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HARLAND AND WOLFF – BURMEISTER AND WAIN MARINE DIESEL ENGINES AND THE INFLUENCE OF C.C. POUNDER ON THE DEVELOPMENT OF THE TWO-STROKE MARINE DIESEL ENGINE

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Harland and Wolff – Burmeister and Wain Marine Diesel Engines and the Influence of C.C. Pounder on the Development of the Two-Stroke Marine Diesel Engine

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SYNOPSIS

The paper, which is a historical review, was inspired by the death of C. C. Pounder, Chief Technical Engineer of Harland and Wolff (H & W) from 1933 to 1964, who died at the age of 91 in 1982. He had in particular been associated with Burmeister and Wain (B & W) in the development of the two-stroke marine diesel. The paper briefly reviews the invention of what is now commonly known as the diesel engine, which led to the first large marine diesel developed by B & W in 1910. The B & W four-stroke marine diesel, developed in association with H & W, who were by far their largest licensee in the inter-war years, is briefly considered. A more detailed account of the development of the B & W two-stroke marine diesel engine and the influence of C. C. Pounder is then given. In particular, attention is paid to the nearly independent development of the H & W opposed-piston two-stroke engine, which flourished after the Second World War until its complete demise in the 1960s when the B & W poppet-valve two-stroke engine became dominant.

INTRODUCTION

C. C. Pounder, whose photograph is shown in Figure 1, died on 18 December 1982 at the age of 91. The Northern Ireland Branch of the CEI then decided that the Annual Lecture in 1983 should be devoted to a Memorial Lecture on the life and work of C. C. Pounder and, in particular, his contribution to the marine two-stroke engine. This paper is based on that Memorial Lecture.

Cuthbert Coulson Pounder was born on 10 May 1891 in Hartlepool, the youngest of a family of six. His father was a blacksmith with his own business. When he was six, his mother died and he was brought up by his stepmother, a lowland Scot who had a tremendous influence on him. He was raised as a Baptist, but later became a High Anglican and finally a convinced Spiritualist.

On leaving school Pounder was apprenticed to the famous engineering company of Richardson Westgarth, who became involved with diesel engines as early as 1912. It is clear that he hated the engine works of his day but found his real vocation in the design office under the leadership of L. D. Wingate.

In 1916 he entered H & W in Belfast as a draughtsman in the pipe arrangement office, where he ultimately became chief draughtsman. In this post he obtained very responsible experience, particularly in relation to the Holland–American liner the *Statendam*, which was launched in 1924 at a time when the demand for North Atlantic passenger ships had fallen to zero. As a result the hull was left unfinished till May 1927 when it was towed to Rotterdam for completion. However, all the machinery units, together with the main pipe systems, were supplied by H & W, and Pounder was responsible for the vast amount of correspondence and drawings which were passed from Belfast to Rotterdam.

He was also involved in a serious problem involving the cracking of bedplates which took him overland, via Moscow, to Odessa to examine a failure. This journey had a lasting impression on him because of the difficulties he experienced with the Russian authorities, in particular being interviewed by the OGPU.

In 1933 he was appointed Chief Technical Engineer, which gave him responsibility for propelling machinery, both steam turbines and diesel engines. There can be little doubt that his great enthusiasm and contribution was in the development of large marine diesel engines for which H & W were to become pre-eminent. Nevertheless he was intimately involved in the design of steam turbine propelling machinery and he was a Member, and Chairman from 1951, of the Steam Turbine Committee of Pametrada until it came to an end in 1962.

