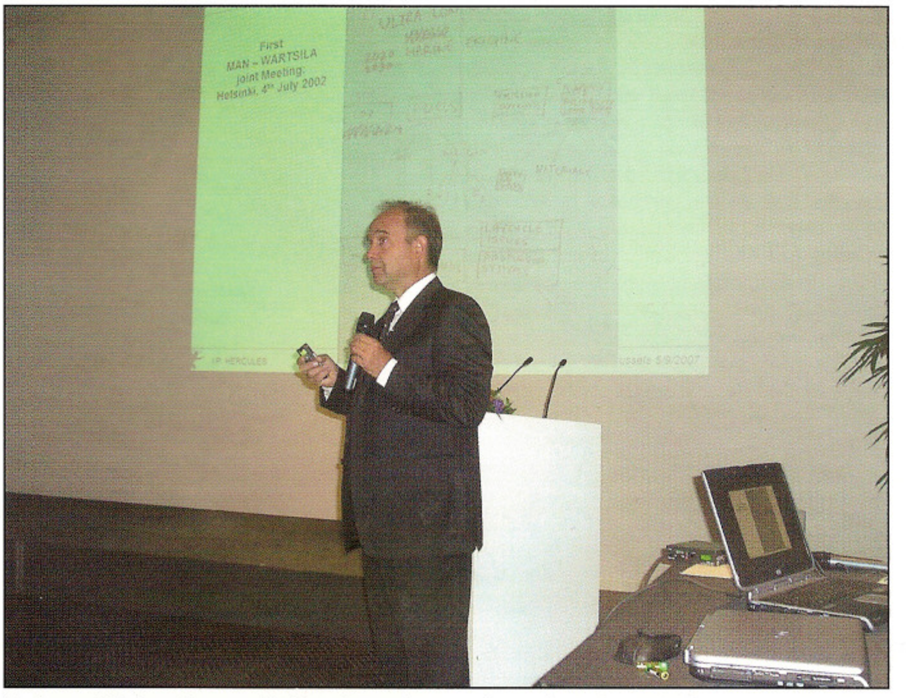
A Herculean task

THE final meeting of Phase I of the mammoth IP Hercules project arrived at some far-reaching conclusions over the future of ship propulsion. A report by *Clare Nicholls.*

IN September, *The Naval Architect* was invited to the final IP Hercules meeting; the culmination of a huge project, which has seen two major engine manufacturers cooperating in order to research technology necessary for higher efficiency marine engines with ultra-low emissions.

Wärtsilä and MAN Diesel each took on around half of the total project, which was subdivided into nine workpackages, with each workpackage further subdivided into two tasks.

Professor Nikolaos Kyrtatos, the project coordinator, introduced this final meeting by giving an overview of the vast scope of the project. After a joint meeting between Wärtsilä and MAN Diesel in July 2002, and following further discussions between the two companies, IP Hercules (High Efficiency R&D on Combustion with Ultra-Low Emissions for Ships) was finally set up in 2003. 42 partners had a hand in the scheme, made up of 60% of industrial participants, 19% universities, 12% research organisations, and 9% users and ship operating companies.



Professor Nikolaos Kyrtatos, IP Hercules project coordinator, introduced the final project meeting in Brussels in September.

The 43-month project was conceived as a long term development strategy, and an umbrella organisation, ULEME, a European Economic Interest Group, was formed by the two main establishments, with a budget of around €33 million for IP Hercules, including €15 million of EU funding.

The main aims were to develop new technologies for marine engines, concentrating on reducing gaseous and particulate emissions, improving engine efficiency, fuel consumption rates, and life cycle costs.

Workpackages summary

There were originally due to be 11 workpackages, but due to a cut in EU funding, only nine were developed. As the packages had already been numbered, however, they are designated numbers one to four, six to nine, and 11.

Workpackage 1 concerned extreme design parameters. Task 1.1 saw Wärtsilä taking on an assignment regarding the mechanics of an engine with extreme design parameters. The objective of this was to study the influence of advanced working cycles on engine performance and emissions, as well as finding design and material solutions for engine components operating under extreme conditions, and performing full-scale and rig tests to evaluate the developments.

