Opposed-Piston Engine Renaissance

Power for the Future

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Background; Paradigm Shift

Diesel 2-stroke opposed-piston engines, known as "OPEs" or "OPs", are substantially simpler, more compact and have lower weight than equivalent powered 4-stroke engines. OPEs are characterised by use of pairs of pistons operating with opposed motions in a common cylinder without need of a cylinder head (Fig.1) and, therefore, avoid the thermal losses, cost, complexity and durability issues of 4-stroke cylinder heads and poppet valvetrain. Induction and exhaust processes are through ports (Fig.1) located in opposite ends of the liner, thus allowing a very thorough purging of the cylinder. The combustion chamber is formed by the two piston crowns in the centre of the cylinder liner, with injectors located on the side of the cylinder liner. Various arrangements have been used for connecting and driving the two opposed motion pistons, all providing perfect or near perfect balance, some also having zero cyclic torque recoil, and some also avoiding load transmission into the crankcase.

Opposed-piston engines have been manufactured successfully since 1890 in Germany, USA, U.K., France and Russia; they have been used globally and extensively for ground, marine and aviation applications. Though emissions regulations in the 1970s lead to the demise of many 2-stroke engines, current and future emission laws and their impact on engine fuel efficiency have paradoxically prompted a re-examination of OPEs because of their potential

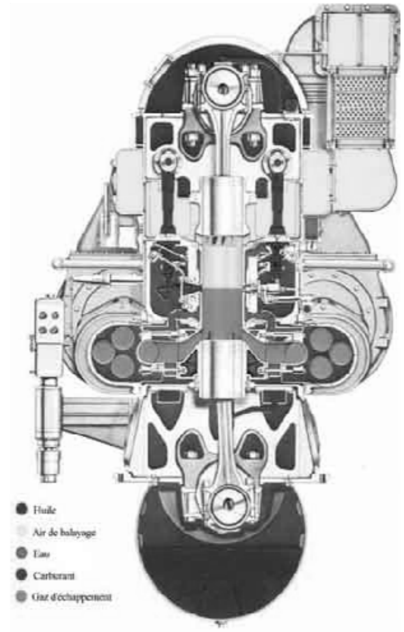

Fig.1 Fairbanks Morse OP Diesel Engine Cross-Section

thermal efficiency, potential low emissions, power density and cost advantages versus the emission compliant four-stroke diesel, particularly for transport applications.

The OPE configuration is extremely flexible in terms of hardware architecture, ranging from pairs of pistons in a common cylinder linked by geared crankshafts (Fig.2), as used in the record-breaking Junkers Jumo 205 and 207 aviation engines from c1930-1945,

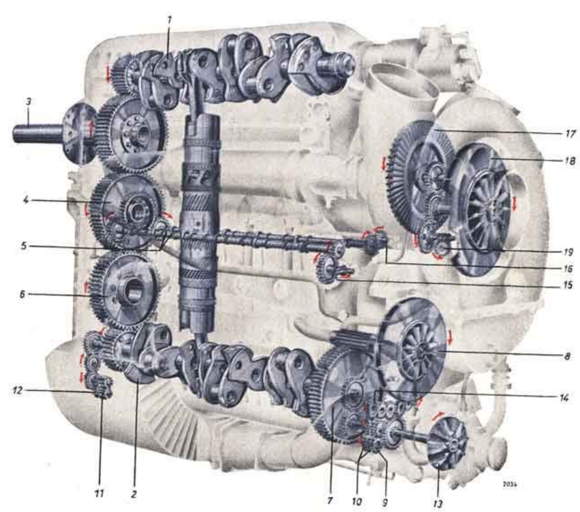

Fig.2 Junkers Jumo 207C Ghosted Image of Drive Train

and the Rolls Royce K60 military engines (1955-current), to the single crankshaft "folded" crank-train of the Rootes TS3 engine (Fig.3) of which ~ 50,000 were manufactured in the U.K. for the iconic Commer truck between 1954-1972.

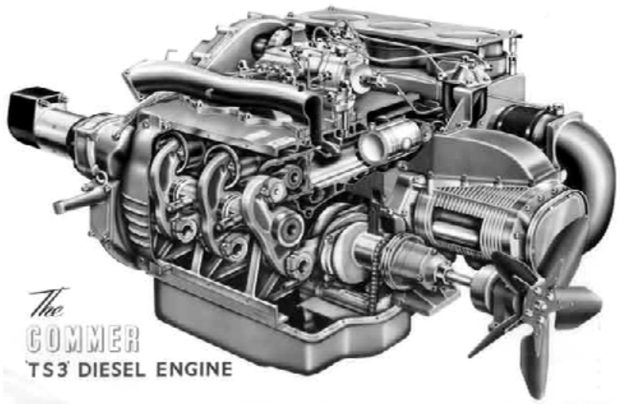

Fig.3 Commer TS3 OP Diesel Engine

Larger OP heavy-duty applications include the Napier Deltic with three crankshafts linking three pairs of pistons in three cylinders arranged in equilateral triangular cylinder configuration (Fig.4).

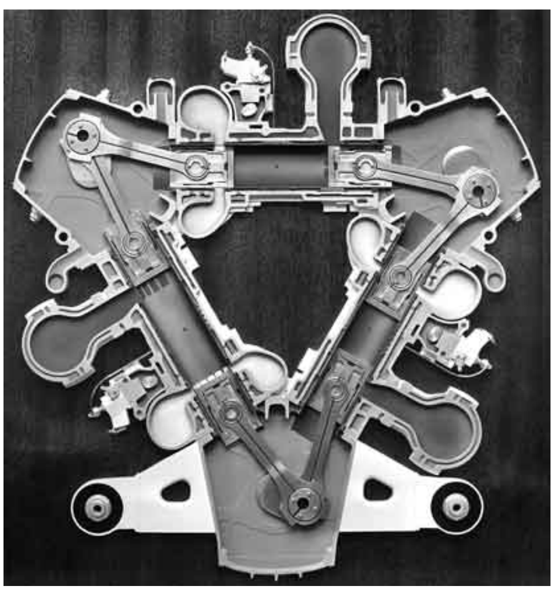

Fig.4 Napier Deltic OP Diesel Engine – View of Cylinder Configuration

The Napier Deltic engine propelled high-speed passenger trains over a period of 20 years and was fitted (1954-current) to many naval fast patrol boats (Fig.5) and vessels.

The Fairbanks Morse 38D8⅛ (Fig.6) with two crankshafts, originally used for U.S. submarines c1936, was subsequently fitted to many of the WW 2 Liberty ships, and is now used in small marine freighters and stationary applications and also as emergency propulsion on U.S. nuclear submarines. The basic design remains unchanged since 1934.

Towering above these OPs are the Doxford cathedral style marine engines (Fig.7) with a single crankshaft (Fig.8), delivering up to 20000 bhp at 115 rpm and powering a wide range of ships from 1920-1990.

Fig.5 U.S. Navy Fast Patrol Boat – with Napier Deltic OP Diesel Engines

Fig. 6 Fairbanks-Morse OP Diesel Engine.

