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THE CONSTRUCTION TYPES EVOLUTION OF INTERNAL COMBUSTION MARINE ENGINES

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Abstract: *Diesel engine has dominated the commercial ship segment since the first powered ships (1912). Improvements over time, of which we mention the transition to two-stroke cycle („Sulzer" – 1905), the introduction of scavenging (1910), adopting turbo charging („MAN" – 1950), direct coupling with the propeller (~1980) and also the constructive modifications determined diesel engine propulsion systems to maintain supremacy in the field, by economy, simplicity and reliability. Low-speed engines with electronically controlled fuel injection and hydraulic drive systems of the exhaust valve are entering service in increasing numbers, opening the way to future automated control engines that reaches powers up to 90,000 kW.*

Since the working principle of diesel engine remains unchanged, the main objective of development is heading towards an improvement of the low-grade fuel combustion ability (without compromising reliability and quantity of exhaust gas emissions) of the turbocharger efficiency, lubrication systems but also of the diagnosing, monitoring and computer aided automation systems. Management programs of maintenance operations and exchange of parts have also an important role in the extension of the period between overhauls and the operating costs reduction.

1. THE FIRST MARINE DIESEL ENGINES

The *diesel* engine has dominated the commercial ship segment since the first powered ships (*1912* – the cargo/passenger ship *"Selenadia"* powered by two Burmeister & Wain engines, four-stroke 8-cylinder with 530 mm bore and 730 mm stroke, each developing 920 kW at 140 r/min).

The oldest powered ship was the 678 tons *"Romanga"* with two propellers, built in 1910 by *"Cantieri Naval Riuniti"* having two four-cylinder Sulzer engines with scavenging windows. Each engine was providing a power of 280 kW at 250 rev/min, with a bore of 310 mm and a stroke of 460 mm. The Anglo-Saxon tank ship *"Vulcanus"* of 1189 DWT with a single propeller, powered by a 370 kW four-stroke cross-head 6-cylinder engine with a 400 mm bore and a stroke of 600 mm was put into service in 1910. Dutch ship builder was *the first motor ship wich received the Lloyd Register of Classification approval.* Between the two world wars, the use of combustion engines in ocean fleet has expanded from 1,3% to *25%.* By 1939 an estimated rate of *60%* of completed vessels in the world's shipyards, included *motor vessels,* compared with only 4% in 1920.

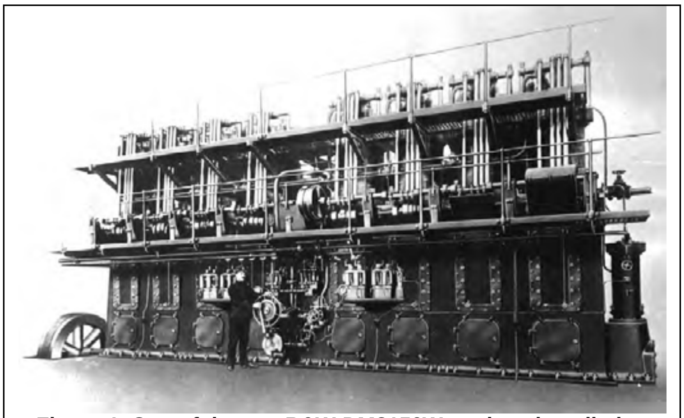


Figure 1. One of the two B&W DM8150W engines installed to propel the first "Selandia" (MAN B&W Diesel)

In late 1920 *the largest engines were the 5-cylinder Sulzer models* with bore of 900 mm (80 kW at 3429 r / min) built under license by *John Brown* in the *United Kingdom*. These S90 engines were specific to the three Rangitiki-class ships with two propellers, since 1929.