Measurement criteria	Design goals	Test results
Mfp	250bar	250bar
Mps	12m/s	12.1m/s
Mep	30bar	30bar
Reduction of power to weight ratio	25%	23.7%

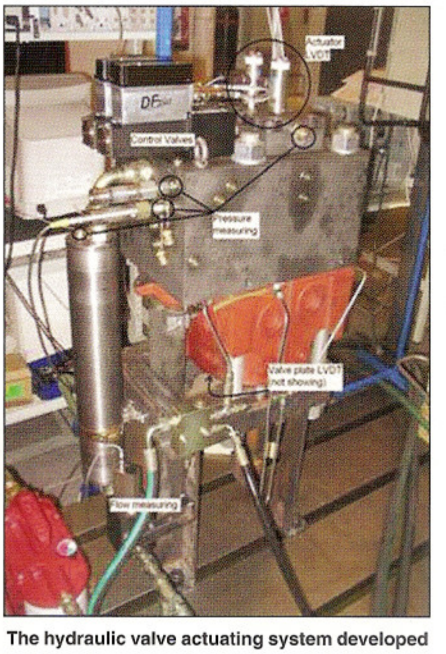
Table 1: The results of testing on a four stroke engine during task 1.2.

A second generation electro-hydraulic valve actuator system was developed and tested in this task, and an optical setup was designed for an extreme value engine. Successful testing took place with 40bar peak cylinder pressure at 900rev/min, and with 220bar static pressure. The conclusion was that the engine was capable of operating over a wide speed and load range.

Task 1.2 was designated to MAN Diesel, and among the partners involved were DAROS, Federal Mogul, Bodycote, and the Technical University of Athens. The title of this task was thermodynamics of engines with extreme design parameters, with an objective of developing a compact, high extreme output engine, capable of operating under extreme conditions, producing a minimum amount of emissions.

Two stroke and four stroke engines were tested, and design tools for optimising load performance, engine emissions, and fuel oil consumption were produced. The developments in this project resulted in the introduction of a compound fuel valve nozzle as standard on all two stroke MAN engines, plus the inclusion of ME-B on small bore engines with a design capable of operating under extreme parameters.

For the four stroke tests, a SIMULINK/MATLAB simulation code identified areas of friction, and also implemented into a cycle calculation programme was a spray-based model for prediction of in-cylinder heat release. The four stroke prototype assisted the development of piston rings which resist higher engine speed and pressure.



The hydraulic valve actuating system developed in task 1.1.

The results of the task indicated that the reduction of the NOx/specific fuel oil consumption (SFOC) trade off can be achieved by altered valve timing. The overall results generally achieved the goals set for the four stroke prototype in this task, depicted in Table 1.

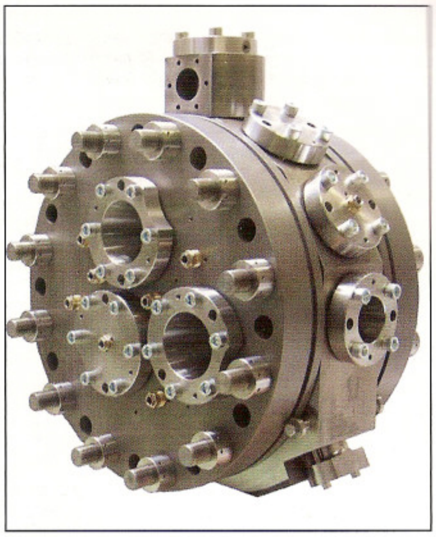
The conclusion for two stroke testing was that increased load on engine components can be met with advanced design and material solutions, and novel CFD and FEM design tools are an essential part of development. Part of the project's objectives was fulfilled, but further development is required to meet all goals.

For four stroke engines, higher engine parameters in certain combinations are an appropriate measure to reduce NOx and SFOC levels, the increase of total friction due to higher engine parameters is mainly affected by the engine speed, and CFD calculation is an appropriate tool for optimising the combustion process of big bore engines.

Workpackage 2 dealt with advanced combustion concepts. Task 2.1 was undertaken by Wärtsilä's Swiss concern, in cooperation with partners including Åbo Akademi University and the Swiss Federal Institute of Technology. The objective of the task, entitled combustion process simulation, was to achieve a better understanding of in-cylinder phenomena such as spray, combustion, and emissions formation, and to apply 3D simulation tools to optimise marine engine combustion systems.

