HIGHER-EFFICIENCY ENGINE WITH ULTRA - LOW EMISSIONS FOR SHIPS

Reporting

Project Information

HERCULES-B

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Final Report Summary - HERCULES-B (HIGHER-EFFICIENCY ENGINE WITH ULTRA - LOW EMISSIONS FOR SHIPS)

Executive Summary:
The project HERCULES-B was the Phase II of the HERCULES programme, conceived in 2002 as a 7-year strategic R&D Plan, to develop the future generation of optimally efficient and clean marine diesel power plants. The project was the outcome of a joint vision by the two major European engine manufacturer Groups, MAN Diesel & Turbo and WARTSILA, which together hold 90% of the world’s marine engine market. The research objectives in Hercules-B focused on the drastic reduction of fuel consumption (and therefore CO2) and the exhaust gas emissions from maritime transport, considering the existing and foreseen composition of the world fleet and fuel infrastructure, as shown in figure Ia.
The targets that formed the vision of Hercules-B projects were to reduce fuel consumption of marine diesel engines by 10% (and therefore reduce CO2 emissions substantially) and to achieve exhaust emissions reductions in the order of 70% in NOx and of 50% in Particulates, by the year 2020. Hercules-B aimed at the development of engines with extreme operational pressure and temperature parameters, considering the thermo-fluid-dynamic and structural design issues, including friction and wear as well as combustion, air charging, electronics and control. To achieve the emissions target, combustion and advanced after-treatment methods were concurrently developed. To improve the whole powertrain, the interaction of engine with the ship, as well as the use of combined cycles in overall system optimization, was considered. The structure of work of this project consisted of 56 subprojects, grouped into 14 Tasks and 7 Workpackages, had a total budget of 25M €, a duration of 40 months.
A short summary of the main research activities that took place within the Hercules-B project are outlined below in items (a) to (g), and the corresponding main results obtained from these activities are listed in figure Ib.

(a) Development of engines that run at extreme operating conditions. This activity led to obtaining a high power output, but also, to high mechanical and thermal loads on the engine components which were specifically designed and tested for this purpose.

(b) Detailed characterisation of the combustion process and of the parameters that affect combustion. This was achieved by performing in-cylinder visualizations and measurements, and using the results in the development and tuning of CFD models

(c) Development of high efficiency and low emission concepts, which involved the experimental investigation and of two-stage turbocharging, along with Miller valve timing

(d) Reduction of exhaust gas emissions by further development of aftertreatment technologies, and by implementation of primary measures such as direct water injection and exhaust gas recirculation. These demonstrated a strong potential in achieving significant reductions of NOx, SOx and Particulate matter emissions

(e) Overall ship power train optimisations using simulations in both stationary and dynamic conditions. Also, optimisations were achieved from the application of a high pressure boiler

(f) Tribology optimisation which involved the development and testing of engine components with new materials and new coatings, and this led to significant reductions of the frictional losses

(g) The development and utilisation of advanced sensing, and its implementation in the context of reliable adaptive control of marine engines
Project Context and Objectives:
HERCULES was conceived in 2002 as a 7 year R&D Programme, of 80M€ budget, to develop new
technologies for marine engines:
• To increase engine efficiency, thus reduce fuel consumption and CO2 emissions.
• To reduce gaseous & particulate emissions.

The R&D Programme HERCULES is the outcome of a joint vision by the two major European engine
manufacturer Groups MAN & WARTSILA, which together hold 90% of the world’s marine engine market.
It was the first time that these two Groups participated together in a project with commonly defined
Research Areas.
Phase I of the Programme HERCULES materialized as the FP6 Integrated Project “I.P. HERCULES”
jointly funded by the E.C. and Swiss Government. The I.P. HERCULES (A) structure of work comprised 54
subprojects, grouped into 18 Tasks and 9 Workpackages, spanning almost the complete spectrum of
marine engine technology. The duration of I.P. HERCULES (A) was 43 months, up to September 2007.
Project HERCULES-B was Phase II of the original 7-year Programme concept. The general targets for
emissions and fuel consumption were retained in HERCULES-B. However, based on the developed know-
how and results of I.P. HERCULES (A), it was possible to narrow down the search area, to focus on
potential breakthrough research and to further develop the most promising techniques (figure II).

The general targets for HERCULES-B were more specific, are consistent with the overall 7-year plan of
the HERCULES Programme, were ambitious yet realistic, in view of the successful results of I.P.
HERCULES (A). These overall targets, respect to economy and environmental impact of marine engines,
were:
• 10% reduction in specific fuel consumption (and CO2 emissions)
• Ultra-low gaseous and particulate emission

The HERCULES-B was a large scale project, integrating technologies in ALL the significant areas of
marine diesel engine development. Specific measurable/verifiable objectives were set, related to each
Work Package, to serve as Indicators of accomplishment. These objectives are outlined below, with
respect to each Workpackage.
The main objectives of WP1 “Extreme parameter engines” involved reaching a maximum in-cylinder
pressure of 220 bar and a mean piston speed of 10 m/s in a 2-stroke engine. In addition, 300 bar and 12
m/s were the respective targets for a 4-stroke engine.
The main targets of WP2 “Combustion” involved the manufacture and use of a transparent cylinder cover
with optical access for 2-stroke and 4-stroke engines for firing conditions of 200 bar, 2000 °C.
Furthermore, work involved fuel injection and combustion full-scale spatial data, to be used in CFD engine
simulation model validation.
In WP3 “Turbocharging” concentrated in multistage turbocharging, with 8 bar charging pressure on the
test engine.
The work in WP5 “Emission reduction methods” involved the application of EGR / CGR / Scrubbing to
achieve NOx reduction below 50%, on test bed and application of SCR with fuel of high sulphur content.
In WP6 “Overall powertrain optimization” a high pressure boiler compounding system was set to achieve
overall power-plant efficiency of 60% during testing.
The main objectives in WP7 “Advanced materials, friction and wear” involved the reduction of 25% in piston ring friction and guide shoe friction. The work in WP8 “Electronics and control” targeted the installation on a test engine of an intelligent management system with self learning and fault tolerant capabilities and comparison of this system with conventional systems.

The general research targets of the HERCULES Programme were the high efficiency and very low emissions in marine engines. The Hercules-B project extended further the research directions that were considered promising during the I.P. Hercules (A) project and considered further research threads with attractive prospects, to attain the general targets of the HERCULES Programme. The total work within the Hercules-B project was structured over 56 subprojects, 14 tasks and 7 Work packages as shown in figures IIIa and IIIb.

The objective of Workpackage 1: Extreme Parameter Engines, was to advance towards the engine of the future. Components were designed and tested on experimental engines operating with pressures, temperatures and mean piston speed which are one step beyond the current state-of-art. By increasing the margin to mechanical failure, it was made possible to study new advanced combustion technologies. Active real time adjustment of valve timing enabled further flexibility in combustion control and operation on advanced working cycles. Improved materials and coatings provided superior thermal and wear resistance, in conjunction with specialized cooling and heat loss minimization designs. The work was performed on 3 special-made prototype extreme-parameter large experimental engines. In Workpackage 2: Combustion, the very large spray combustion chamber facility conceived and built during I.P. HERCULES (A) was commissioned, fully instrumented and the optical measurement infrastructure was completed. The facility was used to provide spatially resolved combustion process data under various configurations. These data was used to validate sub-models for combustion and pollutant formation, so as to validate CFD models capable of predicting in-cylinder processes of marine engines for various arrangements and advanced combustion concepts, including Low Temperature Combustion (LTC) and lean-burn gas combustion. To obtain further validation data, transparent cylinder covers were designed and fitted on a large 2-stroke and a 4-stroke experimental engines, to enable in-cylinder optical access and measurements of velocity field, flame geometry and heat transfer under realistic operating conditions. These engines were fully instrumented with high speed CCD and CMOS cameras, laser fuel spray visualization, IR surface temperature, transient ultra-fast exhaust species measurement equipment. The achievement of very high charging pressures, wider operating range and higher efficiency beyond today’s state-of-art, implies further development in turbocharging systems. In Workpackage 3: Turbocharging, experimental configurations with multiple stages were further developed based on the experience in I.P. HERCULES (A) and were installed on test engines. Electric power-take-in (PTI) arrangements for large size turbochargers provided boost at part load and off-design operation, was developed putting emphasis on high-speed bearing technology. Variable geometry stages were tested in heavy-fuel burning engines. Specific control strategies were investigated on a test bed, to optimize engine and turbocharger geometry for effective charging at every operating condition, as needed by the efficiency and emissions requirements.