The Doxford crank-train, with its long outer connecting rods to the outboard piston was derived

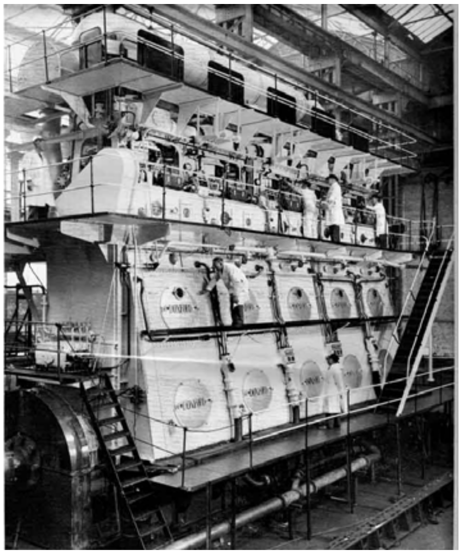

Fig.7 Doxford OP Ship Engine on Test Bed

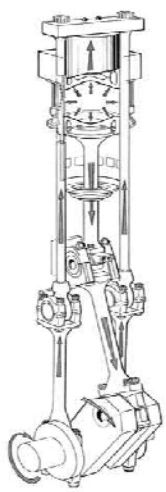

Fig.8 Doxford Piston, Con-Rod and Crankshaft

from early Junkers engines of c1900-1910.

Opposed-Piston Engine Advantages

OP engines evolved because of their ease of manufacture, excellent balance, even in single cylinder form, and competitive performance and fuel efficiency compared to leading-edge 4-stroke engines, all these aspects being realized from the early development period of the 1890s to this day. With the progressive development of the OPE from 1900-1970, other significant advantages emerged, notably simplicity, compactness, high torque capability and ease of servicing, which are all important for mobile use. Complementary benefits of the OPE are lower heat to coolant, enabling smaller radiators, excellent reliability, proven longevity and outstanding multi-fuel capability for gasoline, kerosene and diesel-based fuels as well as gaseous fuels, as demonstrated with several military engines and the Fairbanks Morse 38D8⅛ (Ref.1).

The evidence for these OPE engine performance advantages can be seen in comparative performance metrics. Appendices 1 and 2 show the relative specific outputs per unit displacement and per unit weight of OP engines versus four-stroke diesels from 1900-2010, indicating a clear OPE advantage.

The leading trends for brake thermal efficiency of OPE (Appendix 3) and 4-stroke engines show that for many years the OPE exceeded the 4-stroke efficiency. The main reasons for the unique OPE thermal efficiency characteristics are:

- Minimal combustion chamber surface area /volume ratios with acceptable bore/stroke, thereby reducing combustion heat to the cylinder walls.
- Crank-train optimisation can be used to reduce scavenge air losses and achieve some supercharging.
- Compatibility of long strokes within limiting mechanical rotational speeds; the long strokes help cylinder scavenging, fresh air filling, brake thermal efficiency, air swirl motion and, indirectly, reduce the loading of all the crankshaft bearings. Stroke-bore ratios of 2-3:1 are entirely feasible, which is not the

usual case for 4-stroke engines.

- Ease of generating adequate in-cylinder air motion for fuel/air mixing without the need for re-entrant piston bowl geometries, with their attendant high heat losses, and thermal loading and durability issues.

Combustion waste heat rejection is generally lower than equivalent power 4-stroke engines and this can enable reduced radiator size. Power/bulk comparisons (Appendix 5) indicate better values for the OP engines versus competitive powered 4-stroke engines

Direct cost comparisons of medium- and heavy-duty OPEs and 4-stroke diesel engines indicate that the OPE has approximately 12% lower product cost at equivalent torque, power and emissions. This is because OPs have, relative to 4-stroke engines,:

- Half the number of cylinders
- No cylinder heads or high pressure gaskets (typically 7% of the base engine cost of a current 4-stroke six-cylinder truck engine)
- No valvetrain (typically 6% of the base engine cost of a current 4-stroke truck engine)
- 32% lower material weight, because of the smaller displacement, package and lower cylinder pressures.
- 33% reduced machining time, because of the 34% lower part count
- Reduced assembly time, because of the lower and simpler part count
- Potentially half the number of fuel injectors

The only additional hardware associated with the OPE is the scavenge air pump or blower (Fig.9), which supplies the cylinders with the working air as all 2-stroke engines dispense with the additional exhaust and induction strokes of the 4-stroke cycle (i.e. there is no additional “stroke” or revolution to purge the cylinder of exhaust gas and recharge with fresh air). Comparisons, explained later in more detail, show for equivalent 447kW heavy-duty engines, that the OPE has the similar height as the 4-stroke, but 60% reduced box volume—the latter advantage is larger if after-treatment systems are included.

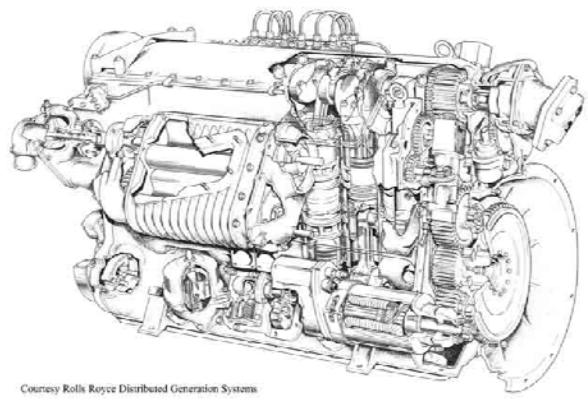

Fig.9 Rolls Royce K60 OP Diesel Engine Showing Roots Blower

With these significant advantages, what caused the demise of the diesel OPEs between 1970 and 2000?

Historical OPE Challenges

The Emissions Paradox

The advent of exhaust emission legislation in the 1970s and the need of exhaust after-treatment systems for very low tailpipe pollutants discouraged the use of 2-stroke engines for the following technical reasons:

- The mindset of the 1970s was that the scavenge air and resultant excess air in the exhaust, implicit with most 2-stroke engines, would render the exhaust too cool for catalyst operation and also oxygen rich, which was incompatible with the then-prevailing technology of stoichiometric after-treatment.

- 2-stroke engines of the 1970-1980 era had higher oil consumption than 4-stroke engines, as lubricating oil was lost through the cylinder ports that handle induction air and exhaust gases. Oil is a major source of particulate emissions.
- Lubricating oils prior to 2000 contained additives that poison catalysts and had high ash residues that plugged the flow passages in the catalyst, these detrimental aspects being lesser issues for 4-stroke engines with their lower oil consumption.
- The absence of cylinder heads with OPEs forces the injector to be mounted on the side of the cylinder, (Fig.10) and this arrangement, with its asymmetrical, limited number of spray directions and close proximity of the spray to the cylinder wall, was considered disadvantageous for low NOx, particulate and smoke emissions compared to the multiple axi-symmetrical spray plumes of a central cylinder head mounted injector, which is typical of the 4-stroke diesel engines.