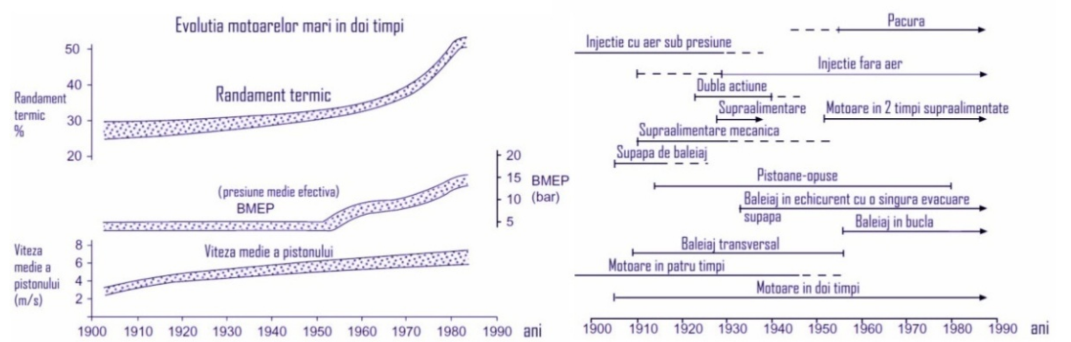


Figure 2. Evolution of large two-stroke engine during 1900-1990

2. INNOVATIONS AND IMPROVEMENTS IN NAVAL DIESEL ENGINE

The adopting of *two-stroke cycle* by Sulzer in *1905* greatly increased engine power. *Scavenging*, introduced in *1910*, eliminated the need for gas exchange valve in the cylinder head to create a simple concept, without valves, which characterized two-stroke Sulzer engines for 70 years (the switch to *uniflow scavenging* came only with RTA-series engines in 1982, because their very large stroke - necessary to obtain a high efficiency of the propeller at lower engine revolutions - was inadequate for scavenging without valves). Testing technology through *research engines* had a very important role in exploring the potential of thermal efficiency and concentration of power.

	RTX-3	RTX-4
Model	4RT-flex58T	4RT-flex60
An instalat	1995	2008
Alezaj (mm)	580	600
Cursa (mm)	2416	2250
Raport cursa/alezaj	4.16	3.75
Cilindri	4	4
Viteza nominala (rot/min)	105	114
Viteza medie a pistonului (m/s)	8.5	8.6
Presiune medie efectiva (bar)	19.5	21
Presiune maxima cilindru (bar)	150	168
Putere/cilindru (kW)	2125	2540
Putere efectiva (kW)	8500	10160

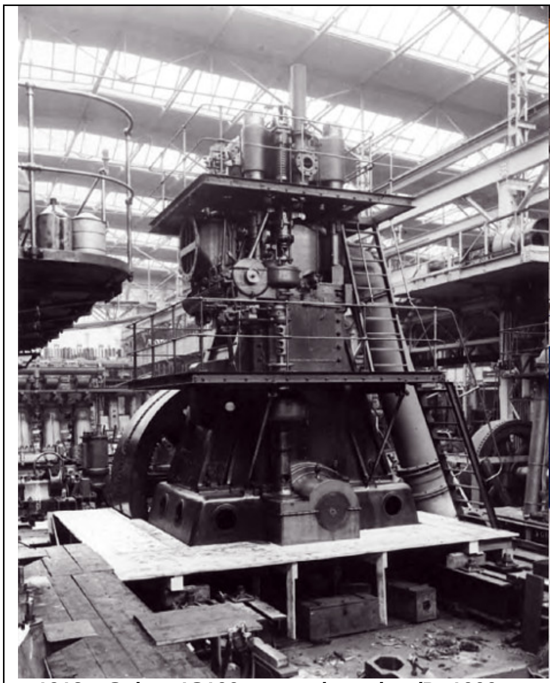
Figure 3. Wärtsilä research engines

Also, the importance of *reducing pollutant emissions* at increasingly smaller limites was also studied in the researches on RTX-4 engine's exhaust (late injection of fuel, fuel emulsification and air humidification system or the use of Selective Catalytic Reduction sytem - SCR - unit capable of reducing NOx emissions to the atmosphere by more than 90% of the level measured at the engine exhaust).

A *major factor* for power increasing and reducing the size and weight of engine, was the adoption of *turbocharging*. Pressure boosting in various ways has been adopted by most engine manufacturers during 1920 - 1930 to ensure an appropriate scavenging: crankshaft driven air pumps, side mounted pumps driven by crosshead levers, blowers and attached or independent type pumps.

Swiss engineer Alfred Büchi, considered *the inventor of the* exhaust gas *turbocharger*, was granted a patent in 1905 and conducted his first experiments at *Sulzer Brothers* in 1911/1915. It has been almost *50 years* after the first patent, until the principle could be applied satisfactorily to large two-stroke marine engines.

Towards the end of 1929, the injection of air-fuel mixture at diesel engines, of which Rudolf Diesel himself wasn't very pleased (the need of a large compresor, with high pressure, often problematic and increased energy consumer, a 15% loss of engine power output to drive the air pump) *was replaced* by *injection without air* (without compresor).