A wide range of emission reduction methods were examined and evaluated in the I.P. HERCULES (A) project. It was shown that some of these innovative methods could be applied to large marine engines, whilst others had substantial potential. Workpackage 5: Exhaust Emission Reduction considered both NOx and particulate pollutants. Regarding particulate matter components, the detailed investigation of emissions under various operating conditions extended the know-how in characterizing these
components. This knowledge was used to support designs for removal of particulate matter and SOx via scrubbing. Regarding NOx, the application of extreme EGR for ultra-low emissions was experimentally investigated on a large test engine, in combination with the application of a novel EGR boiler for energy recovery. Regarding aftertreatment, the limits of operation and boundary conditions for on-board Selective Catalytic Reduction (SCR) were investigated.

The concept of total energy economy onboard ship considers all energy flows at various operating conditions. Regarding the powertrain this has two levels of detail: The better utilization of fuel energy, by recovery of exhaust gas heat through compounding and further, the overall optimization of the propulsive efficiency by considering the engine / propulsor / ship interaction and designing for realistic service conditions. In Workpackage 6: Overall Powertrain Optimization, a new concept of compound design involving a close-coupled boiler on the high pressure side of the engine was investigated on a prototype engine. The overall system had a significant potential for large increases in overall efficiency. Aspects of integration and control during engine transients due to higher thermal inertia were examined. Overall ship propulsion simulation models including engine, propeller and hull modules were extended to include off-design and transient conditions and validated with measured data. These were used to demonstrate optimum subsystem selection for increased fuel efficiency and reduced emission of a ship under various realistic operating scenarios (weather, fouling).

The improvement of mechanical efficiency of engines can directly reduce fuel consumption. The reduction in frictional losses requires development in tribology and wear-resistant materials. In Workpackage 7: Advanced Materials, Friction and Wear, new piston-ring tribology codes were utilised with new friction and wear models, and validated with performance data from test rigs as well as from controlled full-scale piston-ring running experiments on-engine. A new low-friction guide-shoe bearing was developed and tested full-scale on an experimental large two-stroke engine. In both cases the objective was to reduce frictional losses significantly.

Several novel engine components have wide adjustment and performance optimization potential, so that the engine operation can be adapted to the actual prevailing operating conditions. Development of advanced engine management systems was performed in Workpackage 8: Electronics and Control. Evaluation and verification of sensors for NOx, O2 and in-cylinder pressure measurements in heavy fuel operated engines took place in parallel to development of signal processing methods for engine diagnostics. Design of on-engine electronics, as well as interfaces and bus systems with increased reliability, improved confidence in developing and using advanced adaptive control strategies for intelligent engines. State-of-art optimization algorithms were used for adaptive parameter selection in noisy environments and dynamic conditions. Confirmation of the functionality of adaptive control systems with self learning capabilities were achieved by full scale engine test-bed trials.

Project Results:
Upon completion of the Hercules-B project many important scientific and technological results were obtained. These are described in the paragraphs that follow, with respect to each related Task.

Task 1.1: Development of engines for extreme load conditions
The objectives of this Task were (a) to develop and test components specially designed for operation at extreme load conditions of 35% higher firing pressure (up to 300 bar) and 25% higher mean piston speed (up to 12 m/s) compared to the similar existing products, and to study the effect on the engine performance and emissions, (b) to study and validate the influence of advanced working cycles on engine performance
and emissions utilizing variable valve parameters, and (c) to develop advanced in-cylinder measurement techniques.

The work in Task 1.1 referred to the development of new engine components for high specific engine output. The Extreme Value Engine (EVE), located at Aalto University and developed in Hercules-A project, was used as the primary research platform. The target was an engine that could run at the extreme load condition of 35% higher firing pressure (up to 300 bar), and 25% higher mean piston speed (up to 12 m/s), compared to similar existing products. In addition, in-cylinder measurement techniques were developed. During the first project year the main engine components (piston, connecting-rod, gudgeon-pin and cylinder head) that were designed to take the high in-cylinder pressure loading, were completed (figure 1.1a). Furthermore, the EVE engine was prepared for these new components by performing crank-train balancing, and installing new intake and exhaust gas piping. Other new auxiliary components such as fuel injection, hydraulic valve actuation, and others were manufactured and procured. The parts were delivered and the new EVE construction was initiated.

During the second year the main engine components were assembled on the engine. When commissioning tests started engine failure took place and a new gudgeon pin and piston had to be manufactured. Some modifications were made to the components in order to ensure improved lubrication. Engine tests were then run with updated, more conservative start-up procedures. Initially only some of the new components were installed on the engine. Once the engine was operating as expected more components were added to it. Finally, all new components were installed on the engine for running the tests. In the third year the combustion process was researched at high pressure conditions, by varying injection parameters and charge air. The engine was then operated at the above specified conditions and this lead to achieving operation at the targeted conditions of maximum pressure of 300bar (figure 1.1b) and when operated at another load condition the maximum mean piston speed of 12m/s.

The overall achievements during this Task involved (a) the successful execution of simulations and calculations, (b) the successful completion of design and manufacturing of engine components to take the high loading, but, with more effort than what was originally estimated, (c) the challenges involved in building a prototype engine, and the valuable lessons learned from the engine failure experience, (d) the development of advanced in-cylinder measurement techniques and (e) the targets of 300bar firing pressure and 12 m/s mean piston speed on the 2-stroke research engine.

Task 1.2: Mechanical design of engines with extreme parameters
The general objective in this Task was to develop design solutions for the increased thermal and mechanical loads on basic components, for engines operated at extreme conditions. These types of engines are generally subjected to extreme loading parameters in order to boost efficiency and reduce emissions.

In Task 1.2 methods and ideas were developed, tested and evaluated in order to design engine components that were applicable to extreme engine operating conditions. The design solutions focused on improving the capability of various key engine components to withstand increased thermal and mechanical loads. The work during the first project year concentrated on identifying components prone to failure when an engine is operated at extreme conditions. Simulations were performed using CFD and FEM tools for predictions of different stresses and temperature distributions across the specified components. The
engine components involved in the investigations were the valve seat ring, the valve spindle (figure 1.2a) the fuel valve nozzle, the exhaust valve and the cylinder liner. Furthermore, the materials and coatings of these components were specified and selected, along with the production processes to be involved. During the second project year several prototypes of the above mentioned components were manufactured. A test rig was developed and used for the determination of heat transfer coefficients. These coefficients were then used for the tuning of FEM models. Further work involved the completion of the first service tests, with components such as the cooled exhaust valve spindle, and the prototypes were thoroughly inspected after the test runs (figure 1.2b).

During the third project year several test rigs were built and material investigations were carried using these rigs. During this period all prototype components were manufactured, such as the valve seat rings, the insulated injection nozzle, the cylinder liner and main bearings. The prototype components were tested in service conditions. Overall, the main achievements that took place during this task involved (a) the application of advanced simulation tools in various technical areas, facilitating the development of advanced designs, (b) the development of new production methods that enabled the application of advanced materials with improved properties, (c) the introduction of new materials for application to engine components, and (d) the verified potential of several components to withstand higher engine loads, for future engine designs.

