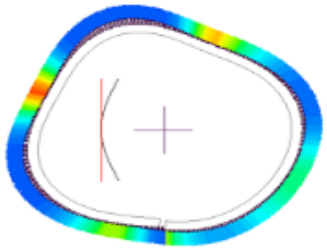
Tested equipment can be applied with low risk on a test engine for the full size validation of new technologies with new fuels and new components as e.g. for an ethanol operated diesel research engine



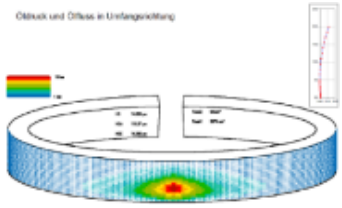
Piston/Liner System – tribology optimization

Enhanced understanding of piston ring pack dynamics and its influence of lube oil film build up have been gathered

mechanical influences

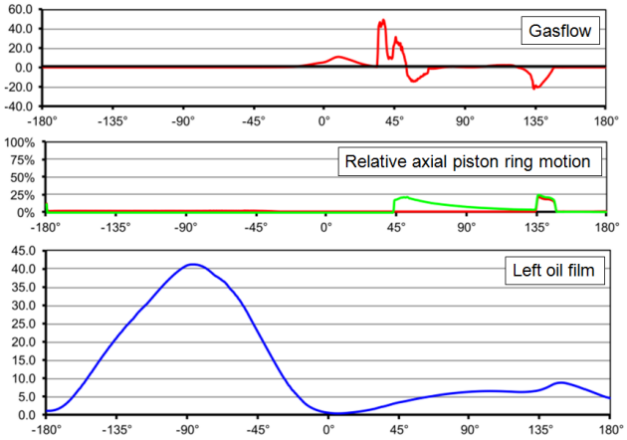


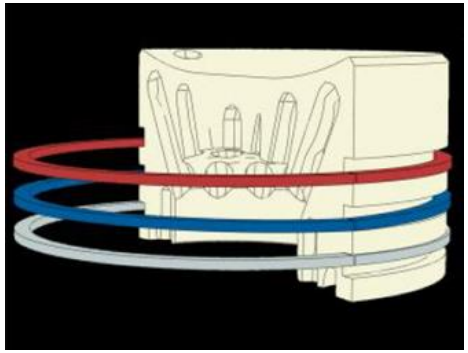
gas dynamical influences



hydro dynamical influences

In a further step a simulation tool to optimize piston ring pack dynamics has been developed

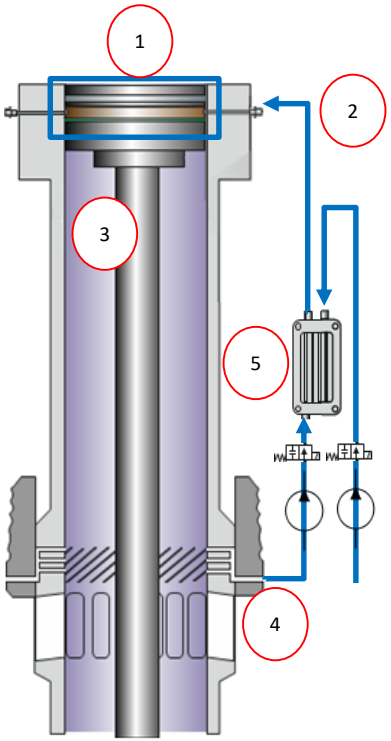




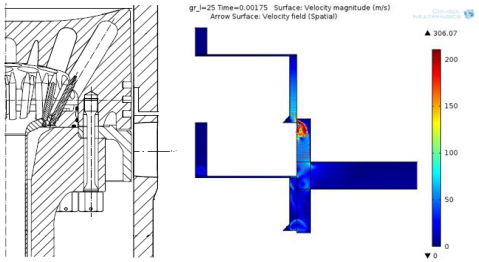
The result has been a **ring pack optimisation** including the determination of suitable material compositions.