1912 – Sulzer 1S100 research engine (D=1000 mm; S=1100 mm; Pe=1479 kW at 150 rot/min.); 1S1000 research engine's bore was not surpassed by any other Sulzer motor until 1968.

2008 –Wärtsilä's RTX-4 research engine from the Diesel Technology center in Winterthur , Switzerland (D=600 mm; S=2250 mm; Pe=10160 kW la 114 rev/min.).

Figure 4. One cylinder research engine

In 1950/1951 *MAN was a pioneer in testing and introducing high-pressure turbocharge*r for medium speed four-stroke engines, for whom the pressure was increased to 2.3 bar. The increasing efficiency of turbochargers and auxiliary equipment development in the mid 1950s, have made possible *the introduction of supercharging systems for large two-stroke engine* manufacturers. They exploited *a common basic configuration: two-stroke cross-head engines*, with *uniflow scavenging* through a single exhaust valve in the cylinder cover, *hydraulically operated,* constant pressure supercharging, exploiting an increasingly higher stroke/bore ratio (up from 4.4:1) and low operating speeds for direct coupling to the propeller.

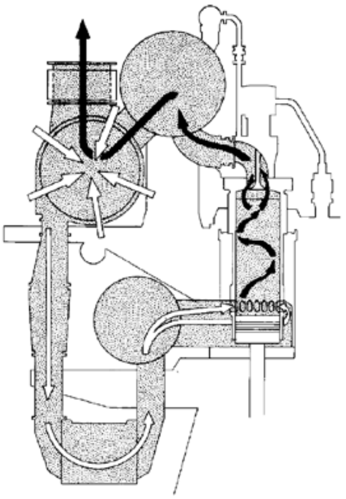


Figure 5. Uniflow-scavenging Burmeister & Wain system.

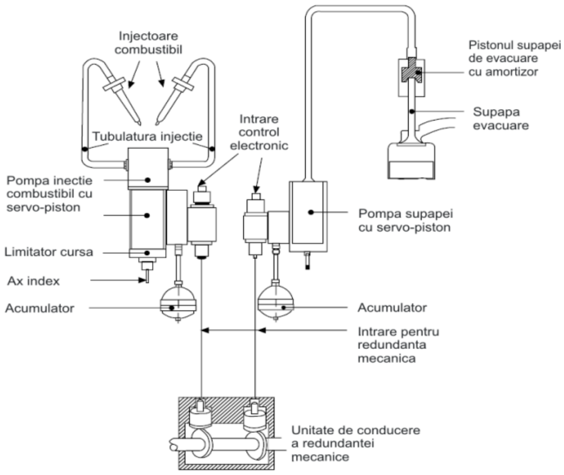


Figure 6. Electronically controlled hydraulic injection and exhaust valve actuation of the 4T50MX research engine from MAN Diesel.

Bores ranged between 260 and 1080 mm with a number of 4 to 14 cylinders and nominal speeds between 55 rev/min and 250 rev/min. The *long supremacy of propulsion systems directly coupled to the engine* (cross-head) reflects the *economy, simplicity and reliability*.

All engines now have *electronic control systems* for *fuel injection* and *exhaust valve actuation* although some manufacturers still maintain the mechanically controlled camshaft models.

Low specific fuel consumptions of up to 154 g/kWh are reached for models with large bore, where the economics can be improved with *turbine systems that exploits the surplus energy of the exhaust gases*. The low-engine performances development, with bores of ~ 600 mm, is shown in Figure 7.

In mid 1990 both Wärtsilä and MAN Diesel (Sulzer) *raised the upper limits of their power*, by introducing models with *large bores* - respectively 980 mm and 960 mm bore - dedicated to *a single propeller propulsion system* of the new ships generation, 6.000 TEU container ships with service speeds of 25 knots or more. The 12-cylinder version of the current MAN B&W K98ME design, providing 74.760 kW, reveals productivity advances achieved since the 1970s, when the 12 cylinder equivalent B&W K98GF engine produced only 36.800 kW. Wärtsilä has improved the RTA96C's design features with 4% up to 5720 kW/cylinder at 102 rev/min, and introduced a model with *14 inline-cylinders*, offering up to 80,080 kW (the maximum power until then had been 65.880 kW, from a 12-cylinder model).