Task 2.1: Combustion process modelling and development

The objectives in this Task were (a) to investigate with CFD and propose combustion concepts that offer improved trade-offs between fuel consumption and emissions, compared to today’s marine engines, (b) to acquire relevant and valid reference data to use as model input as well as model validation, and (c) to develop and/or adapt CFD tools and simulation methods to the extent required to make them useful for simulating marine engine combustion processes.

Task 2.1 concentrated on the implementation of CFD simulation methodology of diesel combustion to large marine Diesel engines. It involved detailed investigation of the individual phenomena that constitute the chain of events during the combustion process. During the first project year the Spray Combustion Chamber (SCC) was used for optical investigations of the spray propagation. A feasibility study was also carried out on advanced optical measurement techniques to be used. After the tests with the SCC various CFD sub-models of spray and evaporation were further developed and improved (break up models, multi-component fuel properties) against the measured data (figure 2.1a).

During the second project year reference data for the fuel spray propagation was acquired by means of shadow-imaging measurements within the SCC. This resulted to obtaining considerable amounts of quantitative reference and validation data. Furthermore, more suitable optical techniques were assessed for the characterisation of the injected fuel spray inside the chamber. A customised illumination setup, based on Mie scattering, enabled testing of real engine nozzles. A PDA setup was prepared for application at the SCC, and a feasibility study for the applicability of exciplex LIF was conducted. Further work involved the development of advanced methodologies for CFD-based combustion system optimisation. The improved simulation methodologies and models were applied to optimise existing and new combustion systems.

During the third year the SCC unit was upgraded and additional optical techniques were implemented. Spray measurements for different fuels, including HFO, were made feasible. In addition, droplet size velocity measurements using PDA technique were made possible. The CFD sub-models were tuned to the
measured data and a new primary breakup model was proposed. Due to the significant number of parameters that could be varied during the investigation, optimization algorithms (DoE) were applied. This resulted in numerous in-cylinder combustion simulations which involved variation of parameters such as the fuel injection, nozzle, fuel type, swirl, EGR, engine main dimensions and combustion chamber geometry (figure 2.1b). The CFD models were further improved through correlation with experimental data, and important areas of engine performance were addressed. Overall, the work carried out during this task resulted (a) to an improved understanding of the in-cylinder processes (b) to an improved understanding of the inter-dependency of combustion chamber geometry and injection nozzle specification, (c) to significantly improved CFD sub-models using the SCC reference data, (d) to considerable improved CFD methodology and therefore predictive power, and (e) to simulation methodologies and models applicable to the optimisation of existing, as well as new combustion systems.

Task 2.2: Experimental and Numerical Combustion Analysis

The objectives of this Task involved (a) the development of prototype cylinder covers with a large number of optical access points (“transparent” covers), applicable to 2- and 4-stroke experimental engines, in order to enable the optical investigation of all points of interest inside the combustion chamber, (b) the selection and development of advanced instrumentation for illumination and visualization of the in-cylinder phenomena, including fuel spray and flame visualization, velocity and temperature field measurement, as well as transient emissions measurements, and (c) the development of numerical simulation codes for novel combustion concepts and emissions formation modelling, using input and insight from the optical in-cylinder investigations.

The work in Task 2.2 involved the development of advanced tools and techniques for experimental and numerical analysis of combustion and emissions, in large bore engines. Local optical data from inside the combustion chamber can improve significantly the simulation models, and also provide important information about the combustion process. Emission measurements from individual engine cylinders can provide important information about the sensitivity of engine emissions on changes in engine operation parameters.

In the first project year an optical access (single) port was developed for the combustion chambers of the 2- and 4-stroke engines. Simple soot luminosity imaging was then performed using the access port, and two-colour pyrometry temperature imaging was applied to the 2-stroke engine. Feasibility tests were also carried out, for the application of laser based measurement techniques (PIV and LDA) on the 2-stroke engine. The initial design of a transparent cylinder cover with preliminary optical port positions was carried out, and FEM analysis for the 2-stroke (2s) and 4-stroke (4s) engines was performed (figure 2.2a).

In the second project year the components of the combustion systems of the 2-stroke and 4-stroke research engines that provided optical access were manufactured. For the 2-stroke engine a cylinder cover with multiple access ports was manufactured. The optical techniques were applied and the first in-cylinder visualisation tests were carried out. These involved high speed imaging of flames, two colour flame thermometry and spray visualization laser-based Mie scattering. Extensive CFD modelling was carried out and the simulation tools were optimised to allow for data comparison with the optical measurements. In addition, emission measurements were carried out using gas absorption spectroscopy techniques in the exhaust duct.

During the third year of the project laser based optical investigations were performed with the optically
accessible cylinder cover on the 2-stroke engine, at different engine loads. Optical investigations were also performed on the 4-stroke engine. The CFD models were then correlated to measured data (figure 2.2b). Finally, fast NOx emission measurements were performed on the 2-stroke engine and soot measurements on the 4-stroke engine.

Overall, the work carried during this task had two main achievements. The first involved the development of optically accessible cylinder covers, and the execution of optical measurements for the investigation of spray pattern and combustion process, using techniques such as (a) high-speed imaging of flame luminescence for investigating flame propagation and flame-piston interaction, (b) two-color high speed pyrometry for measuring flame temperatures, (c) infrared imaging for both visualization of burnt gases during the scavenging phase, and thermography of combustion chamber walls for improved engine cooling concepts, (d) laser-optical spray investigation of spray penetration under real engine running conditions, and (e) time-resolved emission measurements in the exhaust duct of a specified cylinder for possible future emission control and validation purposes.

The second main achievement involved the validation and improvement of CFD combustion simulation tools concerning spray penetration, flame propagation and emission formation, targeting areas such as (a) the optimization of combustion chamber design and engine components concerning SFOC and emissions, in an early stage of the engine development process, (b) the reduction of engine tests and substitution with CFD-combustion simulations, and (c) the preparation for future computer-based optimization strategies of the engine combustion system.

Task 3.1: High efficiency and low emission TC concepts

The objectives of the work carried out in task 3.1 involved (a) the realisation of serial high pressure turbo-charging systems on medium speed marine engines to meet at least 50% NOx reduction, (b) the demonstration of the reliability/durability of multistage turbo-charging systems by endurance tests, (c) the investigation of the potential of high pressure turbo-charging on 2-stroke engines in relation to NOx reduction, and (d) the adaptation of control devices for advanced multistage turbo-charging systems, leading to improved part-load engine performance.
reduction were achieved, as well as the turbocharging efficiency of 76%. This resulted to a SFOC reduction of up to 5-6 g/kWh. Finally, several new technologies were simulated and tested in an attempt to improve load pick-up and low load operation. The work progress with the 2-stroke engine involved starting the engine and partially completing the scheduled test program. The turbocharger efficiency and SFOC-NOx trade-off was measured.

In the third year the knowledge gained from the 2-stroke engine performance optimisation tests was used to improve simulation models. In addition, performance tests on the 4-stroke demonstrated the NOx reduction potential of 2-stage turbocharging in conjunction with other technologies and the results were also used to improve CFD models. More specifically, the high NOx and SFOC reduction potential was demonstrated using Miller valve timing and 2-stage turbocharging (figure 3.1b). Furthermore, a satisfactory operation throughout the load range was achieved, and load acceptance tests were successful. The general activities and technologies that were involved in achieving the above were, the development of variable valve timing technologies (which enabled the use of multistage T/C systems), the modified geometric compression ratio, the air Injection for improved load acceptance, the charge air temperature adjustment devices and the water/fuel emulsion technologies.