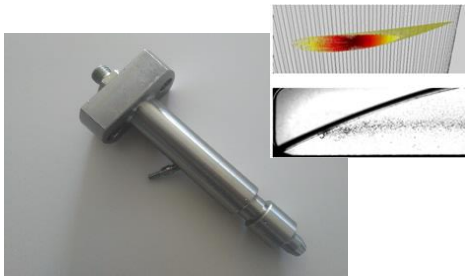
Piston/Liner System – cylinder lubrication concept

Next step has been the complete cylinder lubrication system and its lube oil flow, with quantification of lubrication losses and related contributions to exhaust gas composition.

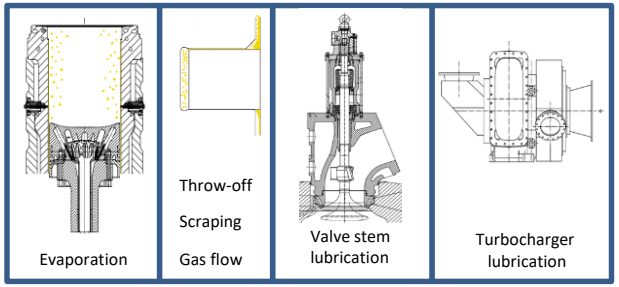


A simulation model to calculate the lube oil flow of the re-circulation process has been developed

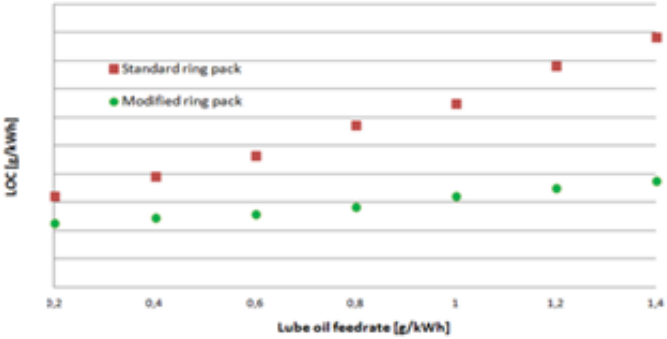




Substantially modified engine components of the new lubrication system concept have been tested.



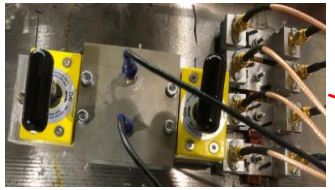
Profound know how on lubricant transportation mechanisms has been composed.



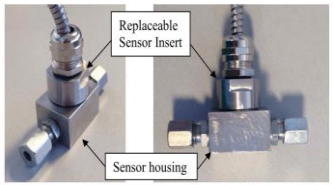
An optimisation of the lubricant flow has been achieved resulting in a considerably reduction of lubrication losses.

Piston/Liner System – lifetime performance control

Further step has been the development
of a fully flexible lubrication system with a new lube oil injector using a simulation model developed to optimize the lubricant spray and injector performance.

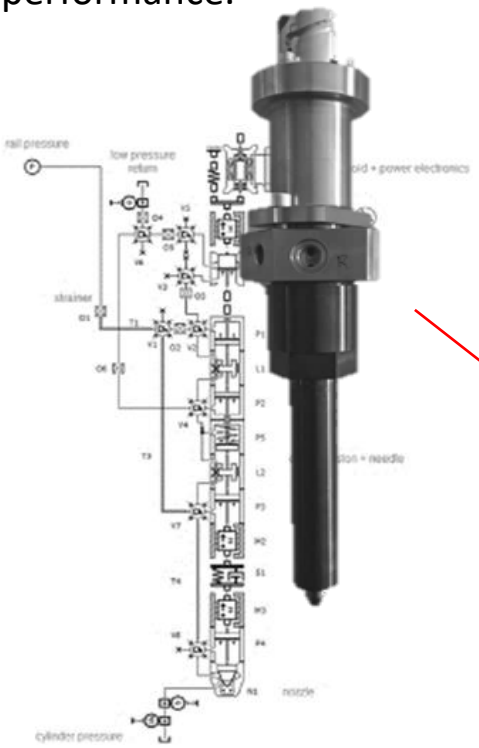


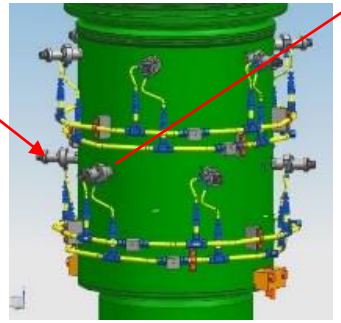
Wear- and scuffing sensor



In-line viscosity sensor

For monitoring of the tribo-system suitable sensor technologies have been identified and developed including prototype testing and initial validation.