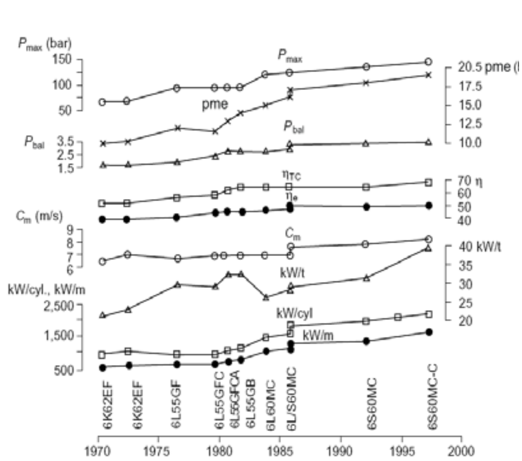


Figure 7. The key parameters evolution of low-speed engine performances (~ 600 mm bore) for a 30 years period (MAN Diesel).

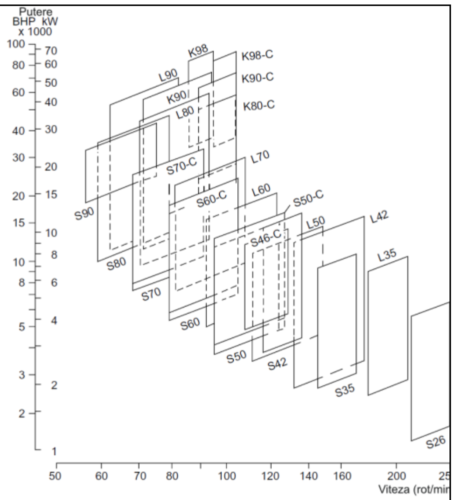


Figure 8. The development program of MAN B&W MC series engines.

The 14RT-flex96C debut engine (80.080 kW at 102 r/min) was finished by Wärtsilä licensees - Hyundai Heavy Industries - in 2007 to equip the first ship of a 8600 TEU container -ship series.

MAN Diesel has *answered the challenge* with a *14-cylinder* versions of K98MC and MC-C models, providing powers up to 80,080 kW at 94 rev/min or 104 rev/min, which were replaced with 14K98ME electronically controlled model that produces up to 87.220 kW at 97 rev/min with a mean effective pressure of 19.2 bar. The first such engine - a version of Mark 7 with *84.280 kW* nominal power at 104 rev/min, *the most powerful diesel engine available at that time* - was expected for delivery in 2008 to equip a container ship.

Specific power limits were raised up to 6950 kW/cylinder by MAN B&W MC/ME two-stroke diesel engines, with a 1080 mm bore. A single 14-cylinders model can provide up to *97.300 kW* for the propulsion of the largest container ships designed, with speeds over *25 knots* (in 1970 the largest container ships required usually two 12-cylinder slow-engine, which develops 61.760 kW).

The continuous *improvement of research programs* for MAN B&W MC and ME slow-engines, and the *development of automated engines* are made at the *R&D* centre adjacent to the group's *Teglholmen* office and factory in *Copenhagen*. In its center is the research engine *4T50MX*, an advanced testing facility, which exploits an unprecedented stroke/bore ratio of 4.4:1. Although the four-cylinder engine with 500 mm bore and stroke of 2200 mm is based on current MC series, it is designed to operate at a nominal mode and combustion pressure higher than any other two-stroke production engine available in present. A power of 7500 kW at 123 rev/min was introduced as an initial reference level for the measurements of performance, temperature components and stresses, combustion characteristics and exhaust emissions, noise and vibrations.

The key parameters measured at this power were equivalent to 180 bar combustion pressure, 21 bar mean effective pressure and 9 m/s piston's medium speed.

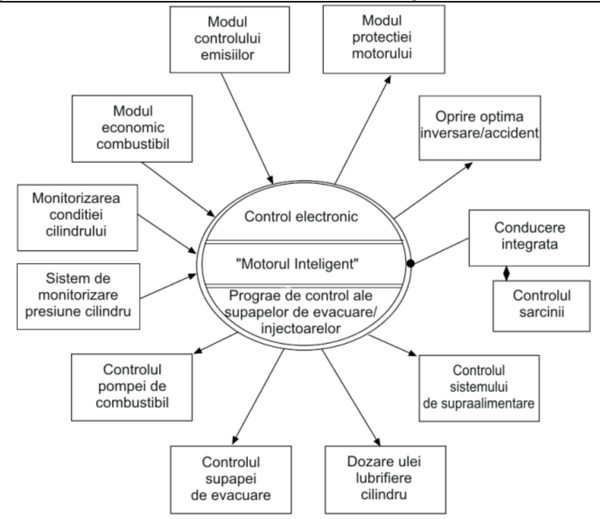


Figure 9. Schematic diagram of "intelligent engine" (MAN Diesel)