When Pounder was appointed Chief Technical Engineer, H & W was, according to him, 'completely dependent upon B & W to the most insignificant detail. Steam turbine and generator designs were non-existent'. So he sent a memorandum to the Chairman of Directors pointing out two things: one, that

Professor Crossland was an apprentice with Rolls Royce Ltd, Derby. He was educated by part-time education, followed by two years full-time study at the Nottingham University College where he obtained an External London BSc (Eng) with honours. On his return to Rolls Royce he worked in the Experimental Vibration Department until, in 1946, he left to become an Assistant Lecturer in Mechanical Engineering at the University of Bristol. Subsequently he became a Lecturer and then Senior Lecturer before leaving, in 1959, to take up the Chair of Mechanical Engineering in the Department of Mechanical and Industrial Engineering at the Queen's University of Belfast. He has served as Dean of the Engineering Faculty and as Senior Pro-Vice-Chancellor before retiring early in 1984. His research interests have been in high-pressure engineering and in the use of explosives for metal forming and welding. Currently he is a Vice-President of the Royal Society, President-Designate of the Institution of Mechanical Engineers and a Member of the Engineering Council. He serves on the Industrial Development Board for Northern Ireland, the Agricultural and Food Research Council and the Council of the Fellowship of Engineering.

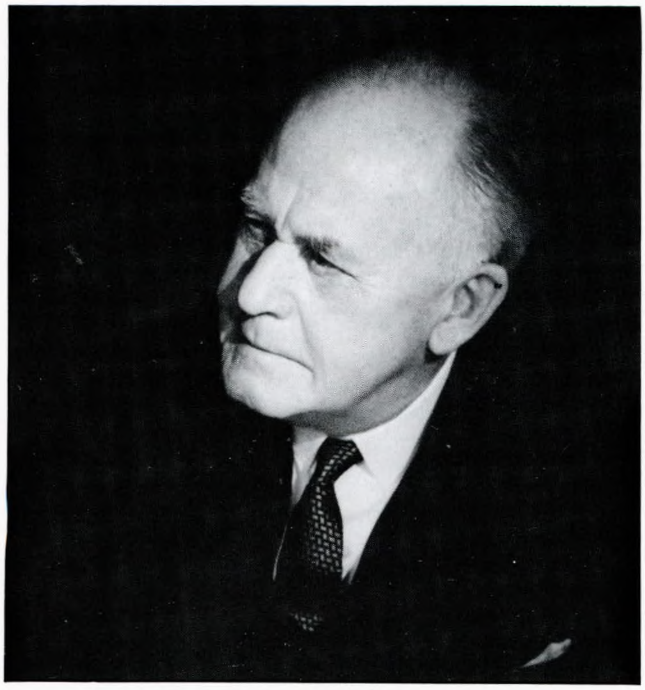

FIG. 1: C. C. Pounder, 1891–1982

the firm must show initiative in steam turbines as it was clear to him that the coming of high-pressure and -temperature steam would transform the marine world as it then was; and two, that H & W should so alter its marine oil engine outlook that, at any time as might be necessary, it could stand completely on its own feet. Rather to his surprise, the memorandum was accepted without reservations or directives. As a consequence, some time before the war came the firm was able to stand alone and pursue its own course in the development of the diesel engine. This led to the 'golden age' of what was essentially the H & W diesel engine.

After the Second World War it obviously annoyed Pounder that engines developed during the war were still regarded by many people as B & W designs and yet they owed as much, and maybe more, to H & W. All of H & W's work on opposed-piston engines and details of every change and improvement made during the war years had to be disclosed to their licensor. The licensor had the right not only to use these developments but also to pass them on to other licensees who might well be competitors of the originators. Reading between the lines, it is probable that Pounder wished to end the agreement with B & W which he thought was of little value to H & W.

H & W continued with the development of the opposed-piston two-stroke engine up until 1964 when Pounder, who had also become a Director more than a decade earlier as well as remaining Chief Engineer, retired at the age of 71. After his retirement, caused in part by a change in personnel but more importantly by the rapid decline in orders, H & W stopped their independent development of the opposed-piston two-stroke engine and again became completely dependent on B & W designs.