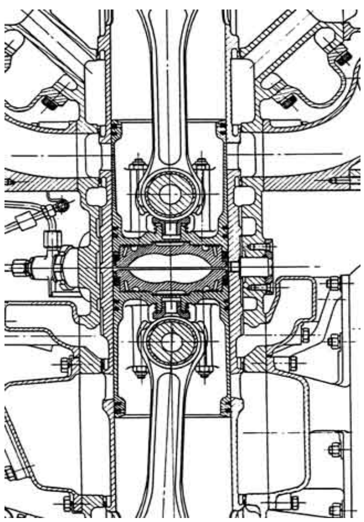

Fig.10 Section through Leyland L60 Liner, Piston and Injector

- There was always a concern of cylinder liner fuel impingement with the side injection, leading to locally rich combustion zones and smoke, and locally high thermal loads on the liner and piston crown.
- This side injection issue was exacerbated by the relatively low injection pressures of the 1970-1990s, forcing the use of coarse sprays with large droplets to fully traverse the cylinder bore; the large fuel droplets are not favourable for rapid evaporation of the fuel and mixing with the air. The axi-symmetrical central injectors of the 4-stroke engines can use multiple injector holes to better atomise the fuel as these central injection sprays only need to travel half the distance of the side sprays of the OPEs, the latter therefore suffering more fuel impingement on the cylinder liner and pistons and worse emissions due to the off-centre spray and poorer fuel-air mixing. The axi-symmetric injectors of the 4-stroke also enable easier access of the fuel to more of the air in the cylinder, because the central position of the injector facilitates multi-directional sprays, whereas side injection restricts the spray plumes to more localised volumes of the air in the combustion chamber.

Before explaining the paradigm shifts in technology over the last 30 years, it is important to note that 2-stroke engines have, due to their double firing frequency versus 4-stroke engines, 30-40% reduced cylinder pressure and gas temperature (Ref.1) than the 4-stroke engine at the same power rating. This translates to the 2-stroke engine having approximately 30% lower NOx emissions than the 4-stroke engine per unit of crankshaft power. OPEs may, therefore, either use 30-50% lower levels of exhaust gas recirculation (EGR) for NOx suppression versus the 4-stroke at the same power or, more probably, 30-50% reduced NOx after-treatment requirements, be they selective catalytic reduction ("SCR") or lean de-NOx systems. This is an important and often forgotten advantage for the 2-stroke OPE in comparing the 2- and 4-stroke emission fundamentals. So how have the historical OPE emissions situations changed?

Firstly, improvements in cylinder bore materials, cylinder bore finishing, piston ring technology, use of synthetic oils, crankcase breathing systems and management of cylinder bore oil impingement has done much to reduce oil consumption of 4-stroke diesel engines; these same advances have even more impact when applied to 2-stroke liner-ported engines.

Secondly, the advent of low ash and low phosphorus oils have reduced precious metal poisoning and cell plugging of catalysts from oil carry-over. These aspects are equally relevant to the OPE 2-stroke as well as the 4-stroke engines. SCR techniques, now being largely applied for NOx reduction on many light- and heavy-duty 4-stroke diesel engines, are also applicable to the OPE.

Thirdly, as with 4-stroke engines, increased availability of very high fuel injection pressures, either via common rail pump systems or unit pump injectors, and the greater ease of manufacturing asymmetrical injector nozzle hole directions, have greatly extended the opportunities with side injection of OPEs for making the injected fuel find more of the air within the combustion chamber whilst also improving the mixing of the fuel and air. This benefits power, emissions and fuel consumption of the OPE, potentially more so than for the 4-stroke engine, as the scope for fuel/air mixing and combustion improvement is significantly greater in the OPE. The relatively long injection plumes of the OPE are also an opportunity to enhance air entrainment and fuel mixing, especially with use of two injectors per cylinder with multiple sprays. Also, the relative ease and efficiency of generating and maintaining swirl in the OPE remains a very powerful advantage for fuel mixing and entrainment. Due to the emphasis on 4-stroke combustion, there has been little exploration on OPEs of the interaction this potent swirl source with piston features that would generate micro-turbulence, and this offers significant potential combustion improvements.

A great advantage modern OPE developers have over their predecessors is access to modern design tools. OPEs have different, and perhaps, more parameters that can be varied to improve combustion and performance. Some parameter changes are difficult to evaluate consistently during testing, but the trends of a parameter change can be modeled consistently and accurately. The ability to analytically model engines not only improves insight into the engine behavior, but also significantly hastens the process and reduces the hardware and iteration costs. Fabrication and dynamometer tests have to be undertaken for only a small subset of potential configurations, greatly decreasing the time, effort and cost to create an optimal combustion system.

Achates Power, Inc. of San Diego, California provides a good example of how development tools can be used to quickly optimize the combustion system. For good combustion, the engine needs to handle air efficiently and effectively. The burnt charge must be expelled, and the fresh charge brought in while minimizing pumping losses and scavenging losses. In a two-stroke engine, some residual exhaust gases will remain in the cylinder; this is generally undesirable since the residual gases will reduce the fresh oxygen mass and residual gases will raise the gas temperature during the next combustion cycle, increasing NOx formation. On the other hand, the air charge system cannot expend too much energy expelling the exhaust gas.

The selection and design of the turbo- and super-charging systems will affect scavenging, as will the design of intake and exhaust manifolds, and the size, location, and design of port bridges.

Computational fluid dynamics (CFD) allow scavenging efficiency (i.e. a measure of the purging of exhaust gas by fresh air) to be estimated as different design options are varied. Below is an image (Fig.11) of the scavenging simulation of the Achates Power A40 OPE that currently achieves 92% scavenging efficiency, which is very good for a two-stroke engine.

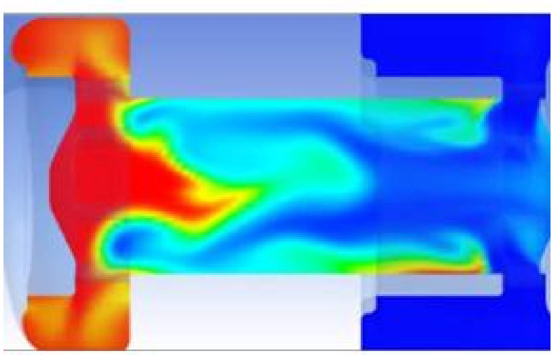

Fig.11 Example of Scavenging Modeling Conducted Using CFD

A single simulation can take days on a super computer, but saves weeks of procurement and testing. Additional simulation parameters can be varied to alter fuel injection and air-fuel mixing, including injection pressure, injection timing, number of injectors, injector orientation, nozzle hole orientation, number of nozzle holes, size of the nozzle holes, and piston bowl shape.

Three-dimensional chemically reactive fluid analysis, like software based on KIVA 3 from Los Alamos National Labs, can model the effect of parameter change on fuel consumption, PM formation, and gaseous exhaust emissions. The inputs to the model must be calibrated for model fidelity.

Changing a fuel injector characteristic—injection pressure or nozzle hole size, for example—will change the fuel spray characteristics, including penetration and drop size distribution. To ensure model fidelity, Achates Power uses a laser Doppler anemometry system (Fig.12) to measure droplet size and spray penetration for model correlation.