Overall, the main achievements during this task, which resulted from the conversion of 3 test engines (two 4-stroke and one 2-stroke) to take on a 2-stage turbocharging system, and the subsequent execution of about 800 hours of tests, were split to those for the 4-stroke and those for the 2-stroke engines. The 4-stroke engine related achievements involved (a) a high NOx and SFOC reduction potential using the Miller valve timing with 2-stage turbocharging (-50% NOx, -5 to - 6 g/kWh SFOC), (b) a turbocharging efficiency of 76%, (c) a developed phenomenological combustion and emission model, (d) good operability throughout the load range, (e) successful load acceptance tests with air injection, and (f) water/fuel emulsions which provided additional benefits in NOx, soot, and SFOC reductions. The 2-stroke engine related achievements involved (a) the gain of important knowledge about the engine efficiency and emissions, obtained from the engine tests performed, and (b) the development of a simulation model for turbocharging system’s efficiency.

Task 3.2: Advanced intelligent turbocharger
The objectives of this task were distinguished between those for the 2-stroke and those for the 4-stroke engines. The objectives for the 2-stroke marine diesel engines were (a) to design, manufacture and implement 2-stage turbocharging, in order to increase mean effective pressure up to 30 bar, with a corresponding combined cycle plant efficiency increase of 2%, (b) to use a PTI/PTO unit, along with engine optimal operation conditions with respect to emissions and fuel efficiency, (c) to extract with PTO, at full load condition, up to 5% of the main engine shaft power with only very limited impact on engine SFOC, and consequently a total SFOC improvement of 2 to 3%. With regards to the 4-stroke marine diesel and gas engine the main objectives involved (a) the design and manufacture of 2-stage turbocharging in order to increase boost pressure up to 8 bar, (b) to establish full turbocharger control with variable flow areas, (c) to develop a PTI facility, and (d) with the combined advanced turbocharging system, to achieve (i) for gas engines a 30 bar mean effective pressure while maintaining the same heat rate and (ii) for diesel engines a 30 bar mean effective pressure with at least the same fuel efficiency, and a reduction of NOx emissions by 50% compared to IMO Tier I limits.

Task 3.2 concentrated on applying two-stage turbocharging on 2-stroke and on 4-stroke engines in order to increase efficiency, achieve reduction of NOx and enhance smokeless operation under load imposition.
During the first project year the essential features of power transfer technology, realised by a high-speed electric machine, were clearly defined. The design of the two-stage turbo-charging systems, applicable to both the two-stroke and four-stroke test engines had progressed. The 2-stage process optimisation was based on a large variety of design parameters. In addition, the integration of PTI/PTO technology was in progress and a novel compact arrangement of 2-stage turbocharging systems for marine diesel engines was developed. The planning for the investigations for the advanced controlled turbocharging systems was initiated.

In the second project year the electric high-speed machines for bi-directional energy transfer between the turbocharger and an electric grid including power electronics, for the two-stroke engine applications were ordered. For the four-stroke engine the new components for the two-stage turbo-charging system were specified. A completely new attachment for two turbochargers was developed and various engine components were upgraded in order to cope with the increased power density generated by the two-stage turbo-charging (figure 3.2a). During this period the integrated PTI/PTO unit was coupled to the turbochargers for two-stroke and four-stroke engine applications. The 2-stage turbocharging for the 2-stroke marine diesel engine was in progress and the tests were planned. In addition, the final tests for the Variable Inlet Guide Vane facility (VIGV) for the compressors were also planned. Further activity involved FEA analysis for the cylinders, the connecting rods and the attachment of the 2-stage turbocharging system. Due to the various technologies involved, such as the charge air bypass, the VTA and the separate waste gates for both TCs, the operating conditions that were examined were numerous. Furthermore, the LP- and HP-cooler were controlled independently and the operation could be done with and without the PTI.

In the third project year the potential of PTI/PTO technology was realised on 2-stroke engines, along with the use of VTA technology (figure 3.2b). In 4-stroke engines, the effects of common rail injection technology and two-stage turbocharging, on the trade-off between fuel consumption and NOx formation, were investigated. Furthermore the effect of technologies, such as VTA, VVT and VIGV, was explored with respect to emissions (NOx and soot) and fuel consumption.

Overall, the achievements during the task, with regards to the 2-stroke engines involved (a) a two-stage turbocharging efficiency of about the 78%, at 6.5 bar scavenging air pressure, with a high degree of Miller timing, (b) a 21 bar engine mean effective pressure, (c) a 40% reduction in NOx emissions compared to a Tier II engine and (d) a PTO of 220 kW at 18000 rpm, for SFOC reductions, and a PTI potential for replacement of the auxiliary blowers.

The achievements with regards to the 4-stroke marine diesel engines involved (a) a VGT using VIGV and VTA turbocharger, achieving a 67%-100% flow rate, and (b) a two-stage turbocharging system with HP-VTA which led to (i) 75% T/C efficiencies at approximately 7 bar charge air pressure, (ii) 50% reductions in NOx emissions compared IMO Tier I limits, at constant SFOC, (iii) 10-14% reductions in SFOC, at constant NOx emissions, and (iv) smokeless operation using variable valve timing.

Task 5.1 Emission reduction methods
The objectives during this task involved (a) the extension or corroboration of the know-how on the characterization of particulate emissions from marine engines with respect to total mass, size distribution and composition along with toxicological tests, and their dependence on parameters such as fuels and engine settings, (b) the development of models for soot and particulate formation mechanisms including classification of different sources for various fuel qualities, (c) the evaluation and further development of
SOx and particulate matter removal technologies, (d) the development and optimisation of engine-integrated SCR systems, (e) the investigation of alternative NOx reduction concepts for emissions reductions beyond 60%, on the basis of further development of “wet”, as well as, “dry” methods and their combinations, and (f) the demonstration of ultra-low emissions concepts applicable to marine engines.

In Task 5.1 the experience in 2-stroke engine particle emissions, (gained during I.P. Hercules (A)), was further extended and corroborated by characterizing the new 2-stroke test engine. In addition, particle emission modelling applicable to 4-stroke engines was used for the determination of devices to remove particulates from both 2- and 4-stroke engines.

In the first project year the emissions for the new test engine were characterised. Furthermore, the particulate removal potential of an SCR unit was evaluated. The most promising technologies for NOx reductions (identified in I.P. Hercules) were addressed and selected for further development. In more detail, the work carried out involved the capture of electron microscopy images showing the morphology of particulates from a 4-stroke engine. The planning of integrated and optimized emission reduction methods was initiated, and the first EGR tests with the medium speed diesel engine were planned.

In the second project year the SOx reduction potential was closely investigated and technologies such as scrubbers were assessed, not only as stand-alone SOx reduction devices but also as components of more complex emission reduction devices. Additionally, “wet” and “dry” NOx reduction systems were further developed to achieve reductions beyond 60%. The main work carried out during the period involved particulate (PM) measurements, where basic features, such as size distribution and mass composition, which were previously identified for the lab engines, were also confirmed for other bore sized engines.

From the analysis of the measured data it was decided to also investigate new measurement methods and evaluate the effect of after-treatment methods on PM emissions. Another main area that was covered was that of NOx reduction concepts and systems. To this extent an EGR unit was tested on a 4-stroke engine and preparation for application of EGR on a 2-stroke engine was initiated. Further work involved the investigation for the combination of charge air humidification with 2-stage T/C. In addition, a Direct Water Injection (DWI) test rig was constructed (figure 5.1a). Finally, SCR activities concentrated on the development of catalysts that were more tolerant to high sulphur fuels. This involved more general aspects such as reliable operation over the whole load range, as well as pre-T/C concepts.