MAN Diesel explains that, in order to achieve the objective of *safety and operational flexibility* it is necessary to *change the fuel injection timing* and the *exhaust valve actuation system*, *while the engine is running*. To achieve this objective, by means of camshaft driven systems, is required a substantial complexity in terms of mechanics, which would affect engine reliability. So it *is required an engine without the traditional camshaft*.

The automation system can actively protect the engine against damage caused by overload, lack of maintenance and improper adjustments. The monitoring and evaluation system is an on-line system with automatic sampling of all engine performance data, supplemented by measurements of pressure in each cylinder. The system will report and intervene when performance parameters indicates unsatisfactory deviations. Cylinder pressure data provided by the measurement system is used for different calculations.

The concept is illustrated in Figure 9, whose upper part shows the operating modes that can be selected in the deck control system or by the automatic control system of the engine. The central part shows the "brain" system: electronic control system which analyzes the overall condition of the engine and controls the operation of auxiliary systems shown at the bottom of the diagram (fuel injection, exhaust valve, cylinder lubricating oil and the turbocharger system).

The *thermal efficiency* of the engine was raised to *over 54%* and, at the same time, the *propeller efficiency* was considerably improved due to minimum engine speeds of up to *55 rev / min.*

Several other *innovations and enhancements*, in order to extend the operating time, the period between overhauls or maintenance operations, and to reduce operating, maintenance and repair costs, would be:

- a *cleaning segment* built at the top of the cylinder liner now controls the upper piston deposits, to prevent the elimination of lubrication oil from that area (Figure 10.);

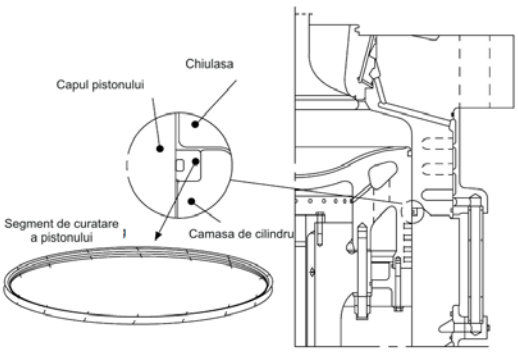


Figura 10. Localizarea segmentului de curatare a pistonului

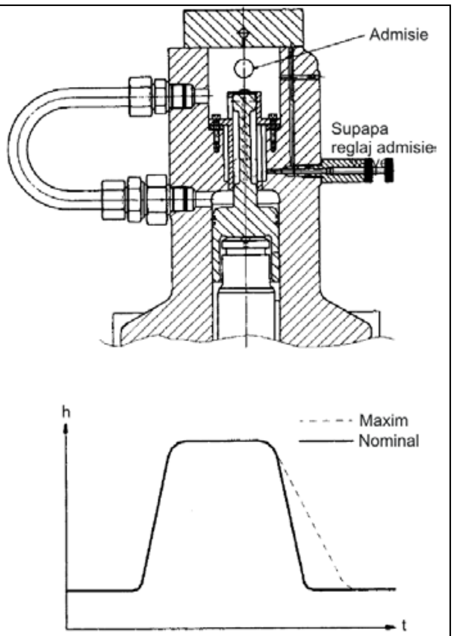


Figura 11. Sistem mecanic/hidraulic de modificare a raportului de comprimare (MAN Diesel)

- *a fuel injection system with three valves* instead of two that cause a more uniform temperature distribution around the main components of the combustion chamber and overall lower temperatures, despite the higher weights (also ,the temperature of exhaust valves and valve seat is lower);
- *a system that maintains a constant combustion pressure* in high-load range by adjusting the variable injection pump and by variating the compression ratio (Figure 11), the latter is obtained by changing the closing time of the exhaust valve;