Common rail lubrication system

All components have been tested on test rigs and finally on a research engine, where the new lubrication system could show a significant cut in lube oil residuals compared to the best series application.

ABB TURBO SYSTEMS, 10TH OCTOBER 2018

HERCULES achievements

HERCULES (2004-2018) R&D program

Dino Imhof

HERCULES achievements

Turbocharging systems for 2-stroke engines

Investigation of electrically assisted turbocharger (PTI/PTO) for 2-stroke diesel engines

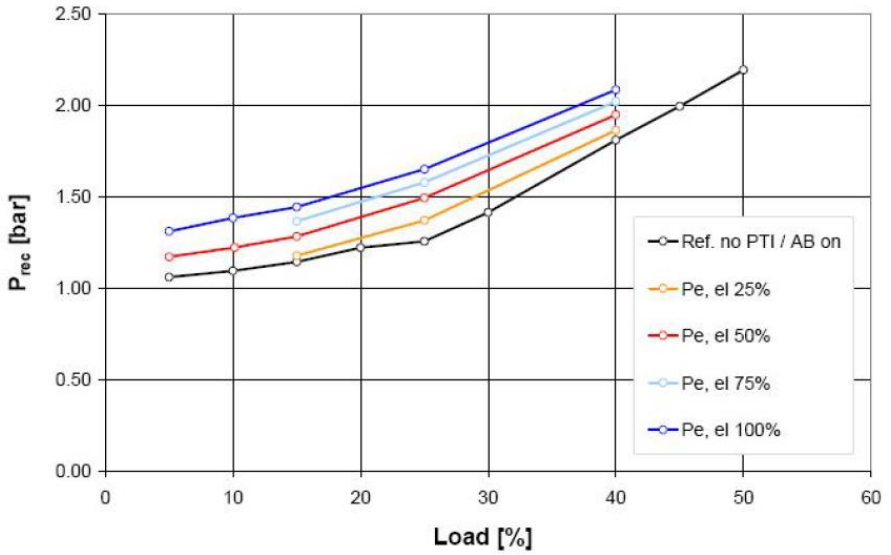
Selected results [2007]

In part load operation, charging efficiencies clearly higher than with the auxiliary blower achieved

- Lower SFOC confirmed

PTI system provides a very high potential for increasing air flow and reducing the engine thermal loading at part load

- Operating range extended towards heavy propeller applications
- Opportunity for realizing higher BMEP at low engine speeds



Improved part load behavior of 2-stroke diesel engines [IP-Hercules]

HERCULES achievements

Turbocharging systems for 2-stroke engines

Investigation of the potential of high pressure turbo-charging on 2-stroke engines in view of NOx reduction

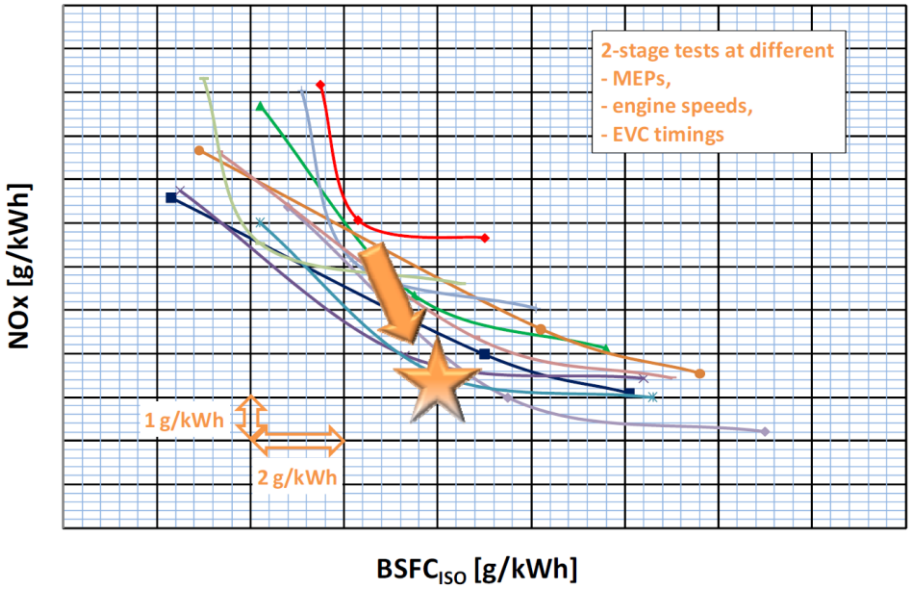
Selected results [2010]