During the 3rd project year particulate emission measurements were performed on 2-stroke and 4-stroke marine diesel engines. The extensive particulate measurement campaigns targeted the effects of fuel oil quality and lubrication oil feed rate on the SCR catalyst. Apart from the measurements, the particulate formation inside the cylinder, during combustion, was modelled. Furthermore, for both engine types, NOx reduction technologies were set-up, the objective being NOx reductions in excess of 60%. The application of SCR on 4-stroke engines, demonstrated the compliance with IMO Tier III levels, and corresponding verification tests on the new 2-stroke engine were imminent (figure 5.1b). Finally, the influence of NOx and SOx after-treatment systems on particulate emissions was investigated.

Overall, the main achievements within this task were in five different categories, these outlined below:
(a) NOx reduction methods using EGR, and this involved (i) the successful application of EGR on the 4-stroke engine and compliance with IMO Tier III limits, and (ii) the construction of low-pressure and high pressure EGR systems for application to the 2-stroke engine,

(b) NOx reduction methods using wetpac technology (ie charge air humidification and direct water injection) involved (i) the unsatisfactory results from the air humidification tests, and (ii) the promising tests
with the DWI technology on a test rig with high water/fuel ratios,
(c) NOx reduction methods using SCR technology, and this involved (i) the investigation of pre-turbo SCR
concepts and integration aspects, (ii) the operation with SCR at low load with respect to reliable engine
operation and sulphur tolerance, and (iii) the investigation of alternatives to SCR including theoretical
considerations and simulations, as well as the preparation and testing of the installations.
(d) Particle measurements, and these involved (i) the gain of important information about PM’s chemical
composition, (ii) the use of electron microscope images that provided information on the particle structure
and dimensions, in order to compare these to model predictions, and,
(e) PM reduction methods, and these involved (i) the use of a condensing scrubber that led to a 40-60%
particulate mass reduction, and (ii) the use of a centrifugal separator that led to a 40-70% particulate mass
reduction.

Task 5.2: Emission reduction - Exhaust Gas Recirculation and After-treatment

The objectives during this task involved (a) the reduction of NOx by 80% on large two-stroke diesel
engines with High Pressure Exhaust Gas Recirculation (EGR) by extreme EGR parameters and variations
of engine parameters, (b) the investigation of the potential increase of the high power energy recovery
from the exhaust gas in the EGR system by introducing a high pressure boiler, (c) the reduction of NOx by
50% onboard a seagoing vessel by development and testing of a full-size High Pressure EGR system for
the main engine of the vessel, (d) the investigation of NOx reduction potential of the Combustion Gas
Recirculation (CGR) technology, (e) the reduction of the energy consumption and wastewater treatment in
EGR systems by investigation on dry scrubbing technologies, and (f) the investigation of the necessary
boundary conditions for the application of Selective Catalytic Reduction (SCR).

In Task 5.2 a significant reductions of NOx from large two stroke diesel engines were targeted using
extreme EGR parameters and variations of engine parameters.

In the first project year EGR and SCR systems, two different ways to achieve significant reductions of
NOx, were investigated. A High Pressure Exhaust Gas Recirculation (EGR) system was therefore
designed to be applied on a seagoing vessel to investigate NOx reductions. More specifically extreme
EGR tests were executed on the 4T50ME-X 2-stroke engine from 5% up to 100% load range and a
reduction of NOx in excess of 85% was achieved. Further work involved the design of EGR components
for the service test that followed, and the installation on the 1100 TEU container vessel (10MW). In
addition, the design of the High Pressure Boiler system was initiated, as well as the production of
improved engine components for the adaptation of SCR on the 4-stroke diesel engine. Finally, the design
of the CGR components was continued.

In the second year considerable efforts were put to the installation of the unit onboard the vessel and to the
execution of the commissioning tests of the high pressure EGR system. The EGR performance service
test was completed (figure 5.2a). More than 180 hours of EGR running onboard Alexander Maersk were
accomplished and NOx reductions above 70% were achieved. The corroded components on Alexander
Maersk were replaced with new improved components. Further work involved the tests with the High
Pressure Boiler. A total of 35 tests were executed on the 4T50ME-X engine. Also, simulation and
conceptual design study was carried out for the CGR technology for application on large 2-stroke diesel
engines. With regards to 4-stroke engines, tests with improved components on a 1L32/44 four-stroke
diesel engine were completed for the application of SCR. The temperatures on a 4-stroke engine with an
SCR installed were verified to be above 340ºC at all loads, therefore allowing operation with HFO
containing 1 to 2% sulphur. The components for the SCR tests on the 6L32/44 engine were produced and
commissioning tests on the 6L32/44 engine were completed.
During the 3rd project year the high pressure exhaust gas recirculation (EGR) unit that was in service was
upgraded by replacing several key components that suffered degradation. NOx reductions above 70%
were achieved, while the target was 50%. A total of more than 600 hours were recorded for the engine in
service using the EGR, with HFO 3% sulphur fuel, and without any negative impact on the combustion
chamber. A high pressure boiler was also installed on the test engine and the test program was launched.
The tests with the High Pressure Boiler showed good correlation between calculated and measured heat
transfer. Additional work involved the feasibility study on dry scrubbing technologies, which was continued
and finalized.
The work on four-stroke diesel engines achieved the target temperature for efficient SCR operation. The
heat flux model used in the study showed good correlation between calculated and measured values
(figure 5.2b). The work was completed with measurements of the components’ surface temperatures that
resulted from increasing the exhaust gas temperature after the turbine. It was found that engine
component temperatures could be kept unchanged by improvements of the affected components.
Overall, the main achievements within this task, (a) for the 2-stroke engine, were (i) EGR proved to be a
suitable measure to provide compliance with IMO Tier III NOx limits, with a SFOC penalty of about 1%,
and CO and Soot emissions at acceptable levels, (ii) service tests confirmed the potential of the EGR as a
NOx reducing technology for HFO operation by achieving a 70% reduction, (iii) service tests provided
significant information about corrosion and deposits on EGR systems, and (iv) only one dry scrubbing
method, based on Ca(OH)2 pellets, was identified as a possible candidate for use with the EGR system,
and this required significant space, and handling of the reacting agent.
The achievements with regards to (b) the 4-stroke engines involved (i) the identification of three different
measures for achieving an increase in exhaust gas temperature after the turbine, (ii) the necessary
conditions for efficient operation of the SCR with HFO, along with acceptable effects on the engine
components, were found to be feasible for application on four-stroke diesel engines, and (ii) that engine
component temperatures could be kept unchanged by improving the components expected to be affected.

Task 6.1: Overall ship powertrain optimisation

The objectives of this task involved (a) the consolidation of a methodology and the development of an
associated simulation tool for ship propulsion powertrain optimal configuration and performance, and (b)
the optimisation of an overall ship powertrain design for real service conditions leading to an increase of
overall propulsive efficiency and fuel economy, and an overall reduction of pollutant emissions by 3%

Task 6.1 focused on the development of a dynamic simulation tool to be used for obtaining optimum
configuration and performance for ship propulsion, and for optimizing the overall ship powertrain for real
service conditions. Dynamic simulations over the entire ship operating profile were expected to identify
critical conditions in terms of emissions. Variations in controller schemes for better loading of the
propulsion system in real service conditions were also considered.
During the first project year, the work carried out involved the development of simulation models. These
models involved propulsion systems, diesel engines, WHR systems, gears & shafts, controllers, hull
resistance and ship manoeuvring. Further development work involved the integration of software tools such as a static propulsion train design evaluation tool and a dynamic simulation tool of propulsion train components (figure 6.1a).

During the second project year the design of the sub-models that constituted the overall ship model was continued, and the developed models were validated against measured data. The data was obtained from two case studies, a large Tanker and a ROPAX ferry. The mean value/first principle (MV/FP) diesel engine model was further upgraded using the measured data. Correlations and validation of the simulation models (figure 6.1b) with the measured in-service data was on-going.