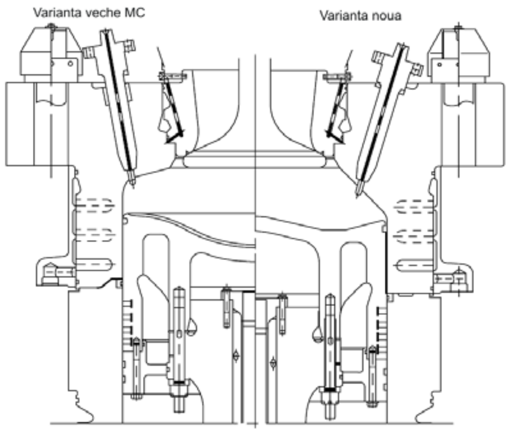


Figure 12. The new MC model of the engine combustion chamber

- *structural changes* to the engine block and plate framebox (Figure 16), to the cylinder liner (Figure 15) and combustion chamber (designed for the new large bore engines, Figure 14);
- *the opportunity of heavy fuel combustion*, progress which has been boosted at mid-1950 by the posibility to neutralize the acid products of combustion by the cylinder lubricants and therefore reduce the wear rate compared to burning diesel fuel; all low-speed two-stroke engines and many medium-speed four-stroke engines are now operating with low-grade fuels of up to 700 cSt/50°C viscosity;
- *reduced fuel consumption* is achieved either by optimizing the fuel injection characteristics depending on load conditions (while a conventional engine is optimized for the task of 90-100% MCR) or by maintaining a constant maximum Pmax pressure upper the engine load; as a result, the maximum pressure can be maintained constant over a wide range of load without overloading the engine (Figure 13);
- *the reducting consumption of cylinder's lubricating oil* - which represents an significantly annual cost, especially for large bores engines - was achieved by introducing *high pressure electronic lubricating system* (important task for the research center R & D which developed in 1997 the Alpha lubrication system, and the prototype was installed next year on a 7S35MC motor); the purpose of this system is to inject oil into the cylinder at exactly the right place and time;

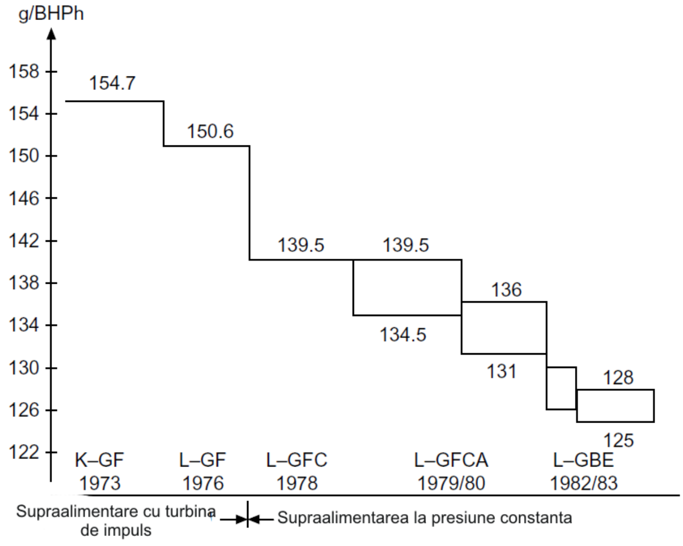


Figure 13 The evolution of specific fuel consumption of Burmeister&Wain two-stroke engines with uniflow-scavenging (900mm bore models)

- The implementation of *quieter* engine and auxiliary equipment *compartments*;
- the *piston rings* were also *reconfigured* (Figure 17), and the manufacturing/treatment materials improved (Figure 18);