Wärtsilä RTX-4 lab engine operated at 23 bar BMEP

Prototype 2-stage turbocharging system based on ABB Turbo Systems A175-L and TPL73-B

- Scavenging pressures up to 7.4 bar(a) at full load
- Equivalent turbocharging efficiency increased by up to more than 10% from the reference single-stage setup
- NOx reduction up to 30% at single load points due to late Miller

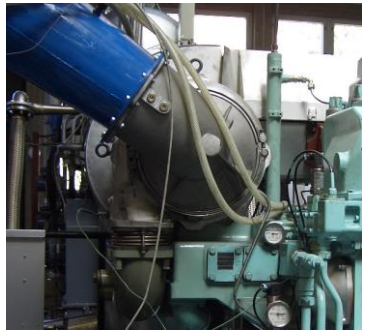
[ATK 2010]



For IMO Tier III NOx levels, 2-stage turbocharging requires additional emission reduction technologies

HERCULES achievements

High-pressure turbocharging concepts



Feasibility tests on a 4-stroke engine at Helsinki University of Technology

Selected results [2006]

W6L20 engine with TPS52X prototype turbocharger from ABB

- Pressure ratio >6
- Sandbags as additional burst protection

NOx emissions reduced up to 35% with early Miller

Based on these preliminary tests, the 2-stage turbocharging technology demonstrators were designed

Helsinki University of Technology [2006]

First industrial engine tests with charge air pressure >6 bar and single-stage TC [IP Hercules]

HERCULES achievements

High-pressure turbocharging concepts with extreme Miller timings

[CIMAC 2007]

2-stage turbocharging on a Wartsila W20 4-stroke medium-speed diesel engine

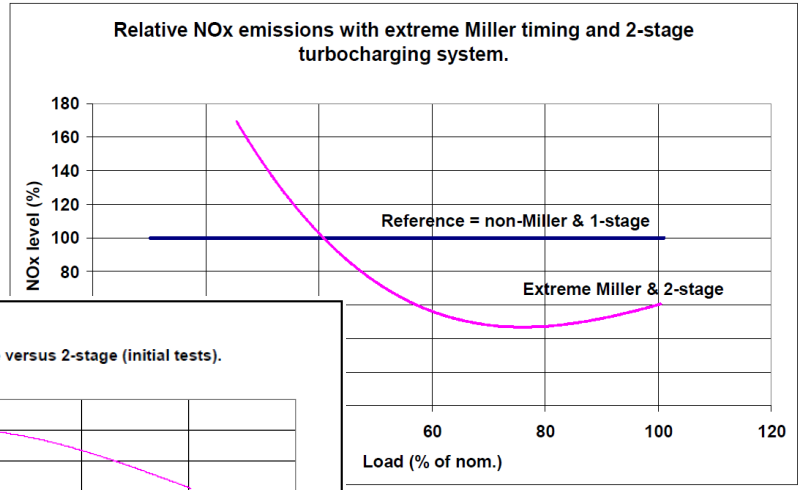
Selected results [2007]