An experimental optically accessible spray combustion chamber was used for testing, and the concept was verified by means of extensive simulation and models. The first tests were at 50bar pressure at 300k and injection pressure of 500bar. CFD combined simulation considered the scavenging process, with the first steps towards full cycle simulation.

A novel experimental facility has been developed for investigating fundamental in-cylinder process at conditions relevant to large marine diesel engine combustion systems, which will be used extensively for producing reference data for the in-depth validation of physical models. A thorough validation study has been performed and deficiencies of existing models have been identified, with further model development initiated. Simulations have also been used for generating additional insight into the governing phenomena and identifying potential combustion system optimisation pathways, and the project won the coveted BP Award for Health, Safety, and the Environment, at the CIMAC congress this year.

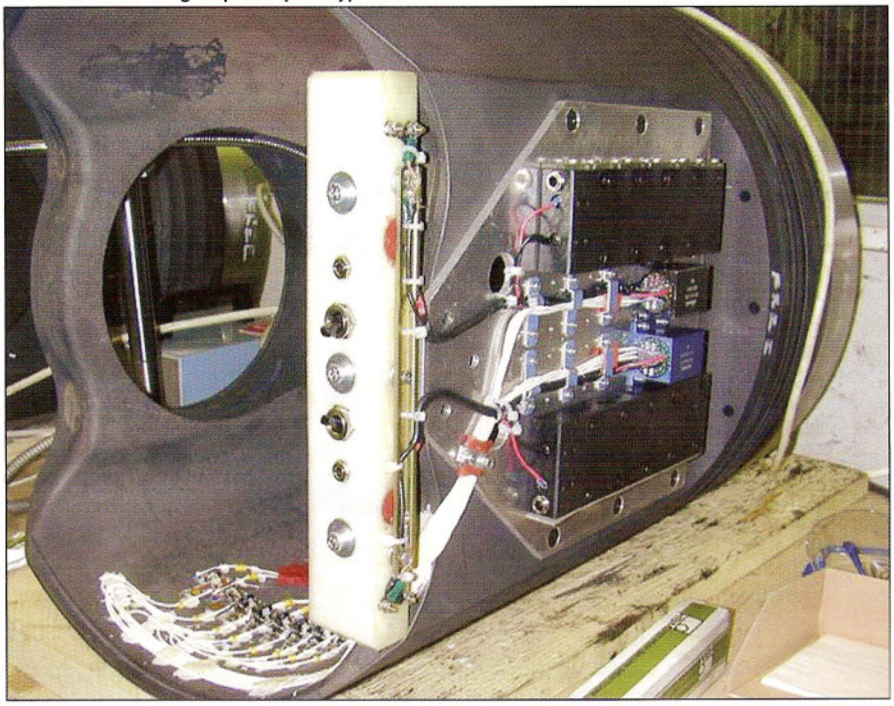


The spray combustion chamber used for testing in task 2.1.

MAN's contribution to this workpackage, task 2.2, dealt with developing numerous models for engine performance and formation of emissions of large marine two stroke and four stroke engines. More than 2000 engine tests were conducted, with parametric tests also taking place on a 4T50ME-X engine, measuring ignition delay for different fuels and operating conditions. In model development, the CFD tool KIVA was used to integrate state-of-the-art submodels for spray, combustion, and emission formation.

There was, however, a need to take the data closer to what went on in the combustion chamber, and more investigation is required for the near nozzle spray. Trends in heat release rates and pressure traces were in agreement with expectations, and a FEM simulation of CFD data was developed for conversion.

Task 4.1: The hot engine piston prototype.



The CFD model was validated with the total number of computations exceeding 10,000 runs. The conclusions were that satisfactory predictions for both performance and NOx emissions can often be made, given sufficiently accurate model input data, but further validation efforts need measurements of local data for comparison.

Workpackage 3 was entitled 'more capable turbocharging systems'. Wärtsilä's task 3.1, variable turbocharging, was carried out with partners including the Helsinki University of Technology and ABB Turbo Systems Ltd. The objective was to investigate the potential benefit of variable geometry and multi-stage turbochargers, in order to provide charge pressure beyond today's levels, by developing and testing prototype components.