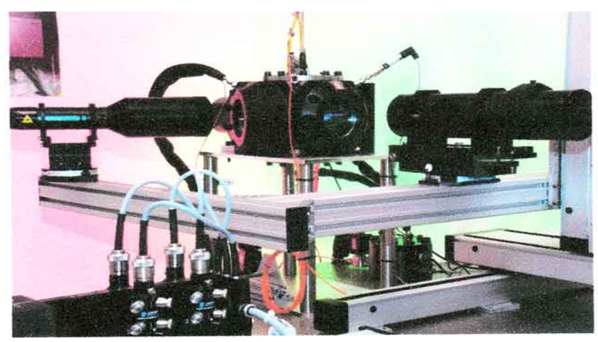

Fig.12 Optical Bench with Laser Doppler

Fuel is injected into a pressurized chamber that simulates the cylinder (Fig.13). Lasers are used to determine the distribution, dispersion, and their velocity and size of the fuel droplets.

Once the spray and air flow models have been correlated with the test rig observations, and other factors identified, the KIVA-based code predicts

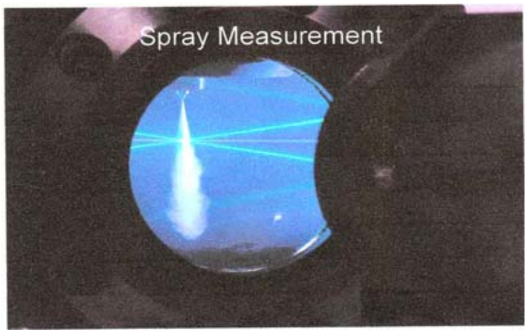

Fig.13 Fuel Spray Pattern

combustion system performance. Calibrating spray models and other key input is essential for model fidelity.

Using KIVA-based code and the other analysis tools, a number of different combustion system parameters can be altered, analyzed and evaluated. Only the most promising combination of parameters needs to be fabricated and tested to calibrate and validate the models. Achates Power, Inc. has model simulation tools to analyze the effects of varying the stroke-to-bore ratio of the engine, and has compared predicted and historical results.

Up to a limit, increasing the stroke-to-bore ratio of an engine increases its thermal efficiency as an engine with a higher stroke-to-bore ratio has lower specific heat loss because of an advantageous surface area-to-volume ratio versus engines with lower stroke-to-bore ratio. The counterbalancing effect, however, is that engine friction increases with stroke-to-bore ratio for a given engine rpm. However, as noted earlier, a thermal efficiency advantage of the OPE design is that two pistons combine in a cylinder to enable a high stroke-to-bore ratio without excessive piston speed. In essence, the OPE design doubles the effective stroke-to-bore ratio compared to a conventional architecture.

The stroke-to-bore ratio of a number of historic OPE are displayed in Appendix 6. The most successful OPEs have stroke-to-bore ratios greater than 2.4:1.

In sum, the advances in engine simulation, modeling, and analysis tools over the last 10 years have enabled significant advances in the ability to design ported, two-stroke OP engines that achieve superior thermal efficiency while meeting the toughest environmental standards in the world.

OPE Mechanical and Thermal Aspects

Though 2-stroke engines are sometimes considered to have fundamental mechanical and thermal issues with the continuous firing of each cylinder, without the beneficial relieving exhaust and air refilling cycles of 4-stroke engines, OPEs have proven their robustness in very successful, long-running and leading-edge production trucks such as the Commer QX8 (Fig.14) and in military vehicles such as the Chieftain Battle Tank (Fig.15) and the personnel carrier FV423 (Fig.16).

Aviation applications include the high altitude Junkers Ju86P-1 (Fig.17) and OP marine applications are the

Fig.14 Commer QX Truck Fitted with TS3 OP Diesel Engine.

Doxford engine in large freighters such as the MV Orenda Bridge (Fig.18) and the Fairbanks Morse 38D8⅛ in smaller vessels.

Fig.15 Chieftain Battle Tank Fitted with Leyland L60 OP Diesel Engine

The Fairbanks Morse 38D8⅛ is also used in very successful stationary applications with dual fuel power generation sets (Fig19).

Fig.16 FV432 Personnel Carrier Fitted with RR K60 OP Diesel Engine

Thermal loading of the piston, piston rings and cylinder liner is alleviated by use of high pressure fuel injection systems with several sprays per injector to reduce the concentration of fuelling and burning near the cylinder liner and outer edges of the piston.

Regarding lubrication issues, the continuously loaded

Fig.17 Junkers Ju86P-1 High Altitude Aircraft

small-end bearing has evolved with substantially greater surface area and spreader grooves to transfer oil to highly loaded regions that otherwise might experience boundary lubrication through lack of oil and overloading. Generally, the thermal problems in the OPE are addressed by providing copious cooling of the piston crown, piston rings, and highly convective cooling of the cylinder liner. Hot strength structural issues are resolved with steel-based materials for the pistons as well as the cylinder liners.

For the high thermal expansion due to the continuous thermal loading, piston rings may use two-piece “gap-less” sealed arrangements that enable large ring gaps without the usual cold start blow-by and compression losses of large ring gaps.

Apart from the gap-less arrangement, there are several approaches. On one hand, the 2-stroke cycle enables larger ring sections, because of the absence of inertia stroke-only loading cycle that occurs in 4-stroke engines. “L” section rings may be mounted at the very top of the piston crown so that they are rapidly energised to seal without the need for high ring tension and these usually larger sections can reduce piston ring pressures, increase the piston ring oil film thickness and are physically more robust for traversing ports.

Fig.18 Freighter Ship MV Orenda Bridge (70000+ Tons) with Doxford 76J8 20000 HP - OPE

On the other hand, the continuous firing and scavenge pressures of the 2-stroke can be used to ensure gas activation of lightweight, compliant and low tension rings to provide excellent sealing. Combinations of both routes are also possible. Special piston ring coatings and inlays, for improved boundary lubrication and reduced scuffing, are also frequently used, and piston ring ends are arranged to avoid intrusion into the ports.

While torsional vibration of interlinked crankshaft systems of OPEs and any twin crankshaft engines requires very careful consideration, modern analysis tools and test instrumentation enable successful optimisation.

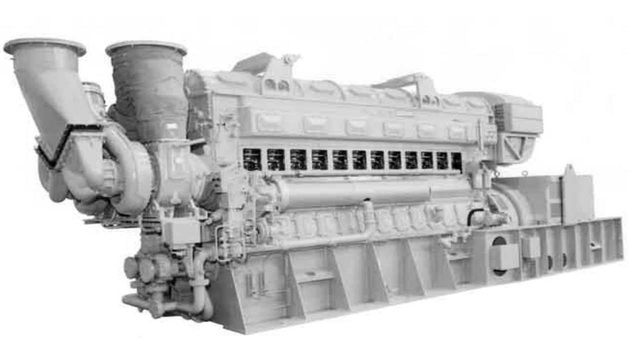

Fig.19 Fairbanks Morse Multiple Fuel Power Generation Set

Much attention is required to mounting the injector in the critical center section of the liner to avoid cylinder liner cracking. Successful coolant and gas sealing of the OPE liners with its multiple ports was achieved in the 1930s using combinations of spring, elastomeric seals and liner/cylinder block interference; most OPE engines have operated with these configurations without issues.