DEVELOPMENT OF THE MARINE DIESEL ENGINE PRIOR TO 1918

Akroyd Stuart engines

Although various engines using hydrocarbon fuels were built in the last half of the nineteenth century, the development of the compression ignition engine, now commonly known as the diesel engine, started with Herbert Akroyd Stuart (1864–1922). Akroyd Stuart, at the age of 21, started work on a Priestman-type engine which had an external vaporiser to produce a combustible mixture from oil and air. The combustible mixture was then used in a spark-ignition engine.

In 1890 Akroyd Stuart patented [1,2] what came to be known as the hot-bulb engine, later referred to as a semi-diesel although it pre-dated Diesel's patent. This engine had an uncooled vaporizing chamber connected to the working cylinder via a small throat. Air was compressed into the chamber and at the end of the compression stroke fuel was sprayed onto the hot wall of the vaporizing chamber, where it vaporized and self-ignited. The fuel was delivered to the spray nozzle from a cam-operated plunger pump which was controlled by a governor or throttle over-riding the suction valve of the pump. When the engine was cold the vaporizer was heated by an external lamp which could be dispensed with once the vaporizer reached operating temperature.

This original Akroyd Stuart engine relied essentially on the heat of the uncooled combustion chamber for ignition, although there was some contribution from the heat of compression. However, in 1892 Akroyd Stuart raised the compression ratio of one of his engines by removing the vaporizer and replacing it with a wrought iron plate into which he fixed a water-cooled spray nozzle. After some difficulty in starting the engine, it reportedly ran for six hours before being stopped by heavy ignition knock. This was in every aspect what is now referred to as a diesel engine, but its potential was not recognized and no further work appears to have been carried out on it.

In 1890 some dozen Akroyd Stuart engines were made by Messrs G. Wailes and Co. in Euston Road, London, some of which were sold and some sent out on approval. Then, in 1891, R. Hornsby and Son Ltd acquired the world rights for the Akroyd Stuart engine. After some further development, including improving the injection pump to avoid coking of the sprayer nozzle and controlling the pump delivery by a by-pass valve located at the spray nozzle, they marketed the engine under the name 'Hornsby–Akroyd'.

By 1896 they had raised the power by increasing the compression ratio, which necessitated cooling part of the vaporizer. This increased the part played by the heat of compression although the engine still relied partly on the heat from the uncooled part of the vaporizer.

Hornsby–Akroyd engines were built under license worldwide and in 1895 they began building two-cylinder vertical marine engines of 10 hp. They grew in size and horsepower and in 1903 Hornsby supplied the British Admiralty with a engine with four cylinders of 629 mm (25 in) bore and 343 mm (13.5 in) stroke, developing 400 hp. In Denmark and Sweden, the Hornsby–Akroyd engine was modified to power fishing boats. Hornsby alone had sold ten thousand engines by 1900 and many more were produced by their licensees.

Diesel engines

Rudolf Christian Karl Diesel (1858–1913) received his technical education at the Technische Hochschule München, where he studied under Professor Karl von Linde, who was famous for his work on refrigeration and heat engines. After graduating he worked on refrigeration, which led to an interest in a combustion cycle based on the idealised Carnot cycle, and in 1892 he wrote a short paper, published in 1893, expanding his views on what he referred to as a 'Rational Thermal Engine'.

These ideas were the basis of his patent[3] of 1892 in which he proposed five possible combustion cycles, although his choice was that involving isothermal combustion as prescribed by Carnot. According to the patent, the proposed engine worked to the following four-stroke cycle:

1. Air is sucked in through the inlet valve during the first stroke.

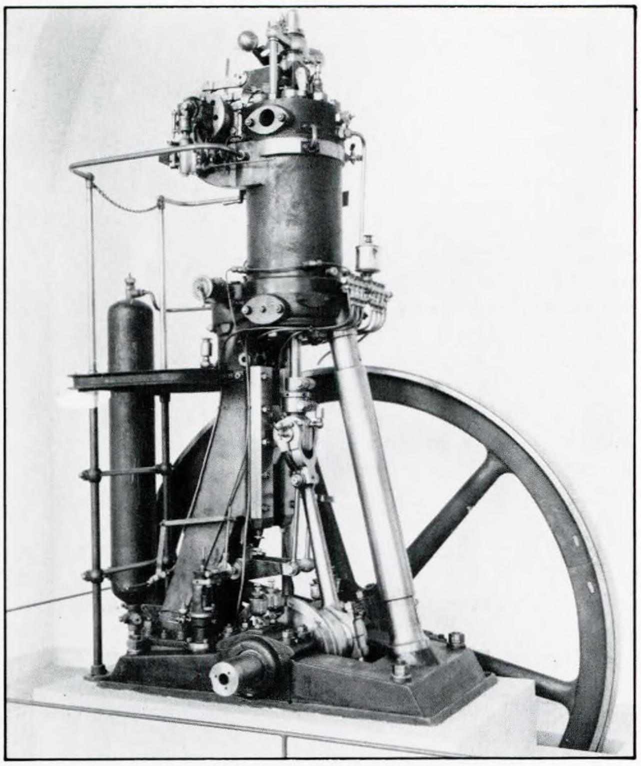

FIG. 2: Experimental diesel engine (1897)

2. During the beginning of the second stroke the air is compressed while water is injected to give isothermal compression. At an appropriate point, water injection ceases so that the temperature at the end of compression is 800 °C, which is more than sufficient to ignite the fuel, and the pressure is 24.8 MPa. During this last part of compression not only is no water injected, but the cylinder is insulated to cut-down heat losses.
3. During the first part of the third stroke, coal dust or some liquid or gaseous fuel is introduced at such a rate as to give isothermal expansion as it burns. The fuel is then cut-off and the expansion completed in the heat insulated cylinder down to atmospheric pressure.
4. In the fourth stroke the gases are exhausted through an exhaust valve.

It was claimed that the temperature of the cylinder wall was lower than in any ordinary steam engine so that normal materials of construction and normal lubricants could be employed.

After filing his patent, Diesel looked round for somebody to back the development of his engine. However, backers were put-off by the high peak pressure quoted in the patent, and after further analysis Diesel concluded that a much lower peak pressure of 4.4 MPa was acceptable. This change was sufficient for Maschinenfabrik Augsburg A.G., who combined with Maschinenfabrik A.G. Nürnberg in 1898 and in 1908 became M.A.N., to agree to build an experimental engine.

After considerable development a satisfactory performance was achieved in 1897 when a test on a 250 mm bore and 400 mm stroke engine, shown in Figure 2, gave brake power of 13.3 kW (17.8 hp) at 154 rev/min and a full load brake thermal efficiency of 26.2%. This was a much higher efficiency than other steam or internal combustion engines of its day. However, this engine had few similarities to the original patent: no water injection, water cooling of cylinder and cylinder head, liquid fuel injected to give somewhere near constant-pressure not isothermal combustion, and liquid fuel injected and atomised by an air blast. Work was initiated on a coal-dust burning engine after the 1897 acceptance test.

The main differences between the engine finally developed by Diesel and the Hornsby–Akroyd engine already in production in 1896 were that in the engine developed by Diesel ignition was achieved solely by compression, which implied a high compression ratio, whereas the Hornsby–Akroyd engine still had a hot-bulb and needed some initial source of heat for starting, and also Diesel's engine had air-blast injection whereas the Hornsby–Akroyd engine had solid injection.

Air-blast injection needed a supply of high-pressure air which introduced extra complexity, and by the middle of the 1920s airless injection had started to be introduced on diesel engines. Air-blast injection has since become extinct.

So ultimately the differences were marginal, and perhaps the conclusion must be reached that Akroyd Stuart was unfortunate to have designed an engine which worked with very little expensive development. Consequently, there was no driving force to pursue his successful compression ignition experiments of 1892.