At part load operation of a two stroke engine, it was found that turbocharger efficiency using a power take in (PTI) system was higher than an auxiliary blower, giving lower SFOC. The PTI system also provided high potential for reducing thermal loading, and the jet assist and air injection into air receiver is an effective means to improve load acceptance behaviour of four stroke engines, enabling a two step load application.

For a two stage turbocharger, the results showed a 46% to 58% reduction of NOx at high loads, and a 1.4% reduction of SFOC at 100% load, with part load performance safeguarded using a variable inlet valve closure system.

The conclusion was that the PTI system reduced SFOC by up to 4%, and thermal load up to several hundred degrees centigrade at low load operation. This project also won a CIMAC 2007 Congress best paper award.

In task 3.2, 'intelligent turbochargers', MAN's objective was to investigate the benefits of variable geometry turbocharger systems to substantially improve operating behaviour, implying savings in fuel consumption and reducing emissions. Project partner Kemmerich Elektromotoren tested an asynchronous electrical unit yielding 380kW at 18,000rev/min with an electric brake.

Diffusers with quasi-3D vanes were successfully examined on a burner test rig. Prototype tests took place on two turbocharger systems, TCA55 VTA/PTI/PTO, and TCR 22 & TCR 20 VTA. Automatic variable turbine flow areas (VTA) yielded improvements with respect to efficiency and emissions during cruise and part load of low-speed diesel engines.

PTI was shown to be able to be applied to a turbocharger for low-speed diesel engines, using a high-speed electric motor, enhancing smokeless operation during transients. The Miller cycle was applied to a 6L32/44CR medium-speed engine, and involving two stage turbocharging with intercooler improved the trade off between NOx formation and fuel consumption. Additionally, variable valve timing moderated the Miller cycle at part load, preventing visible smoke emission.

Novel features might include alternative applications such as double angular contact bearings with ceramic balls, separate lube oil circuit for the bearings, air cooled rotor packages, and water cooling applied to the stator winding.

Workpackage 4 concerned combined cycle, with Wärtsilä taking on task 4.1, 'hot engine and turbocompounding', in conjunction with Mahle

GmbH and M Jürgensen GmbH, among other firms. The objectives were to investigate the benefit of combined cycle/turbocompound systems, simulate different turbocompound alternatives, and test prototype hot engine components.

A turbocompounding system was evaluated, using simulations of hot engine combined cycles with a given engine heat balance, and a prototype system design was built with a Wärtsilä 20 engine and a two stage turbocharger. During testing, 10% exhaust bypassed both turbines, and mass flow was measured at the orifice.

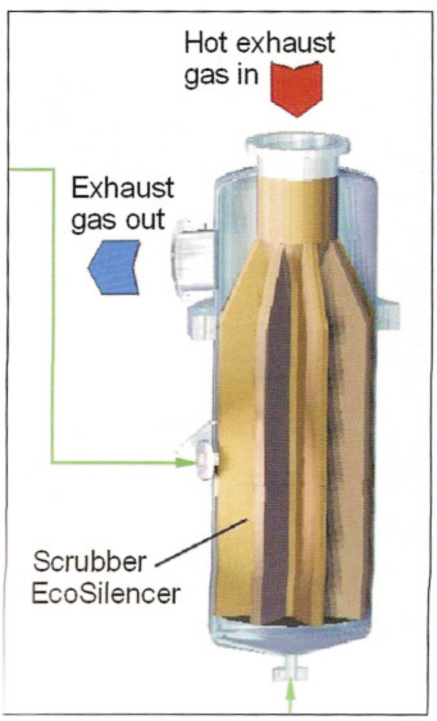
New material and casting technology development for the cylinder liner was completed by Jürgensen. During the cylinder liner research, thermal and mechanical properties of all liner materials were tested, and casting techniques developed towards improved thermal fatigue.

Hot engine pistons and exhaust valve seat rings underwent successful prototype testing, and these components are heat and hot corrosion resistant. Total efficiency of hot engine based combined cycle/turbocombined system was clearly shown by comprehensive cycle simulations with around an 8% improvement against a standard system. A further conclusion was that turbine fouling can be successfully combated with a developed steam injection system.