It is also recognized that the OPE cylinder liner can be arranged to be unloaded axially compared to 4-stroke cylinder bores which are required to cope with local cylinder head gasket and bolt loading effects; absence of these axial loads reduces bore distortion and helps reduce engine friction. The same axially unloaded cylinder liner characteristic means that OPEs are ideally suited for potential application of low thermal conductivity materials, such as ceramics, for reduced heat losses, which will most likely be another future step to improved thermal efficiency.

General Applications

OPEs have been successful prime movers in all forms of transport, including light-, medium- and heavy-duty vehicles, and in aviation and marine use. Additionally, OPEs have and continue to be used for stationary applications including power generation and various forms of pumping, using both liquid and gaseous fuels, with both spark ignition and compression ignition. Looking ahead, the OPE with modern oils, FIE and after-treatment is even better suited for these uses with compelling advantages in package, weight, cost effectiveness and potential for brake thermal efficiencies (BTE) in excess of 45% fuel energy at low emission levels. In short, a renaissance of OPE technology is taking place, with several initial potential areas of application. One particular market segment, i.e. the heavy-duty (HD) truck engine, is a major opportunity.

Heavy-Duty Truck

Emissions and Fuel Efficiency

The OPE is considered a lower cost route to ~45% BTE, and beyond, than the current very highly boosted 4-stroke engine, at post 2010 emission levels, 45% + BTE being the efficiency target for future heavy-duty (HD) diesel engines for U.S. trucks. Historically, automotive 4-stroke HD engines have been forced to address the ~ 90% reduction in NOx and particulate emissions since 1997 by use of ~30% cooled EGR with the remaining being handled by NOx-reducing after-treatment and regenerative particulate traps.

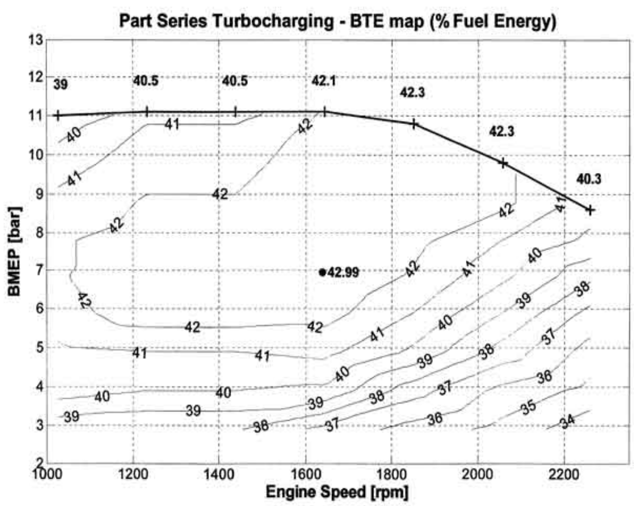

Fig. 20 Brake Thermal Efficiencies (BTE%) for Part Series Turbo-charging

Though the SCR systems for NOx after-treatment are sufficiently powerful to enable the HD engines to regain some of the efficiency sacrificed through controlling the in-cylinder combustion for lower emissions, the SCR needs consumable urea addition in the exhaust and this has similar costs to diesel fuel. The net situation is that the effective brake thermal efficiency of HD engines, allowing for the cost of the urea, remains close to 43%, without turbo-compounding. As a reminder, the experimental lightly turbocharged 19L Leyland L60T/AW OP research engine with a peak torque of 2810Nm (2075lbft) at 1850 rpm, developed without emission constraints c1964, showed a large zone of 42% BTE (Fig.20) with BTEs in excess of 40% above 35% load.

Performance

What can the OP engine offer to the current and future severely emission-constrained scenario? Firstly, for a given power requirement, a modestly turbocharged OPE would only need to deliver 10-12 bar bmep to match the 20-24 bar bmep of the 4-stroke; 12 bar bmep is well within the capabilities of a mildly turbocharged OP engine, as demonstrated by the prototype L60 engine fuel efficiency contours (Fig.20) and the current Fairbanks Morse 38D8⅛ engine.

As the 2-stroke OP, of equivalent displacement, would be operating at a significantly lower bmep than the 4-stroke, e.g. 12 versus 24 bar, a fairly moderate exhaust gas recirculation (EGR) level, by current 4-stroke practice, of 20% EGR should be adequate with the OPE to reduce the NOx emissions to 0.35g/kWh with maximum cylinder pressures approximately ~70% of the 4-stroke cylinder pressures.

By contrast, U.S. HD 2010 engines are typically operating at 30% cooled EGR, 4 bar absolute boost pressure and peak cylinder pressures of 180-200 bar at maximum torque equivalent to 21 bar bmep to reduce NOx to 0.5g/kWh. The difference in NOx is primarily due to the lower maximum bulk gas temperatures of the 2-stroke because of the EGR and lower boost pressure and temperature. There is confidence that a modern OPE side injection system will be able to approach, and possibly surpass, the engine-out particulate levels of a 4-stroke central injection combustion system at the 20% EGR level required by the 2-stroke OPE.

The good smoke and particulate characteristics of the Fairbanks Morse 38D8⅛ engines, with relatively unsophisticated FIE, goes some way to supporting the previous OPE emission claims. So, how does a two-stroke OPE compare with a 2010 4-stroke truck engine?

HD Cost, Package & Weight Comparison

Modest boosted bmep levels (Table 1) for a 12 L three-cylinder OPE were assumed from previous and current OPE engine performance (Ref.1) for a speed range of 800-1800 rpm; this speed reduction trading the power advantage of the 2-stroke for downsizing efficiency and reduced mechanical losses.

Typical OPE stroke/bore ratios of 1.2 x 2 were assumed, similar to those of the HD 4-stroke (Fig.21), and bore spacing of 1.4 x cylinder bore were assumed for the OP engines, though lower values are achievable with modern cylinder liners (Table 1). Twin exhaust and intake manifolds (Fig.22), are envisaged for the OPE, as per most previous arrangements, with a twin crankshaft configuration because of the need for high crank-train stiffness at the high cylinder pressure requirements of HD engines.

Engine Type	Four-Stroke	Two-Stroke
Water Cooled	In-line 6	3 cyl
kW	447	447
RPM	2200	1800
Bore (mm)	144	126
Stroke (mm)	165	2x160
Displacement (L)	16	12
Predicted bmep (bar).	13.27	11.13
Estimated Weight (kg)	1394	943
L x H x W (m)	1.2 x1.05 x 0.75	0.6 x1.18 x0.54
Estimated Bulk (L)	945	382
Estimated Cost ($US @ 500 units per year)	12156	10705
kW/L (Displacement)	28	37
kW/L (Bulk)	0.47	1.17
kW/kg	0.32	0.47
$US/kW	27.19	23.95

Table 1 Four- and Two-Stroke Heavy-Duty Truck Engine Parameters

In the case of OPEs with contra-rotating crankshafts, cyclical torque accelerations are also cancelled, further enhancing the vibration-free characteristics of the OPE and increasing the life of all crankcase mounted auxiliaries.