Marine applications

Nearly all the early applications of the diesel engine were in stationary land-based installations, although as early as 1903 Diesel sailed on a diesel-engined canal boat in France. In 1906–07 the French constructed a diesel-engined submarine powered by a 300 hp M.A.N. reversible diesel engine, while diesel auxiliary engines made by the Scottish branch of Mirrlees, Bickerton and Day were installed in HMS *Dreadnought*.

In 1908 the Dutch company Stork-Werkspoor, who had been a M.A.N. licensee, built an engine to its own design suitable for ship propulsion which was installed as an auxiliary propulsion engine in the schooner *San Antonio*. In 1910 they installed a six-cylinder 500 hp engine in the 1179 ton tanker *Vulcanus*.

The real step forward in the marine application of the diesel engine came in 1910 when the East Asiatic Company ordered three ocean-going 7400 dwt motor ships, two from B & W and the third from the British Company of Barclay, Curle and Company. Each of the ships was to be fitted with two B & W reversible eight-cylinder four-stroke diesel engines with a total power of 1838 kW (2500 ihp)* or 1486 kW (2020 bhp) at 140 rev/min.

Barclay, Curle and Company built the two engines for their ship under license from B & W. Ivar Knudson of B & W had negotiated an agreement with Diesel in 1898 and he had been responsible for the construction of an experimental engine in 1898. In 1904 they had begun to build stationary diesel engines and production had steadily increased in number and power output. It was Knudsen's enthusiasm which led to the design of the main engines for ocean-going ships.

The first of these motor ships, the *Selandia*, was launched on 4 November 1911 and she departed on her maiden voyage to Bangkok on 12 February 1912, returning to Copenhagen on 26 June 1912. At a service speed of 12 knots she consumed about 10 ton of fuel oil per day compared with 30–40 ton of coal in a comparable steam ship. Figure 3 shows the engine room of the *Selandia*. The same machinery was still in this ship when she was lost off Japan in 1942.

Early cooperation between H & W and B & W

The B & W Oil Engine Co. Ltd was formed in Glasgow for the construction of diesel engines in Great Britain in 1912 with a share capital of £500,000. O. E. Jorgensen from B & W was appointed as Manager. Originally the company was to have been associated with Barclay, Curle and Company, and their Managing Director and another Director were on the original Board when the prospectus of the Company was

* The horsepower quoted are metric horsepower, as used in countries where the metric system has been in operation for a long time. A metric horsepower is 75 kgf m/s, which is 1.37% less than a British horsepower or equivalent to 735.5 W.

issued on 30 March 1912. In about 1913 H & W purchased from Barclay, Curle and Company their part (one-third) of the share capital of the company and they also took over the manufacturing license for B & W engines.

During the First World War, H & W acquired the rest of the shares of the B & W Oil Engine Co. Ltd, which ultimately became H & W Diesel Engine Works, Glasgow, and Lord Pirrie was appointed a Director and then Chairman. In 1917 B & W issued to the Glasgow company, and thus to H & W, a license for the construction of B & W engines throughout the British Empire.

When the B & W Oil Engine Co. was established in 1912 Lord Pirrie of H & W allocated them part of the site formerly occupied by the London and Glasgow Engineering Co. Ltd, which became the Finnieston Works. Late in 1912 the Manager, O. E. Jorgensen, was joined by V. Mickelson as Chief Designer and his Assistant J. Moller and a year later by A. Hammer as Test Engineer.

In 1915 Jorgensen was replaced by F. E. Rebbeck, later to become Sir Frederick Rebbeck and Chairman of H & W. It also began Rebbeck's long association with the development of the marine diesel engine. Within a year of his transfer to the Belfast Works of H & W in 1919, as General Manager, steps had been taken to start the building of diesel engines in Belfast and key members of the Finnieston technical staff were established there in 1921.

The first engines to be built at Finnieston were for three existing steamers (the *Bandon*, the *Pangan* and the *Chumpon*), which had a gross tonnage of 3500 t and a service speed of 10½ knots. The single diesel engine fitted was a six-cylinder single-acting four-stroke crosshead type with a 670 mm bore and 1000 mm stroke, developing a shaft power of 956 kW (1300 hp) at 110 rev/min. These re-engined ships went into service in August 1914, December 1914 and January 1915, and according to Pounder these engines were still functioning excellently 20 years later.