Task 4.2 saw MAN investigating how to optimise the combined cycle process for a thermo efficiency system, and identifying the requirements for each component in the process, with the key components being a two stroke diesel engine, a boiler/steam turbine, and a power turbine.

In order to test the hot engine concept under realistic operation conditions, a Mitsui-built 10K98MC engine was modified by fitting an adjustable short circuit duct between the scavenging receiver and the exhaust receiver. The results showed that there was increased heat load on the exhaust valve and piston, and slightly increased heat load on the liner and cover. SFOC increased by approximately 2g/kWh due to reduced purity at compression start, but NOx emissions were nearly unchanged.

Design of an EGR prototype system, investigated at a test plant in Copenhagen for task 7.2.



Fore and aft end bypass from the exhaust receiver to the scavenging air receiver used in task 4.2.

The application of a complete combined cycle system on a seagoing vessel was not realistic within the range of the project, but engineroom application is taking place aboard a Savannah class Hapag Lloyd vessel, and completion was due by the end of September.

With workpackage 6, the spotlight fell on emissions reduction methods (internal – water), and task 6.1 was about water injection techniques. Wärtsilä was charged with confirming the NOx-reducing potential of these techniques in laboratory tests, as well as modelling and simulating water injection processes, including onboard testing of the resulting systems.

Pre-calculations for the Wetpac H intake air humidification system for four stroke engines and a direct water injection (DWI) system for two stroke engines were both simulated, and on the basis of feedback from field, endurance, and lab tests, the systems were improved. Installation took place onboard *MV Manon* from Wallenius Marine, but there were teething problems with the components. The problems were corrected but more running hours are needed.

The next generation system was installed aboard another Wallenius Marine vessel, *MV Tristan*, featuring three 6R32BC auxiliary engines, and no problems arose. The DWI system gave a 50% NOx reduction in laboratory tests, which is appropriate for the target field test installation of an 8RT-flex 96C engine, and the system was optimised by generic algorithm approach. Maersk's *Maersk Montana* has now had a prototype system installed, and first tests have been run.

This project has not yet finished, as more running hours are needed for the onboard installations.

Part of task 6.2 concerned a fuel water emulsification (FWE) system for four stroke engines, undertaken by MAN. The aim was to investigate the NOx reduction potential of the system, and to confirm the applicability of water emulsified fuels in combination with next generation injection systems. The other part of the task related to two stroke engines, investigating the NOx reduction potential and the influence on engine performance parameters of the Scavenging Air Moistening (SAM) system.

A DWI system was installed aboard *Maersk Montana* as part of task 6.1, and emissions monitoring equipment was fitted for task 8.1.

A four stroke 32/44 test engine was successfully operated at different loads with varying mixing ratios of heavy fuel oil and water, and the results showed that with increasing water content, the fuel viscosity increases. This has to be taken into account when designing a FEW capable injection system. Operating the engine on fuel water emulsion significantly reduces NOx emissions at all load points, but up to 30% water results in a minor increase in fuel consumption for high load points. High water content increases the ignition delay at part load, and there was an almost deposit-free combustion chamber.

Test runs of a SAM system took place on a 4T50ME-X research engine, before a mini-SAM system was installed aboard Wallenius Lines' *MV Boheme*. A full SAM system installation took place aboard another Wallenius vessel, *MV Mignon*, while the ship was being extended, though the process could not be finalised until after the extension took place, as the time and complexity of the installation was underestimated.

The conclusion from the SAM system testing showed that NOx emissions could be reduced by 30% to 50%, with a SFOC penalty of approximately 1% per 10% of NOx reduction.

Another form of internal emissions reduction was the subject for workpackage 7: exhaust gas. Wärtsilä's share of the package, task 7.1, was entitled 'internal measures', and had the aim of reducing particulate emissions from marine engines. Also involved in particle measurement techniques and evaluation methods was the Swiss Federal Laboratory for Materials Testing and Research (EMPA).

At low loads (10%), particulate emissions with low NOx concept were slightly higher than with a standard concept, and with two stroke engines, the main fraction of the particulates emissions range was from 20nm to 50nm. Number size distributions and masses were stable in terms of the total number of concentrations and mean particle diameter independent from engine conditions at the single load points.