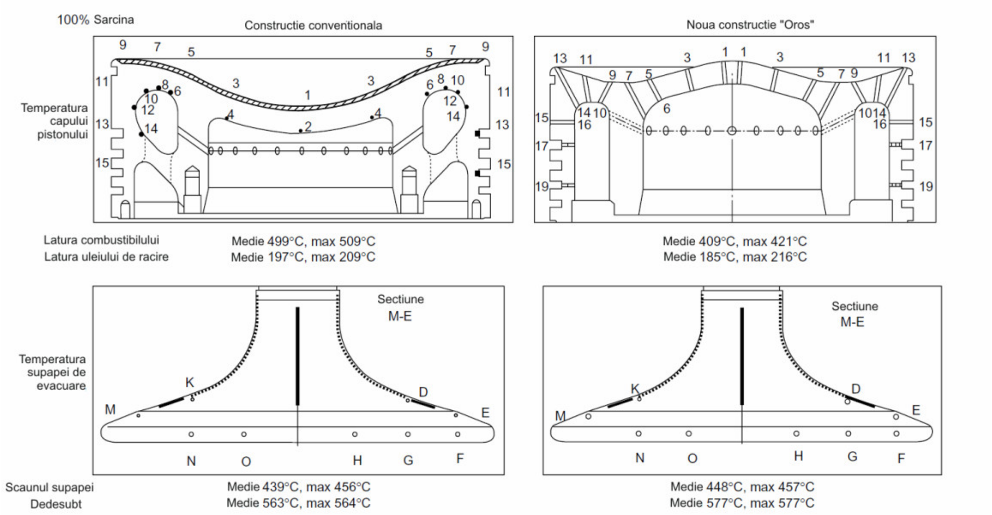


Figure 14. The new "Oros" form geometry (right) of the combustion chamber helped reducing the measured temperatures

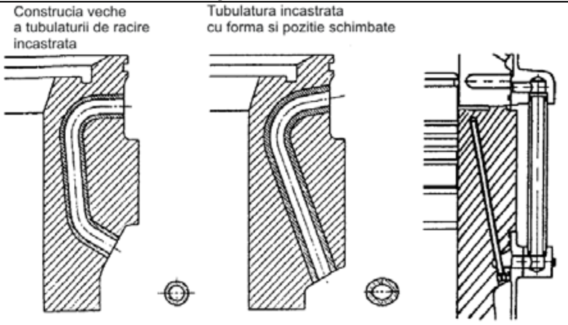


Figure 15. Modifications to the MC engine cylinder liner cooling.

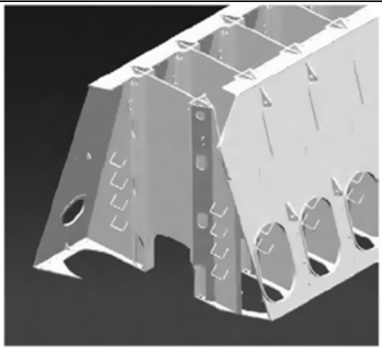


Figura 16. A triangular plate framebox

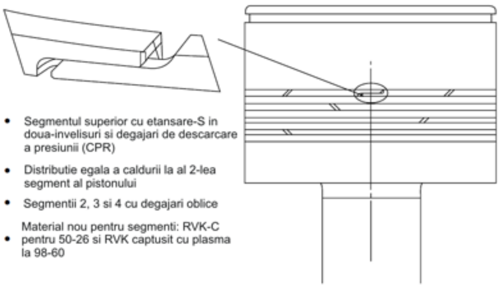


Figure 17. Configuration of upper piston ring

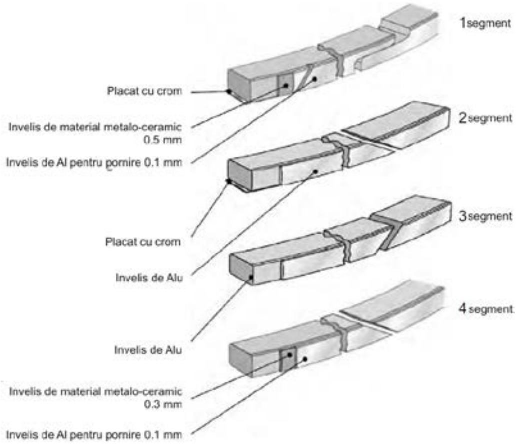


Figure 18. Piston rings with treatments/coatings

3. CONCLUSIONS

It is *difficult to predict* if the diesel will be threatened by *new engine types* but any changes demanded by the use of *cleaner fuels* (liquid or gas) could promote the well-known rivals such as *gas engines and gas turbines*.

Until now, the diesel engine is up to the challenges coming from nuclear propulsion (steam) and gas turbines. Yet the both have found applicability, respectively in warships, and gas turbines in fast ferries and cruise ships.

Rising *fuel prices* (although the use of gas turbines in parallel with diesel is still a solution for high power installations) and *diminishing fossil fuel resources* accentuated the problems of gas turbines, and this fact can still bring back into use the *nuclear propulsion* systems, in the long term.

A valuable support will continue to come from *specialists in turbocharger*, *fuel treatement*, *lubrication*, *automation*, *materials improvement*, *diagnostic/computer-aided monitoring systems* and as well from *maintenance and overhauls management programs*.