A further vessel, the *Mississippi*, built at the Govan Yard of H & W, entered service in 1914. It was a twin-screw vessel with a gross tonnage of 4700 t and the same engines as the *Bandon* class giving a total shaft power of 1878 kW (2500 hp) at 105 rev/min. Between that time and the end of the First World War 10 more diesel-engine installations were built using the same basic design.

Although H & W were licensees of B & W from 1922 onwards, up until the 1950s H & W were by far the largest licensee and produced many more large engines than B & W themselves. The enormous developments in marine diesels during this period were very much joint developments in which H & W played in a significant part.

DEVELOPMENT OF THE FOUR-STROKE MARINE DIESEL ENGINE FROM 1918

Single-acting crosshead engines

According to Pounder,[4,5] the B & W four-stroke single-acting crosshead design was strong and heavy with a high degree of reliability. It quickly gained dominance over other designs and for nearly twenty years it held undisputed supremacy at sea for shaft powers of 2205 kW (3000 hp) in a single-screw vessel and 5145 kW (7000 hp) in a twin-screw vessel. An engine of this design developing 2572 kW (3500 hp) on six cylinders at 115 rev/min weighed 320 tonne.

The engines were enclosed, force lubricated and the air, exhaust and fuel valves were cam operated through long push rods with the camshaft driven from the crankshaft. The engine was reversed by swinging the push rod rollers clear of the cams, moving the camshaft longitudinally by a scroll-gear until the reverse set of cams came into line with the rollers and then swinging the push rod back onto the cams.

The air for starting the engine was provided by independent motor-driven two-stage compressors which discharged into storage reservoirs at 2.5 MPa. Fuel was delivered by a group of cam-driven oil pumps to the cylinder fuel valves, where it was atomised by blast air at 6 MPa supplied by a three-stage air compressor at the forward end of the engine and driven from the crankshaft. Figure 4 shows a typical engine of this design.

With the later application of two successive systems of pressure induction, ie exhaust turbocharging in 1929 and under-piston-charging in 1934, the sales life of this basic type was extended into the 1950s. Pressure-charged engines were built with shaft powers of 8826 kW (12 000 bhp) for twin-screw vessels, using two ten-cylinder engines of 740 mm bore and 1500 mm stroke at 115 rev/min. Figure 5 shows a cross-section of the under-piston-charged four-stroke engine, while Figure 6 shows a typical engine of this design.

Single-acting four-stroke four-cylinder trunk-type stationary engines with a 630 mm bore and 850 mm stroke were sold to Egypt in 1923. They had less head room because of the absence of a crosshead and they found application in the *Ulster Monarch* class of cross-channel ships built in 1929/30 which had ten-cylinder engines of 630 mm bore and 980 mm stroke.

Four similar engines, but with the stroke further increased to 1200 mm and having twelve cylinders and pressure-charging on the Buchi principle, were installed in the *Reino del Pacifico* in 1931. At 135 rev/min these engines developed