Engine tuning parameters did not turn out to have a large enough influence to reduce particulate emissions significantly, whereas fuel quality did have an impact. A good characterisation of particulate emissions was achieved within the scope of the project, and default engine parameters already resulted in low particle emissions. Correlation with after-treatment technologies investigated in task 8.1

suggested that there is no feasible way to internally reduce particle emissions from marine diesel engines to a similar extent to automotive engines.

In task 7.2, MAN also dealt with internal exhaust gas emissions reduction methods, with the objective of reducing the NOx emissions of a two stroke engine by 50%, using exhaust gas recirculation (EGR) or combustion gas recirculation (CGR) technologies. The two methods were developed at a two stroke test plant in Copenhagen.

EGR was applied to the second iteration of a 4T50ME-X engine, and the particulate emissions were measured according to ISO-8178. The results of component development on the EGR system brought about a reduction of up to 70% for NOx emissions in a two stroke engine, with a 3.75g/kWh SFOC trade off.

A new EGR scrubber with good performance and demist efficiency, plus a CGR valve were developed and tested for two stroke engines. There was a significant increase in particle size along the exhaust gas track, and a significant reduction of the organic carbon fraction achieved by modification of the piston and piston rings. Also, the influence of fuel properties on the particulate matter chemical composition for four stroke engines was identified.

Workpackage 8 dealt with emissions after-treatment. Task 8.1, 'after-treatment methods', was allocated to Wärtsilä, with the objectives of developing practical and reliable methods for emissions monitoring in service, extending emissions measuring technologies for single cylinder measurements, and further developing non-thermal plasma (NTP) and wet scrubbing technologies.

Sick Maihak provided an emissions monitoring system, which was installed aboard *Maersk Montana* and is operational. Final communication with the vessel's control system still requires additional work; therefore no data is currently available.

NTP has been used to demonstrate NOx reduction at laboratory scale, under conditions representative of the exhaust gas composition from a Wärtsilä test engine, but the conclusion from these experiments was that there was no potential in this technology. A wet scrubber was tested on a four stroke 32 medium-speed engine, operating on HFO with a sulphur content of 1.45%. An average SO_2 removal of 95% was demonstrated, plus a 42.8% reduction of particulate matter.

Single cylinder emissions measurement has been developed on the basis of pre-tests and simulations, and the indirect measurement method was chosen, sampling the exhaust gas from a single cylinder into a dead volume. The measurements did not yield quantitatively accurate emission values, but seemed well suited for the comparative evaluation of emissions of the individual cylinders.

MAN took on task 8.2, which was entitled 'new measurement methods', and was divided into two parts. The first part, which MAN undertook itself, was development of measuring methods, with an objective of developing practical and reliable methods for emissions monitoring, designed for onboard use and complying with the requirements of the NOx technical code. The second, carried out by the National Technical University of Athens, aimed to develop individual cylinder NO measurement, and install the system on a multi-cylinder marine diesel engine, executing NO measurements from a specified cylinder.

Results from IMO/FTIR NO_x comparison test, February 2007

	NOx (as NO_2)	
	IMO [g/kWh]	FTIR [g/kWh]
cycle value 1	19.18	19.20
cycle value 2	19.20	19.20
cycle value 3	19.09	19.13
cycle value 4	19.16	19.18
cycle value 5	19.08	19.09
cycle value 6	19.14	19.22
cycle value 7	19.12	19.16
mean, 1-7	19.14	19.17
st. dev. 1-7	0.044	0.047
t-value	1.278 (<2.179)	
F-value	1.169 (<4.284)	