The main *objectives of development* are heading towards an *improvement in the capacity of burning low grade fuels* (fuels derived from coal and oil residues), in *increasing durability* of components and *extending of periods between overhauls*, lowering production and installation *costs* and *simplifying* operation and routine maintenance, without compromising *reliability* and the *exhaust emissions* amount.

(D=960 mm; S=2500 mm; Pe= 5720 kW/cilindru)

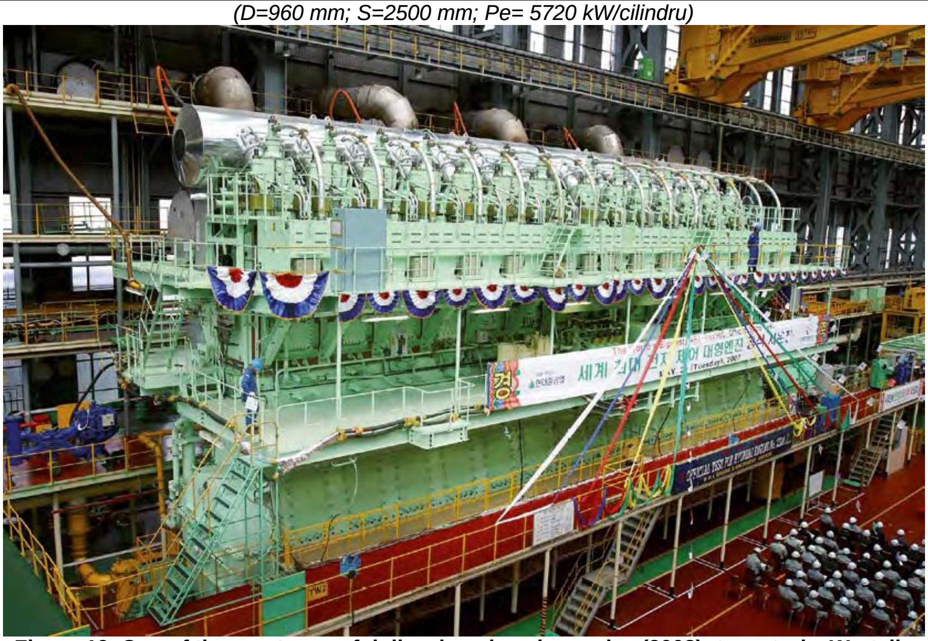


Figure 19. One of the most powerful diesel engines in service (2008): two-stroke Wartsila RT-flex96C low-speed engine, with 14 cylinders, which develops 84.420 kW (Hyundai Heavy Industries)

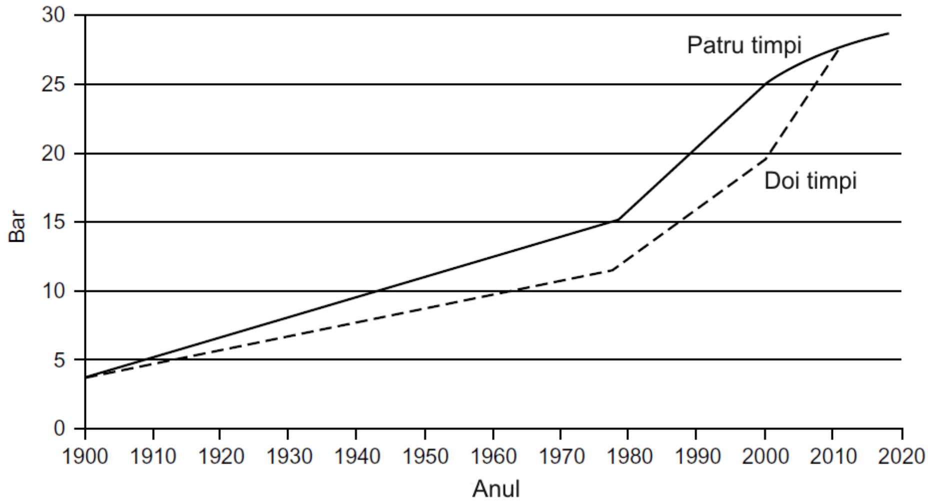


Figure 20. Estimated development of mean effective pressure for the four-stroke and two-stroke diesel engine (Wartsila Corporation)

4. REFERENCES:

[1.] Pounder's Marine Diesel Engines and Gas Turbines (9th Edition) – Woodyard, Doug © 2009 Elsevier.