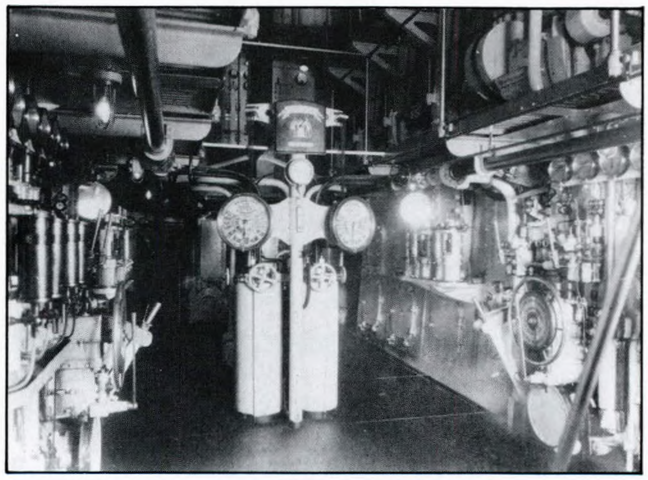

FIG. 3: Engine room of the *Selandia*

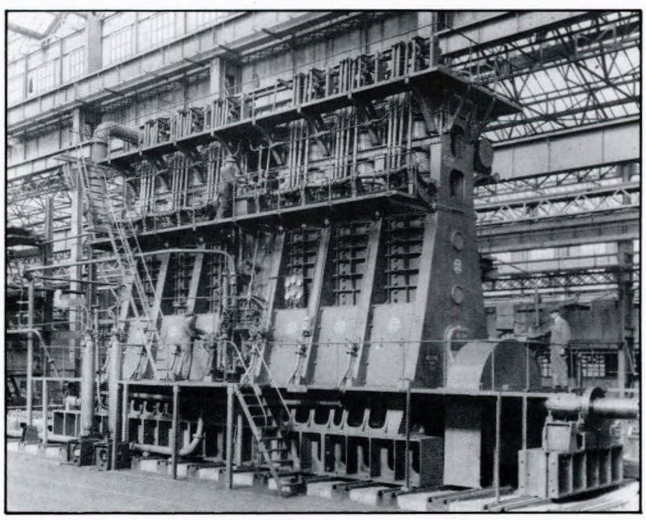

FIG. 4: Six-cylinder, single-acting, four-stroke crosshead engine with a 740 mm bore and 1700 mm stroke. Shaft power 1420 kW at 90 rev/min. Installed in the *King Edgar* in 1927