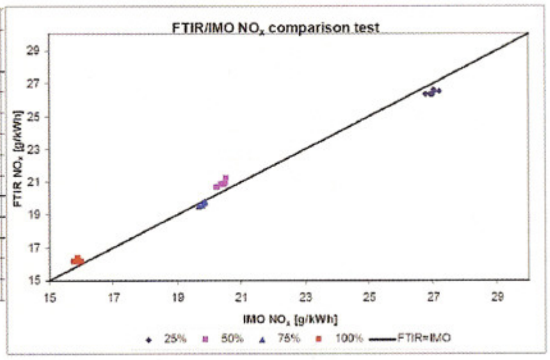
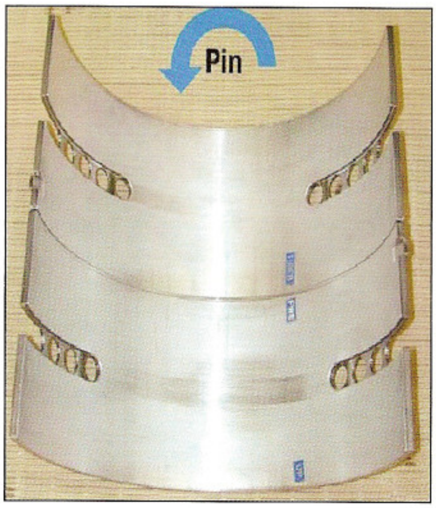


Table 2: The results of comparison tests between IMO-approved gas analysers and a FTIR multi-component gas analyser for task 8.2.

I.P. HERCULES Objective	Year 2007 Targets	Year 2007 Achievements	Comments
Specific Fuel Consumption	- 1%	-1.4%	WP3, WP4
NOx emission	-20%	-50%	WP7 (EGR) WP6 (Direct Water Injection) WP6 (Wetpac Humidification) WP3 (2-stage T/C)
Other emission components	-5%	-20%, HC -40%, PM -90%, SOx	WP7 (EGR) WP8 (Wet scrubber) WP8 (Wet scrubber)
Reliability *(Present TBO 18,000 hrs)*	+10%	Up to 8,000 hrs testing	WP9 (liner, rings)
Time to market *(Presently 60 months)*	-10%	Within 42 months	WP9 (MR sensor "*TriboSen*")

Table 3, showing the overall results of the IP Hercules project.

During task 8.2, a FTIR emissions monitoring system was tested onboard *CMA CGM Verdi*.



Partially grooved big end bearing after 15% overspeed test during task 9.1.

For the first part, two NOx sensors were installed and calibrated, one on a 4T50ME-X test engine, which clocked up approximately 1000 running hours without problems, and the other was installed aboard *CMA CGM Verdi* on a 10K98MC engine. This second sensor originally worked for 60 hours, but then broke down. However, after repairs, it functioned during *Verdi's* seven-week round trip from Valencia to China. No engine performance has yet been recovered though, which is needed for the verification of measured NOx levels.

Comparison tests between IMO-approved gas analysers and a FTIR multi-component gas analyser also took place, using a 4T50ME-X engine, with the results shown in Table 2.

With the second part of the task, commissioning tests of an extended probe to measure NO on an individual cylinder took place. The most effective probe was found to have a total length of 571.5mm, an effective length of 500mm, with quartz used as the inside tube material. Engine tests were completed on MAN B&W's L16/24 engine at the National Technical University of Athens. There was also investigation into the probe's resistance to blockage due to soot formation.

Workpackage 9 investigated a reduced friction engine, with Wärtsilä carrying out task 9.1. The objective of this section of the project was to identify areas with the highest potential for reduction of the mechanical losses of medium-speed four stroke engines, and to generate and test concepts to reduce these losses.

Significant differences depending on engine size were found during friction loss testing, and a non-metallic bearing material with improved mixed friction properties and reduced friction losses was developed. Also created were a new bearing geometry concept, a tribometer which accurately determines friction losses and wear resistances of piston rings and cylinder liner materials, and a hydraulic simulation model and device to predict and measure the fuel injection rate of a common rail fuel injection system.

An updated common rail system with optimised fuel injection for a 1000kW/cyl engine achieved a significant fuel consumption reduction, and a reduction of vibration levels was gained with the development of a tuned/adaptive mass damper.

The results of the various tests showed that in large engines the proportion of bearing friction loss relative to that of the power unit was much larger when compared to truck engines, and a new bearing design with reduced friction losses and 5°C lower overall temperature demonstrated excellent performance in both high-speed idling operation and full load endurance testing.

Task 9.2 was entitled 'tribo optimisation', and was taken on by MAN. The goals of this task were to identify tribological methods which had the highest potential to improve engine efficiency, develop engine components with reduced friction losses, test the final designs, and attempt to control cylinder condition on line.