In the third project year the simulation tool for ship propulsion powertrain optimal configuration and performance was further developed, and was exploited towards emission reductions and improved propulsive efficiency. Various control and actuation strategies were investigated and tested in a validated simulation environment. The simulations for the Tanker case study achieved a reduction in fuel consumption and emissions (NOX and CO2) by 3%, and a further 10% reduction was achieved at the expense of lower service speed. The results from the simulations of the ferry case study revealed a possible 3 to 8% reduction in emissions, while maintaining the same ship speed, if the current configuration was optimised and a reduction of above 5% if the configuration was modified.

The overall achievements in the task involved, (a) a proved concept that propulsion train designs and their operation can significantly be improved with the use of a simulation based approaches, (b) a test bench was created for the evaluation of new or modified concepts and products, (c) readily available tools for both stationary and dynamic simulations, and (d) the fact that a reduction in sfc and emissions, in both case studies examined (ie Tanker and ferry cases) of about 3% and 5%, respectively, was feasible.

Task 6.2: Combined cycle with boiler for high pressure side

The objectives of this task involved the integration of a boiler in the 2-stroke diesel engine exhaust gas path before the turbocharger, as an integral component of the engine. An innovative compound system was to be designed in order to achieve a total efficiency of about 60% and a low capital cost, which would result from the reduced volume of the total configuration, in relation to conventional solutions.

The work in Task 6.2 involved the investigation of the integration of a boiler as an integral component of the engine, carried out by simulations and field testing activities. During the first project year two case studies for different ship types were investigated and these involved a combined cycle plant on a container ship and on a bulk carrier. The design of the boiler for the high pressure side of the engine was in progress, and the initial main layout for the test size boiler element was defined (figure 6.2a).

In the second year, a more detailed evaluation of the design criteria for the application of a boiler on the high pressure side of the exhaust gas turbocharger was carried out. The evaluation of the boiler basic design, water/steam path and exhaust gas path, with regards to pressure drop and heat transfer, was completed. Further work involved the design of full scale boiler element for testing, in combination with high pressure EGR on the 7MW test engine 4T50ME-X, in Copenhagen. The boiler was installed on the engine and more than 40 different tests were performed, forming the basis for the continued optimization of the boiler element design. A second test boiler element was designed and installed on the vessel Mathilde Maersk for confirmation of corrosion and erosion resistance in real operating conditions. The long
term test data that was acquired from measurements on-board the vessel Mathilde Maersk were analysed. Further work was carried out in the evaluation of design options for different applications such as EGR, WHR by-pass lines with power turbines (full scale WHR systems), and WHR by-pass lines without power turbines (WHR systems with only steam turbines).

During the third project year a new high pressure boiler concept was developed. Once the design of the boiler system was completed the testing was carried out at the research engine and onboard a container vessel. The new boiler system was also introduced as a test element in addition to a WHR system, and tested (figure 6.2b). The control system for the boiler was developed and constructed.

The achievements within the task were (a) a new, flexible basic boiler element made readily available for commercial application, where the boiler element could be used as both, an evaporator element and a super heater element, and (b) a high pressure boiler application that provided an increase in the system’s efficiency by about 60%, especially in connection with by-pass lines for power turbines or EGR and WHR systems.

Task 7.2: Tribology-Optimization

The objectives within task 7.2 were (a) to apply a piston ring tribology simulation code, with new friction and wear models and to improve understanding of tribological behaviour, (b) to design novel piston rings and use materials to reduce the overall friction of the piston ring package by more than 25%, without compromising wear rate and reliability, (c) to develop and apply advanced measurement techniques in order to assess piston ring performance under test rig running conditions, (d) to assess piston ring performance under controlled full scale running conditions, (e) to develop novel low friction guide shoe bearings, (f) to install on the engine and perform measurements on guide shoe bearings in order to verify friction and wear performance with long term testing / calculation, and (g) to reduce the overall friction in guide shoe bearing by more than 25%. In Hercules-B project Task 7.2 unlike the other tasks, was split into two parts, these being Task 7.2a and Task 7.2b. Both tasks are described in detail below.

In Task 7.2a the development and use of various test rigs led to the collection of experimental data which could be utilized in the implementation and verification of theoretical models, suitable for piston ring tribology simulation.

In the first year the conceptualization of full scale testing of piston ring tribology was investigated. Experimental data from the reciprocating test rig (RTR) for the piston ring friction investigation was made available. The development of a novel guide shoe bearing, running with lower frictional losses, was processed using a numerical model that was based on the tribological interface and on the experimental results from the RTR. Furthermore, the first set of experiments on the Block On Ring test-rig (BOR), for the evaluation of piston ring friction and wear, were completed. In addition, a parametric study and tests of the wear resistance at the piston ring and cylinder liner interface was initiated. The conceptual design of the guide shoe for low friction operation on large bore engines was completed providing an estimated friction reduction potential in excess of 20%.

In the second year tests were continued on the two test rigs. The investigations and the validations of the fundamental mechanisms of friction were completed. Further investigations were carried out on the RTR rig and involved tests at conditions that were closer to engine actual conditions. Such tests involved the use of a cylinder liner at elevated temperatures. The measured data from the rig tests was used for
correlations with the data from the simulation models. The second test rig (L16/24 test rig) was modified and more tests were performed (figure 7.2a(i)). The results from the guide shoe friction tests revealed that the 20% reduction in the mass of guide shoe system and the reduction of the outer dimensions lead to a reduction on frictional losses by 26%. In addition, a third friction test rig was under development. In the third project year considerable work was carried out on the reciprocating test rig, which was modified in order to run measurements of oil film thickness and frictional forces, simultaneously. In addition, the liner segment of the rig was honed at different geometries and results about the frictional forces were obtained. The simulations revealed that the friction in the piston ring pack could be reduced by 30%. Further work involved simulation work and tests carried out for the optimisation of the guide shoe bearing (figure 7.2a(ii)).

The overall achievements during task 7.2a involved (a) the gain of an extensive experience in understanding the tribological situation for the components examined, (b) the investigations and knowledge gained about different material combinations and surface structures for application to the piston ring and cylinder liner interface, (c) the development of numerical models, (d) the development of (i) a new low friction piston ring package that provided a 30% reduction of friction (simulated conditions), (ii) a new cylinder liner material and (iii) a new low friction guide shoe bearing with a 20% less weight that provided a 26% lower frictional losses, and (d) the fact that all three aforementioned components have already entered service conditions.

The second part of Task 7.2 involved the work carried out in Task 7.2b. Task 7.2b concentrated on extending further the knowledge in tribology in order to improve the performance of the piston. Experimental results were correlated with simulations of the lube oil film, and an optimized piston ring pack was designed with respect to service stability, improved friction properties and overall lifetime.

In the first project year investigations were carried out relating to the properties of different lube oils, piston ring materials and cylinder liner surface properties. In addition, existing simulation models, and more specifically sub-routines, were further developed. A test rig was built to evaluate the lube oil distribution (figure 7.2b(i)) and a piston ring pack was prepared to be used in field tests. During the second project year the test apparatus for the engine tests and for the tribo-test rig were developed. The results from the tests were used for the validation of a simulation model and the validation process was completed by extensive field tests. Engine tests were successfully completed and the evaluation was in progress. The investigation of materials was also completed, and the evaluation process was initiated. Finally, the long term field tests of the new piston ring pack concept were ongoing. In the third project year measurements were used into the novel simulation tool in order to enhance its prediction capabilities (figure 7.2b(ii)). The influence of gas dynamics was taken into account and this led to the development of a model for simulating ring twist. Furthermore, the hydrodynamic influence on the piston ring motion was investigated. Finally, the long term performance of the new piston ring pack was validated. It was demonstrated that improved material compositions increased the life time and improved the wear characteristics of the tribo system. Finally, a novel piston ring pack simulation tool was successfully developed.