The gear-train linking the crankshafts would be sited at the flywheel end (Fig.22) and would be used to drive many of the auxiliaries that need not be belt driven. The turbocharger(s), linked to the manifolds on each side of the engine, would be sited at the rear of the engine, above the flywheel housing.

Both 2- and 4-stroke engines are assumed to have similar common rail injection systems, operating at similar injection pressure levels.

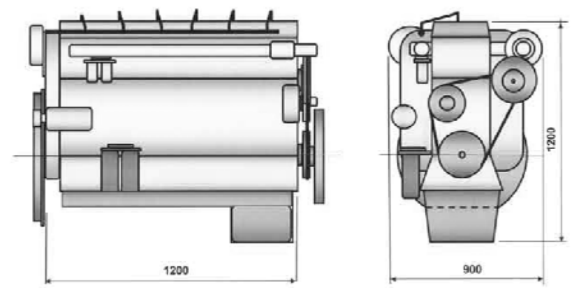

Fig.21 HD Truck 16L – L6 – 4S Schematic

The resultant three-cylinder OP engine package (Fig.22) can be seen to be approximately the same

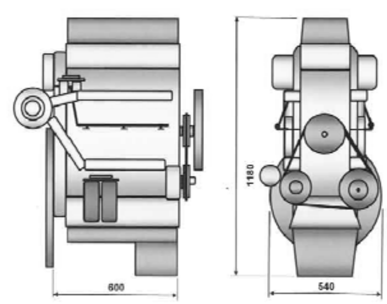

Fig.22 HD Truck 12L – L3 – 2S Schematic

height as the 4-stroke, but having 28% reduced width and length, mainly due to the half-cylinder count of the 2-stroke and the substantially narrower gear-train.

Weight (Appendix 7) and cost data as (Appendix 8) comparisons indicate that the 2-stroke OP engine could be some 32% lighter than the equivalent performance 4-stroke, and some 12% lower cost, excluding potential exhaust after-treatment cost savings.

The disparity in the percentage weight and cost difference is due to the following basic assumptions:

- A similar level of fuel injection, drive and auxiliary complexity is required for the 2- and 4-stroke configurations; two injectors per cylinder are assumed for the challenging HD performance and emission requirements.
- Similar engine management systems are required for both engines because of the same injector count.
- More complex exhaust manifolds and EGR systems are required for the 2-stroke OP engine versus the 4-stroke, because of the twin manifold configuration of the 2-stroke OP engine and the necessary pressure differential across the 2-stroke ports.

For NOx after-treatment, the difference in engine out NOx would be reflected by approximately 50% smaller SCR catalyst for the OP than the 4-stroke NOx catalyst. The particulate trap and the oxidation catalysts are assumed to be of similar displacement that are required by the 4-stroke.

Power for the Future

Recent re-examination of the innate advantages of the OP engine emphasizes its suitability for current and future challenges, offering significant operational and cost advantages for the same manufacturing volume. Unusually, these advantages are available with current product and manufacturing technology, and attainment of OPE benefits are low risk in terms of product engineering resources and customer acceptance.

References

Ref.1 The book “Opposed Piston Engines Evolution, Use and Future Applications” by Jean-Pierre Pirault and Martin Flint. Pub SAE International. ISBN 978-0-7680-1800-4. Available at http://books.sae.org.

About the Book Authors

Jean-Pierre Pirault has worked 40 years in powertrain engineering with Vandervell Products, Ricardo, Ford, Jaguar and AVL. He is now with Powertrain Technology Ltd, an engine consultancy in the south of England.

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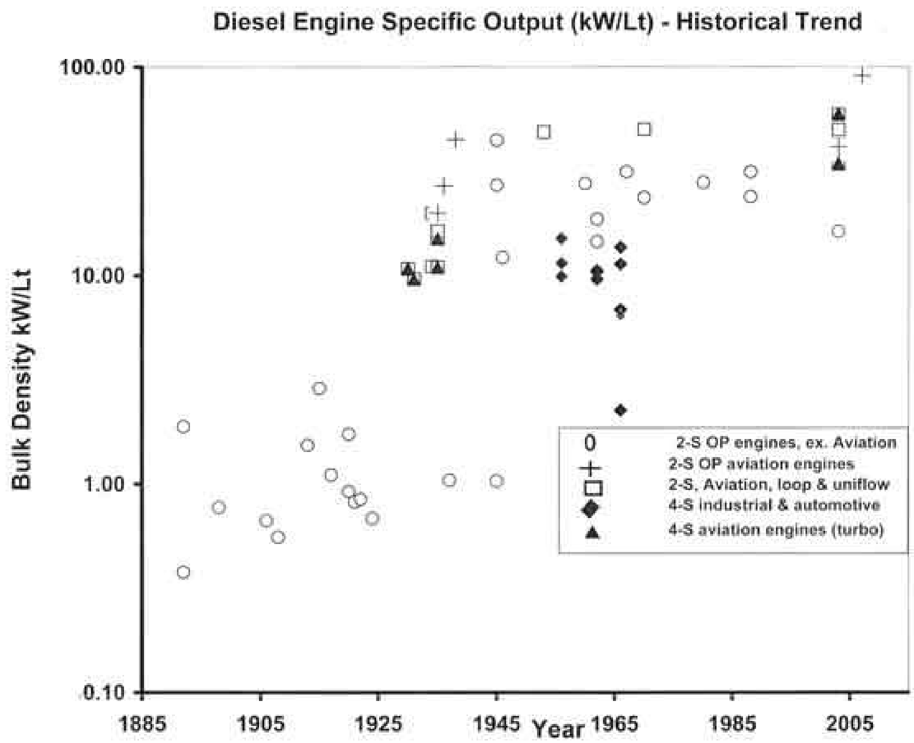
Accuracy and Representation

This paper is published by Achates Power, Inc. and the above book authors' interpretation of available data and is not intended to misrepresent products, persons, corporations or history. Great effort has been made to present accurate information and check the acceptability of product descriptions with relevant sources and manufacturers.