Simulation tools and calculation codes were developed to show friction losses on the piston ring, piston skirt, and main and crack pin bearings. Test rigs to measure piston ring friction, pressure drops, and ring movements were developed, manufactured, and tested, including runs on test engines. The housing in a main bearing installation was simulated and optimised, plus new sensors for on line control were implemented in a test rig.

New low-frictional engine components, including bearing shells, have additionally been developed and tested on a test rig for an eight cylinder serial engine, leading to a friction loss reduction of around 10%. Laser cladding coating of piston ring grooves were investigated, and a wear-resistant coating was established, which is said to resist edge melting and heat flux.

The final workpackage, number 11, concerned an adaptive and intelligent engine. Wärtsilä undertook the adaptive engine side of the project with task 11.1, and the objectives were to create engine systems and components which adapt to prevailing operational conditions and the component status, investigate self-learning systems based on monitoring with reliable measuring equipment, and develop engine mode changes based on manual or self-detected requirements.

Measurements on a Wärtsilä 34SG engine determined real world signal behaviour for knock detection and monitoring, and a Wärtsilä W20 engine was used for process modelling of advanced control of PTI/PTO systems, using dynamic simulation tools. The method implementation for this advanced control is subject to further development on the turbocharger side.

Advanced engine balancing diagnostics for common rail engines was tested and verified, as well as a new method to ensure advanced fuel injection system reliability by a novel redundancy strategy. This project has generated several patents and scientific papers, and a significant part of the work has already been industrialised, or will be in the near future.

MAN took on task 11.2, the intelligent engine side of this workpackage, coordinating with shipowner and constructor Kristen Navigation Inc. The aim of the task was to develop engine control and monitoring systems with self-adaptive characteristics to respond to variations in operating or boundary conditions, engine operating mode changes based on manual or automated procedures, and to test software and hardware for subsystems such as exhaust gas bypass, variable turbine geometry, NOx measurement techniques, and on line combustion pressure measurement.

Testbed engine used in task 11.2 investigations into intelligent engine control.

Development work and experience was gained in engine process modelling techniques, such as neural networks and polynomials, and optimisation algorithms were analysed and applied. A complete mechanism to optimise off line engine operation was created, and four different test programs with a total of 113 single operating points were run.

First installation of autotuning software on a MAN Diesel 4T50MX engine took place in May 2007, with a second installation incorporating improved software being completed in June 2007. In September, the software was due to be installed onboard an in service vessel.

Phase I successfully completed

Some research and results are still to be completed in various workpackages, but overall, this stage of the project is complete. With two CIMAC Congress best paper awards received, and already over 20 articles published in the international technical press featuring the project, it seems that there has been a lot of attention on the vast remit of the venture. The Japanese government even announced the intention to initiate a similar project a few months ago.

The overall targets set for completion by this year have been met, and in some cases exceeded, with reliability not able to be assessed in statistical terms. The full set of results is shown in Table 3.

This, in fact, is only the completion of phase I of the project, as phase II is set to be launched by the end of the year.

The future: Hercules B

Ralf Marquard, senior vice president for research and development of medium-speed engines at MAN Diesel, submitted a proposal for the continuation of the overall Hercules scheme, at the Brussels final Hercules meeting. Hercules B would have the aims of reducing specific fuel consumption by 10%, and continuing development of ultra low emissions, in preparation for IMO tiers II and III NOx emissions legislation.

MAN and Wärtsilä would again coordinate the whole project, and 42 other participants have already signed up, made up of 47% of industrial partners, 23% universities, 13% research organisations, 9% users/ship operator companies, and 6% classification societies. The proposal suggests a €35 million budget, over a 36 month duration. Eight workpackages have already been devised, comprising:

Workpackage 1:	Extreme parameter engines
Workpackage 2:	Combustion
Workpackage 3:	Turbocharging
Workpackage 4:	Alternative fuels
Workpackage 5:	Exhaust emission reduction
Workpackage 6:	Overall ship powertrain optimisation
Workpackage 7:	Advanced materials, friction, and wear
Workpackage 8:	Electronics and control

For further information and regular updates on the project status, the website address of the project is http://www.ip-hercules.com.