Overall, the main achievements during this task were (a) the fact that testing approach demonstrated the feasibility of some new sensor applications offering “first time available” measurement results which provided new insights into the piston ring dynamic and led to an improved understanding of tribological aspects, (b) an improved simulation model in terms of enhanced prediction capabilities of key parameters
such as the piston ring motion, blow-by values and lube oil distribution, (c) an improved piston ring pack simulation model which yielded results that correlated extremely well with the measured data and can therefore be considered as a very precise tool to support piston ring pack development, (d) the fact that material investigations demonstrated the possibility of improving the wear characteristic of a tribo system considerably and (e) the field testing results that proved the enhanced performance of the investigated piston ring pack in terms of controlling the wear characteristics of the tribo system and increased considerably the life time of a cylinder unit.

Task 8.1: Advanced sensing and reliable adaptive control

The objectives during this task involved (a) the development of advanced signal processing methods for engine diagnostics with emphasis on knock, injector behaviour and diagnostics of fuel injection equipment, methods for increased reliability and performance, (b) the development of new design methods and architecture for increased reliability of electronics design, (c) the development of diagnostic methods and adaptive control schemes for engine control applications, where advanced control strategies improved performance and engine usability, with more detail in the development of a model based engine management scheme focusing in increased robustness and reduced number of adjustable parameters, and (d) the testing of prototypes on full size engines of the aforementioned developments.

In Task 8.1 different aspects of engine control systems were addressed, including both hardware and software. The engine performance, fuel consumption and emission levels of modern marine engines depend on the ability of the engine’s control system to perform its tasks in a robust and fault tolerant manner. Advanced signal processing methods for engine diagnostics were developed, along with new methods for improved reliability of the electronics involved.

During the first year several advanced signal processing methods were developed. These involved diagnostics of cylinder knock (figure 8.1a) diagnostics to identify the start-of-combustion and diagnostics of non-uniform fuel injections. These fault diagnostics were validated on both 4-stroke and 2-stroke applications. Furthermore, new design methods and architecture were developed to achieve increased reliability of the electronics comprising the control system. Finally, a speed-load controller applicable to 2-stroke engines was developed.

During the second year signal processing algorithms were designed for application in engine diagnostics. In addition, fault tolerant and adaptive control design and prototype testing were performed in areas such as the detection of liner scuffing, exhaust valve timing and IMEP calculations. Further work involved the successful evaluation of the Common Rail (CR) diagnostics on a test rig (figure 8.1b) and the successful evaluation of an adaptive waste-gate control for the Dual Fuel (DF) engine.

During the third year the adaptive control schemes were further developed, along with the hardware electronics that supported their functionality. The update involved the inclusion of monitoring the cylinder liner and the close loop cylinder pressure control. The method for detecting the start of combustion was field tested and factors that affected its accuracy were identified. Finally, the requirements and constraints for the development of safety critical system were investigated.

The overall achievements within the task involved (a) the development of measurement technologies and methods for in-cylinder pressure control, (b) the development of concepts for fault diagnostics for
common-rail fuel injection systems, (c) the development of a general purpose adaptive control method and, (d) the knowledge gained from the study of safety critical systems.

Task 8.2: Intelligent engine

The objectives within this task involved (a) the evaluation and verification of sensors for use in 4-stroke diesel engines operated with HFO, for monitoring NOx, O2 and in-cylinder pressure, (b) the development and evaluation of control strategies including suitable algorithms for the Design of Experiments (DoE), engine modelling and optimization, and (c) the evaluation of the functionality of the developed adaptive control system on the test-bed.

Task 8.2 described the development of a prototype of an adaptive engine management system. The main features of the new control system were to ensure engine operation at an optimal set-point (low fuel consumption and low emissions) at each point in time, unsupervised control map optimisation, and monitoring of all safety related measured values.

During the first year a detailed survey was carried out about engine performance and emission sensors that could provide continuous monitoring data for the engine management system. The most promising sensors were identified and approved for procurement, and also for further evaluation on the test bed. On the control system side, software and hardware components, along with various optimization algorithms, were investigated. Evaluation of direct and model based optimization algorithms were in progress and a new modelling technique was proposed. The hardware and software concept of the adaptive prototype was finished and programming had commenced.

During the second year, the NOx/O2 sensors were evaluated by performing engine tests and taking measurements at specified operating conditions (figure 8.2a). Different optimizations algorithms were implemented and evaluated. One of the algorithms of the prototype adaptive engine control system was finalised and was subjected to functionality evaluation within a typical test environment. 

In the third project year the model based optimisation algorithms were further researched (figure 8.2b). The online optimisation algorithms were tested in a simulation environment in LabView, as well as the offline algorithms. A detailed engine model was included in the simulation environment for improved accuracy. Different control strategies for engine map optimization were also developed. Furthermore, the overall intelligent engine management system was first tested in a simulation environment and then on the test bed.

Overall, the achievements within the task involved (a) the development and verification of a prototype adaptive engine control system generally capable for online-optimization of the engine’s characteristic maps, (b) the knowledge gained from the application of different optimisation methods, (c) the comprehension of how important the quality and reliability of sensors are, to the purpose of providing accurate input to an adaptive control system and, (d) the identification of the potential of optimising the engine cylinders individually.

Potential Impact:
Contribution towards impacts listed in the Workprogramme
The research objectives in HERCULES-B addressed the drastic reduction in CO2 emissions from engines in maritime transport, considering the existing and foreseen composition of the world fleet and fuel infrastructure. The principal aim in HERCULES-B was to reduce fuel consumption of marine diesel engines by 10% to improve efficiency of marine diesel propulsion systems to a level of more than 60%, and thus reduce CO2 emissions substantially. An additional concurrent aim is towards ultra low exhaust emissions from marine engines by the year 2020. Today diesel propulsion systems power 99% of the world fleet.

The HERCULES - B objectives are provided in Table 1 in terms of percentage changes related to current Best-Available-Technology in-service, for shipboard prime movers, with at least one installation reference worldwide in 2006.

The approach in HERCULES-B targeted the development of engines with extreme operational parameters in terms of pressure and temperature, considering the thermo-fluid-dynamic and structural design issues, including friction & wear as well as combustion, air charging, electronics and control, so as to achieve the efficiency / CO2 target. To achieve the emissions target, combustion and advanced aftertreatment methods was developed. To assess the whole powertrain, the interaction of engine with the ship, as well as the use of combined cycles in overall system optimization was considered.

The scope of the project included all the technology interrelations needed for a holistic approach to marine engine efficiency improvement and emissions reduction. Specifically, work was performed in the following areas:

• Development of extreme parameter engines.
• Thermo-fluid dynamics of combustion engine processes analysis and visualization.
• High pressure air charging with multistage, intelligent, variable-geometry units, with electric motor / generator coupling allowing engines with extreme values of operating parameters.
• Internal (in-engine) measures for emissions reduction as well as external measures (after-treatment of exhaust gases), scrubbers and filters. NOx reduction technologies based on exhaust gas recirculation and selective catalytic reduction when using heavy fuel oil.
• Higher diesel engine operating temperatures and advanced close-coupled boiler combined-cycle, with power turbines.
• Advanced metallic and composite materials for low friction bearing components for heavy duty, high wear or extreme load applications.
• Total ship economy issues, for overall energy and emissions optimisation of ship powertrains for various operating conditions and engine lifetime performance issues.
• Use of microelectronics and advanced optimal control for adaptive engines, with new primary sensors and analysis software for malfunction diagnosis and real-time monitoring, with self – learning for adverse operation and failure compensation.

At the end of the HERCULES project, the following GENERAL results in NOx and CO2 reduction had been achieved:

1. NOx (Measures are non-additive)
   50% reduction with Exhaust Gas Recirculation (EGR) (WP 5)
   90% reduction with gas aftertreatment via SCR – Selective Catalytic Reduction (WP5)
2. CO2 / fuel consumption (Measures are additive)
   10% with Waste Heat Recovery (WP6)
   1% with Advanced Control (WP8)
   0.5% with reduced engine friction (WP7)
   3% with ship-engine overall optimization during voyage (WP6)

3. In addition to the above results already achieved, the developments in
   - WP1: Extreme parameter Engines and
   - WP3: Turbocharging,
   will lead to an additional 2% reduction in CO2 / fuel consumption in future (2020) engines with higher
   operating parameters.