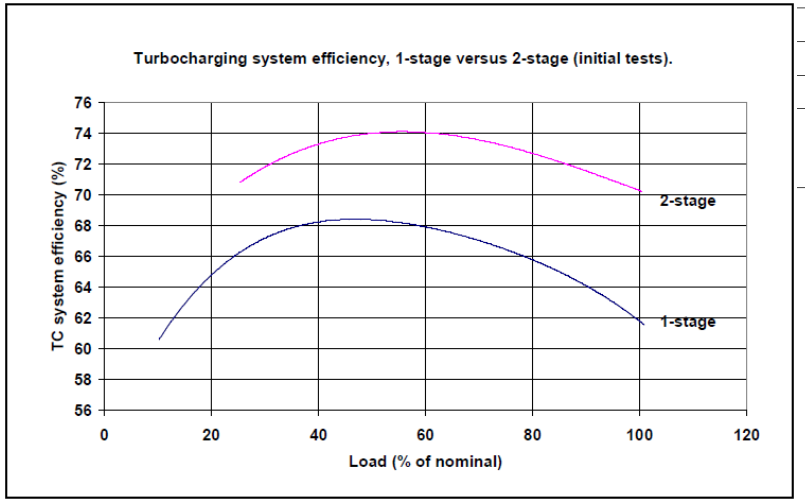
NOx reductions around 50% achieved with extreme Miller timings in combination with 2-stage turbocharging

Full load BSFC and thermal load improved due to the increased TC efficiencies and boost pressures

Engine startup and low load operation with extreme Miller

- Smoke emissions (cold combustion chamber)
- VVT technology required

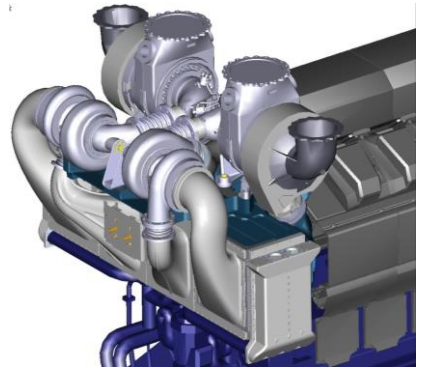




First modern medium speed engine equipped with 2-stage turbocharging system [IP Hercules]

HERCULES achievements

High-pressure turbocharging concepts with extreme Miller timings



High efficiency and low emission TC concepts

Selected results [2011]

[ATK 2010]

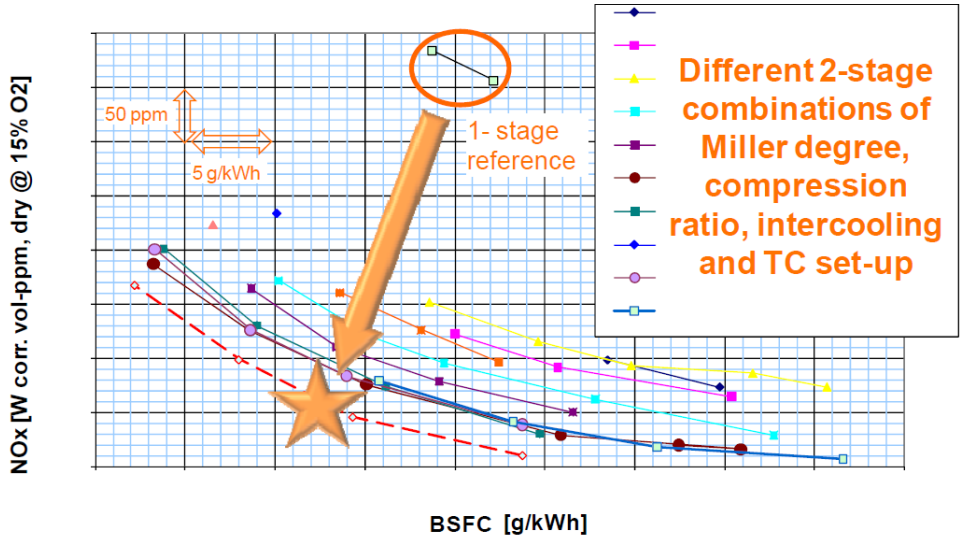
Around 60% NOx reduction achieved with serial high pressure turbo-charging systems on medium speed 4-stroke marine engines

- - 3% BSFC simultaneously

Demonstration of the reliability/durability by endurance tests

- Vaasa: 500h / PSI: 170h

As a consequence of the low temperature combustion, not only NOx emission, but also thermal loading of the combustion chamber components are reduced



Turbocharging efficiency of ≥74% achieved [Hercules B]