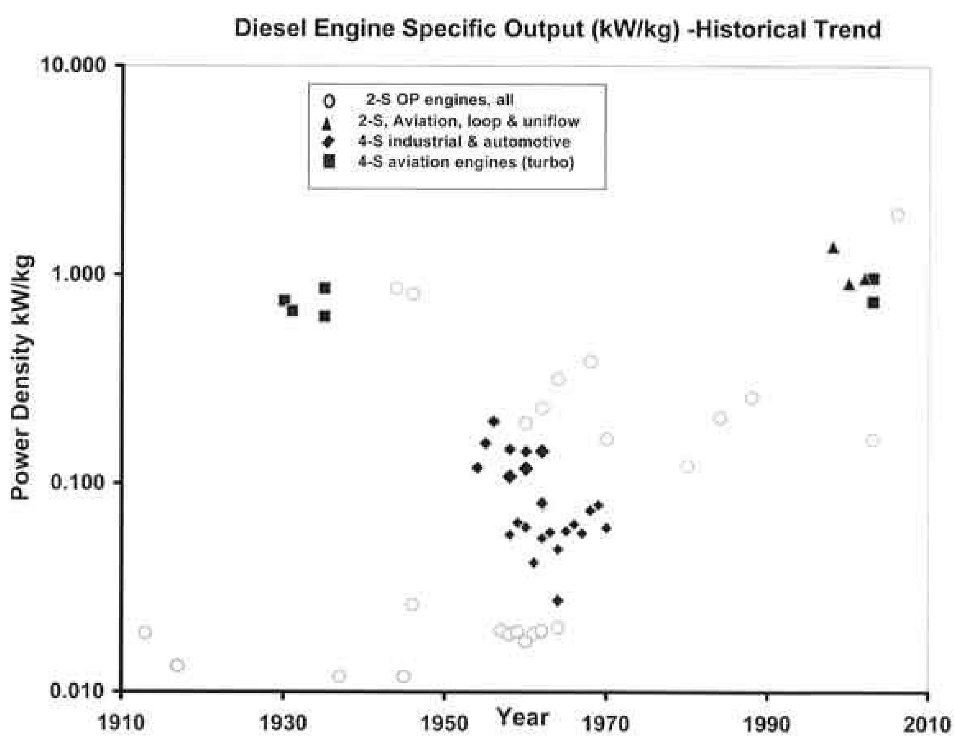
Appendix

The appendices 1-8 below feature various data charts mentioned in the text.

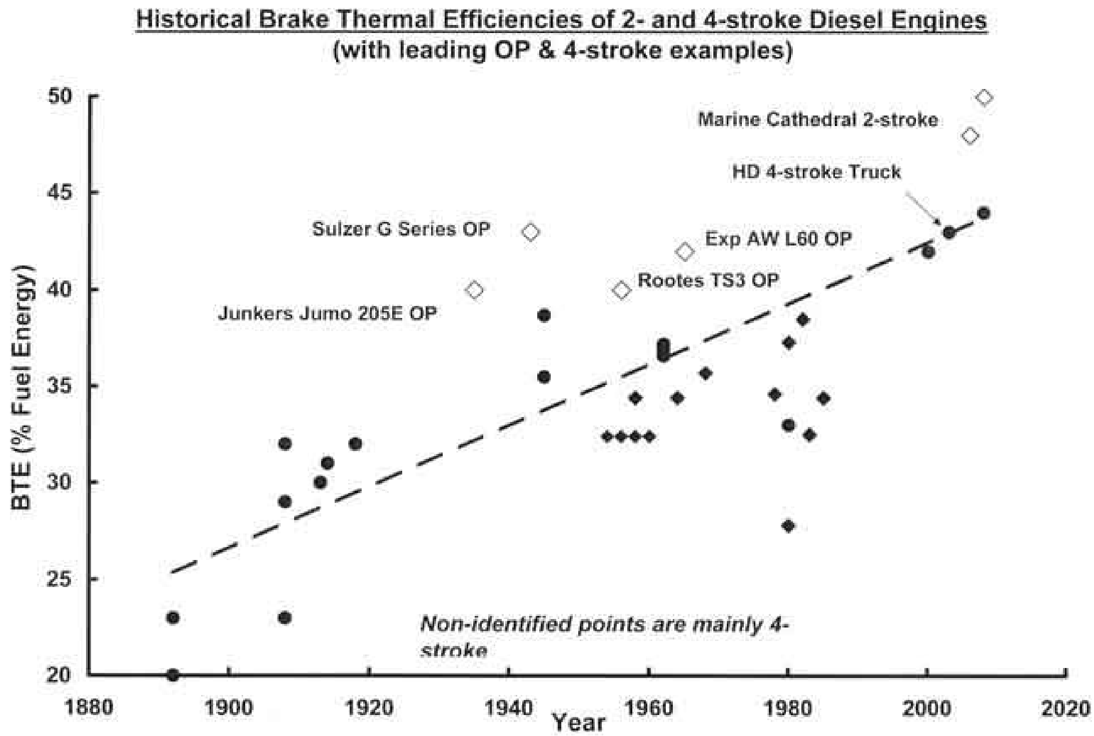
Appendix 1: Historical Trend of Power Density (kW/L) of both Four- and Two-Cycle Engines



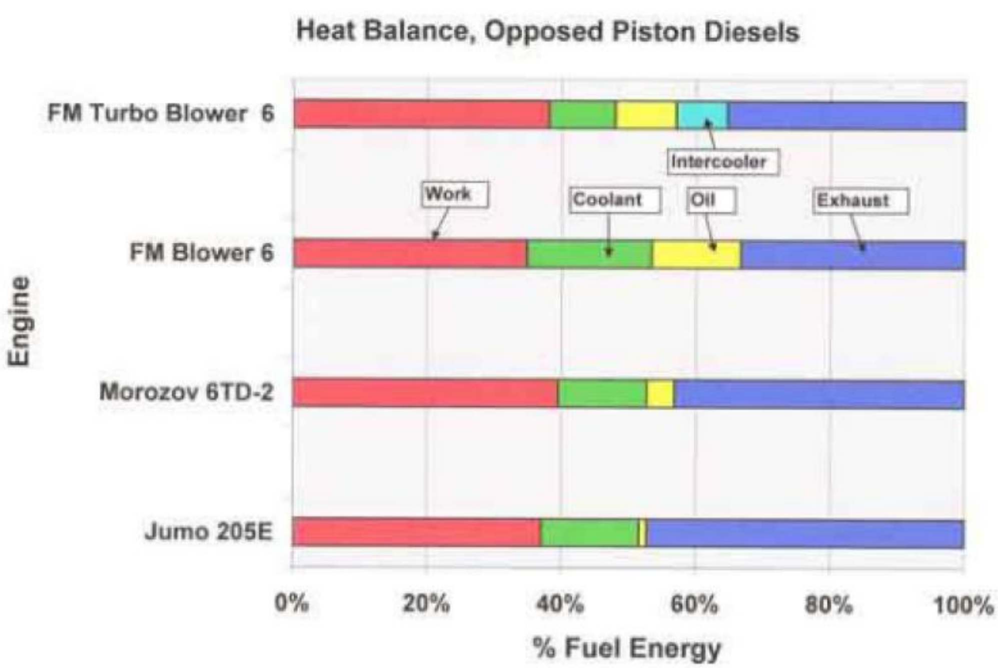
Appendix 2: Historical Trend of Power Density (kW/kg) of Four- and Two-Cycle Engines