In addition, specific measurable / verifiable Objectives achievable within the duration of the project had
been set. The project delivered a number of prototype engines operating with improved efficiency and
reduced emissions, featuring one or more of extreme parameter operation, advanced emissions reduction
methods, advanced electronics, real-time in-cylinder combustion monitoring and control. The development
was supported by design, simulations and experimental work on purpose-made state-of-art test rigs.
 Certain specific new technologies developed, were demonstrated onboard new-built ships, as Validation
 Platforms in a real operating environment.
 Therefore, the Project HERCULES-B addressed with authority the challenges of The greening of surface
 transport in the area of maritime transport.
 In specific the HERCULES-B project contributed directly to the individual Expected Impacts included in
 the The greening of products and operations.
 (1... Contribution to CO2 reduction emissions from surface transport operations aligned with Kyoto targets.
 For road transport research will aim by 2020 at a 40% CO2 reduction for new passenger cars and light-
duty vehicles and 10% for new heavy-duty vehicles (both based on 2003 figures)....)
The principal objective of HERCULES-B was improvement of the efficiency of marine internal combustion
engines. This is directly correlated to CO2 emission reduction. Marine diesel engines are today the most
efficient thermal powerplant with 50% thermal efficiency. A 10% improvement in overall powerplant
efficiency was achieved in HERCULES-B. The combination of CO2 / fuel consumption measures may
increase this to 15% improvement in total in the future.

(2... Reduction of exhaust and local emissions in view of the compliance with future legislation at European
and international levels and to allow national and local authorities meet their air quality engagements....
The second principal objective of HERCULES-B was to reduce all other gaseous and particulate
emissions from marine diesel propulsion system to levels always below the (expected) future international
legislation for marine powerplants.
A reduction of up to 90% of NOx emissions via aftertreatment was achieved in HERCULES-B.

European Added Value and Strategic Significance

Marine diesel engine developments require a multidisciplinary approach and has traditionally been an area
where Europe leads the world.
Based on the successful results of the FP6 Integrated Project I.P. HERCULES (A), by a consortium of 42
organizations, led by the two world leading European marine engine manufacturer company groups, MAN
and Wartsila, it was agreed to proceed to the second phase of the work, already conceived in 2002,
refining the targets and emphasizing fuel efficiency in parallel to emissions reduction.
In the HERCULES-B consortium, the two major partner groups cover together about 90% of the world’s
marine engine market (medium- and low-speed engines). All the other industrial partners are top
companies in the world market, with several of these industrial partners being the world’s leader in their
field.
The Research Institutes and University Laboratories are renowned worldwide for research excellence in
their field.
The tie-up of these European world-leading Organisations and the integration of research capacities, in a
project of such magnitude and long term scope, aiming at specific objectives with strategic impact of
global significance, exemplify the European dimension of cooperative R&D research excellence.
The main European added value of the HERCULES Programme is that in no previous occasion a grouping
of this magnitude has been assembled in marine engine RTD, pooling scientific / technological capacity
and material resources and large-scale experimental facilities, with a common vision in developing ultra-
low emissions efficient marine engines. In the majority of cases there have been previous bilateral
cooperation links between partners, but it is important to note that 16% of the partners participated for the
first-time in a shared-cost RTD proposal for European Community support.
Cutting edge research networking is inherent in the project, since there was 7 large-scale engine test
facility sites, 11 University Laboratories and 5 Research Institutes taking part in the Project.
The strategic significance of HERCULES-B was primarily in three areas
1. Preserving and improving the competitiveness in an area of European Industrial supremacy and
success, namely marine propulsion engines.
The participation of the two major European Marine Engine manufacturing groups which together hold
90% of the world marine engine propulsion market, cooperating with major component suppliers,
reinforced the position of these companies in the world market.
By collaborating in R&D both with competitors and cooperating firms, within an appropriate structure and
with management systems in place to guarantee control over the outcome, firms could derive large mutual
benefit, towards retaining their market position.

2. Reducing air pollution from ships, benefiting society in general.
The vision of HERCULES, of drastically reducing emissions and at the same time increasing of engine
efficiency and thus reducing of CO2 emissions, will potentially affect the vast majority of ships (new-
buildings and through possible retrofit technology also existing ships). It will therefore have a significant
societal implication of worldwide effect.

3. Improving shipping industry competitiveness through marine engines of reduced fuel consumption.
Europe is both the greatest user and the most important provider of shipping services, with a beneficially
owned fleet representing around 35% of world tonnage. The functioning of international shipping is
therefore of major importance to the European shipping industry and to Europe as a competitor and
consumer in world services and products markets. In terms of external trade, 90% of total exports of the
European Union is transported by sea.
One major ship operating cost is in the engine fuel cost, which may be 60-80% of the total life cycle cost of
Thus, the vision of HERCULES to increase marine engine efficiency, hence reduce fuel cost, complies with the users demands and will improve the shipping industry competitiveness.

Exploitation of project results

HERCULES-B is an interdisciplinary RTD project of wide thematic spectrum, since engine development requires parallel progress in many technological fronts. The project is consolidating the breakthroughs and the technologies proven successful in I.P. HERCULES (A) and is considering further potential breakthroughs in several technologies.

Innovations within HERCULES can be widely classified in 3 categories.
1) Basic scientific concepts or primary technology
2) Component or system prototypes
3) Prototype application test installations

Some of the areas where innovations were made in the HERCULES-B Project are:
- Power cylinder technology for “extreme” mechanical and thermal load in marine engines
- In-cylinder measurement, observation, visualization methods for large engines
- “Intelligent” variable geometry, multistage, power assisted turbochargers
- Exhaust gas recirculation, scrubbing and aftertreatment methods in heavy-fuel engines
- New sensors and emission measurement methods for large engines
- “Low-friction”, low wear, piston ring and guide shoe materials for engines.
- “Adaptive” control of marine engines

The Table 2 provides an overview of the potential exploitation items stemming from the RTD work within the various Workpackages and also an indication of the time span (short/medium/long) to exploitation.

Already some of the developments above have been turned into new products.
From Task 3.1 High efficiency and low emission Turbocharging concepts, results have been incorporated in the two-stage turbocharging technology on Wartsila commercial engines.
From Task 5.2 Emission reduction – Exhaust gas recirculation and aftertreatment results have been incorporated by MAN in a commercial aftertreatment system for the removal of >80% of NOx.
From Task 7.2.a Tribology-optimisation, a low friction guide shoe design offering 26% less friction and 20% less weight has already been installed in service with large bore MAN engines. Further, a new liner material emanating from this Task have been used in service for 4 MAN engines, with 16 more engines in the pipeline.
In Task 8.1 Advanced sensing and reliable adaptive control, results in the form of new control strategies have been developed for load-sharing techniques between gen-sets and are now applied on Wartsila production engines. Further, methods for cylinder-pressure control which enable optimal control of combustion, as developed in this Task are now applied on Wartsila production engines.

Dissemination
The project official public website (www.hercules-b.com) contains a complete description of the structure of the project and also:
• Presentations and 6-monthly progress updates per Workpackage / Task
• Presentations of Achievements and major results
• Papers in Conferences and Publications in Journals
• Articles and Publicity in the Technical Press and Media.

The public site had an average of 50 external visits per day in 2011.
A large number of articles were written in the trade and popular press and several press releases were presented in the press.
More than 30 scientific papers were presented in peer reviewed in conferences and journals.

List of Websites:
http://www.hercules-b.com

Related documents


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