HERCULES achievements

High-pressure turbocharging concepts with extreme Miller timings

Integrated Emission Control Technologies

Selected results [2014]

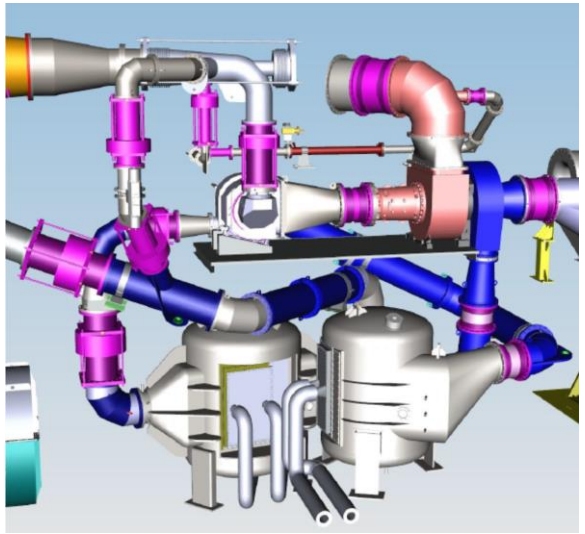
Advanced turbocharging combined with flexible, integrated emissions control systems

- 4-stroke engines
- 2-stroke engines

Concept tests with 2-stage turbocharging and integrated systems

- Various EGR concepts
- SCR with optimized urea injection

2-stage turbocharging system for 2-stroke engine

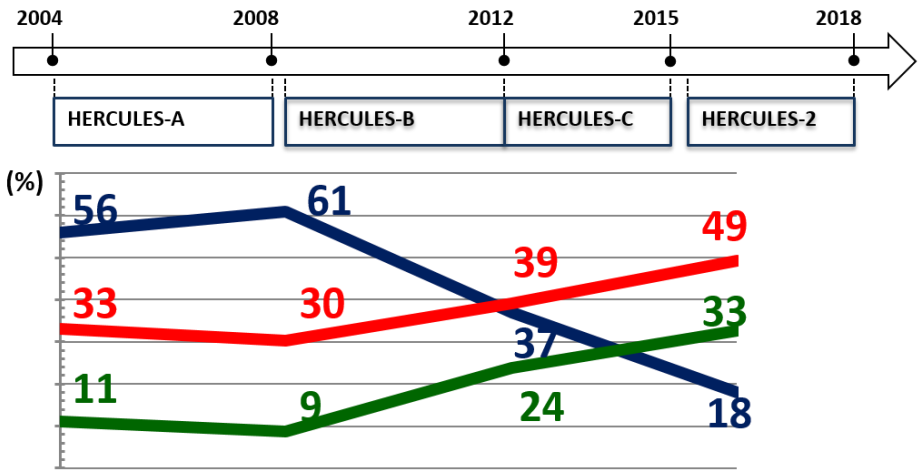


W6L20CR engine with 2-stage turbocharging

Prototype systems developed and realized on technology demonstrators


ABB

Percentage allocation of budget into 3 main areas of R&D in the 4 HERCULES Projects (189 subprojects)



Total 102 M€

43%

38%

19%

Q: The picture of overall spending Efficiency (43%), Emissions (38%), Reliability (19%) reflects the overall achievements in the HERCULES series?

Technology items in products and related technology areas

TECHNOLOGY AREA / TECH ITEMS	COMBUSTION	TURBO CHARGING	EMISSIONS ATU	MATERIALS FRICTION	MONITOR CONTROL OPTIMIZATION
Multi-Turbo/ VVT		✓			✓
PTI/PTO		✓			✓
Increased Pmax. Cyl.	✓	✓		✓	✓
Cylinder auto-tuning					✓
Water-in-Fuel	✓		✓		
SCR			✓		✓
Tribology				✓	
WHR- Hot Engine				✓	✓
EGR			✓		✓
Cylinder cut-out					✓
Dual Fuel /Multi Fuel	✓				✓

Q: The Technology Outcome items in relation to the Technology Areas for HERCULES series shows a substantial emphasis in Monitoring & Control. Is this an expanding area requiring extra effort in the future?