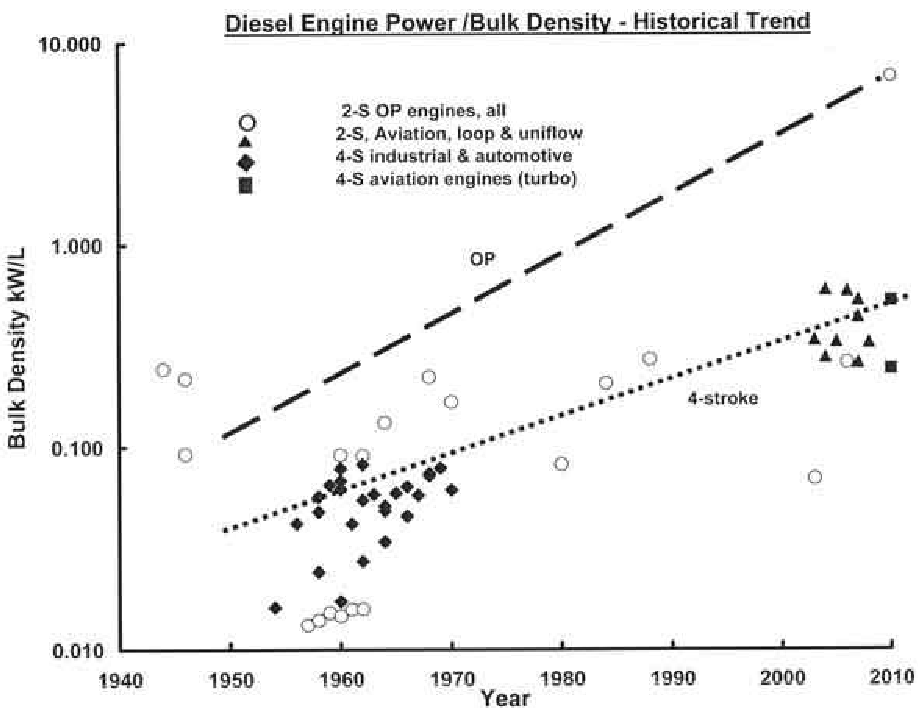
Appendix 3: Historical Trend of Brake Thermal Efficiencies (%) of Four- and Two-Cycle Engines



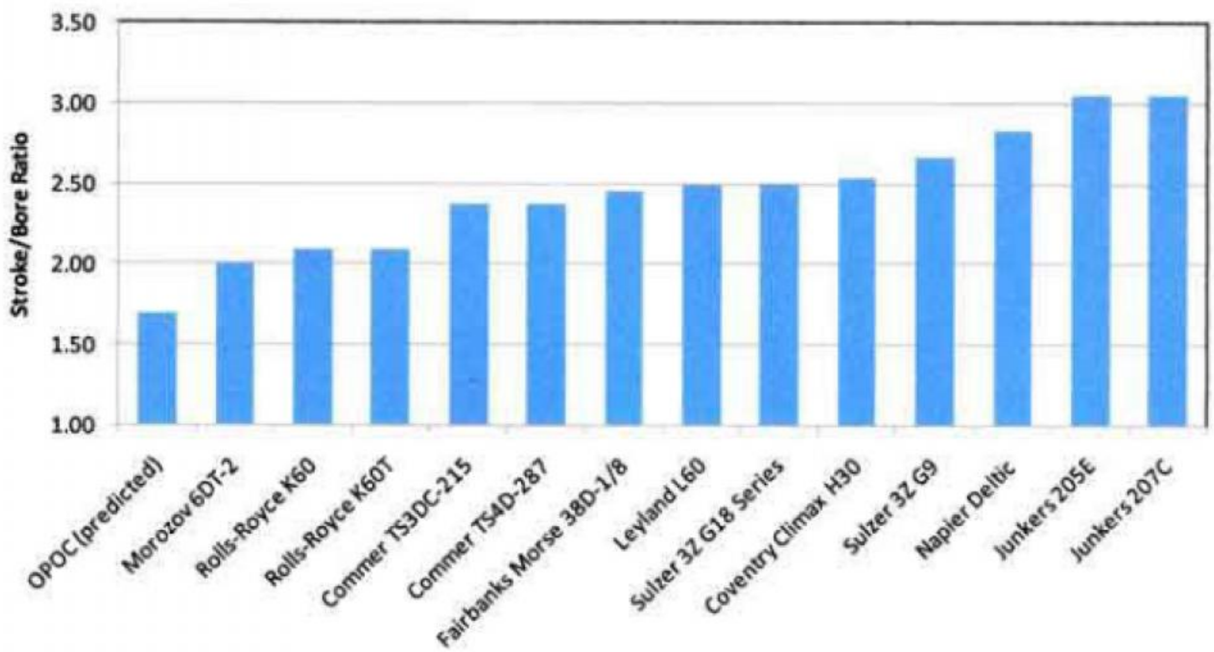
Appendix 4: Heat Balance of Fairbanks-Morse, Morozov and Junkers Jumo OP Engines



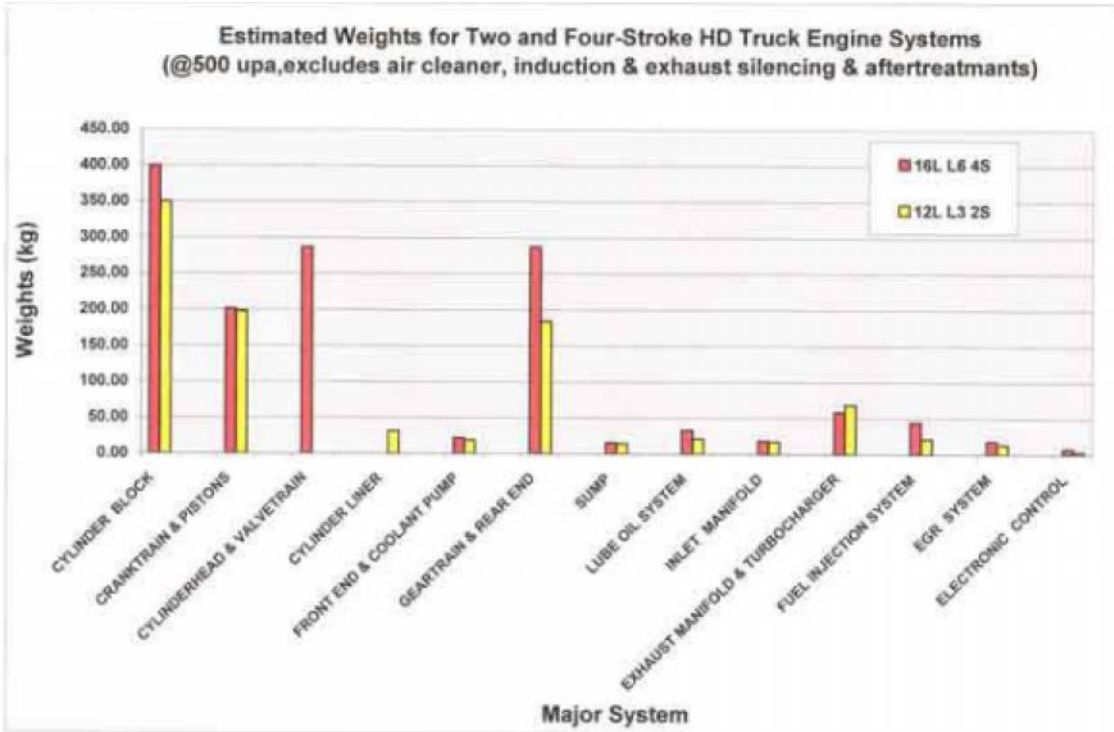
Appendix 5: Historical Trend for Power Bulk (kW/dm3) of Four- and Two-Cycle Engines



Appendix 6: Stroke/Bore Ratios of Various OPEs



Appendix 7: Two- and Four-Cycle 450kW – OP Truck Diesel Engine –Weight Comparison



Appendix 8: Two- and Four-Cycle 450kW – OP Truck Diesel Engine – Cost Comparison