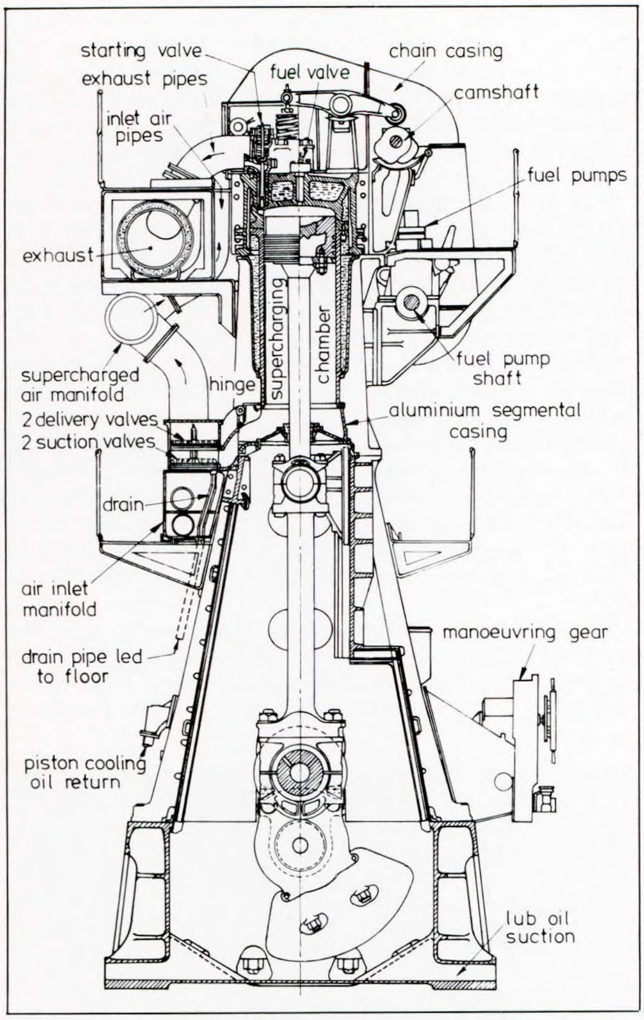

FIG. 5: Single-acting, four-stroke, pressure-charged engine

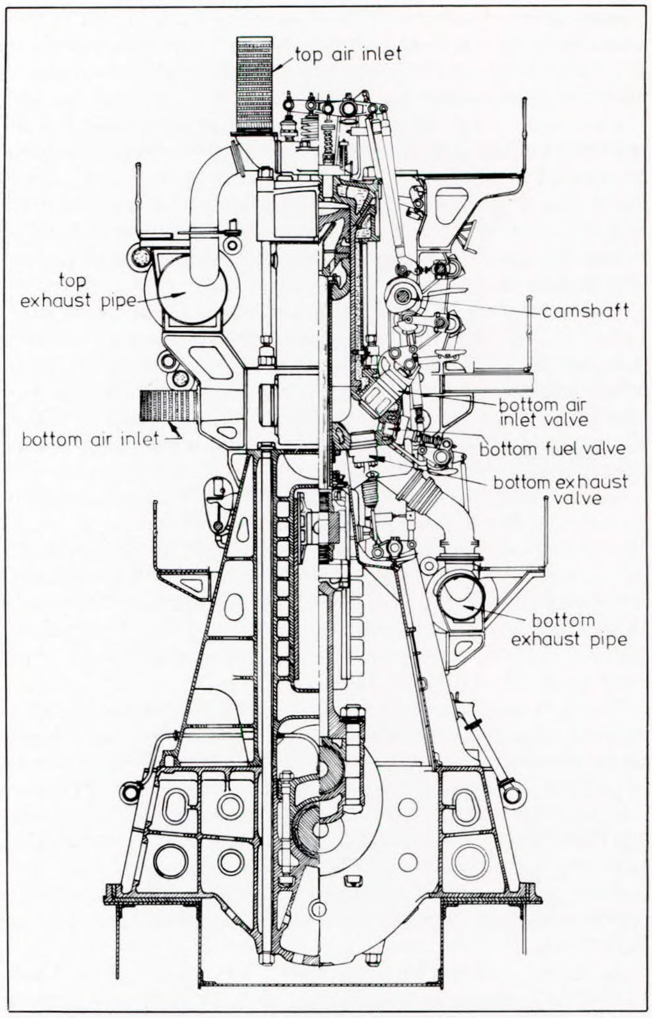

FIG. 7: Double-acting, four-stroke crosshead engine

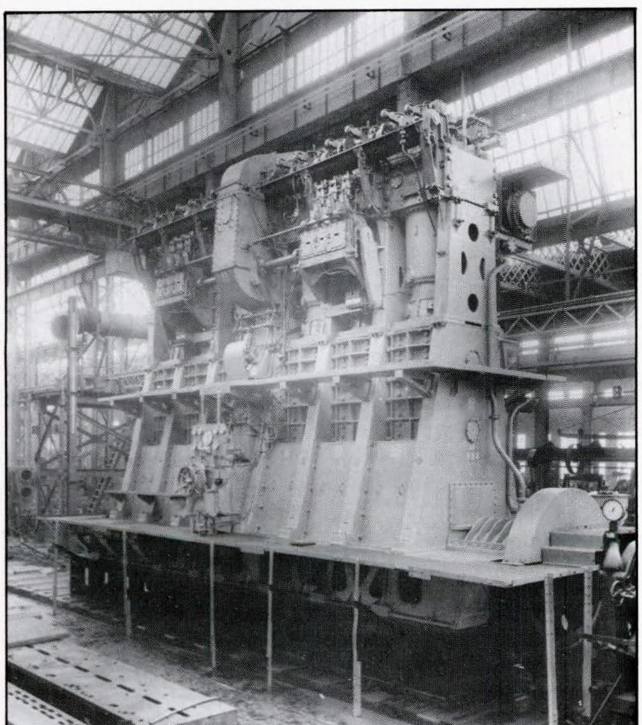

FIG. 6: Six-cylinder, single-acting, four-stroke crosshead engine with under piston charging and 740 mm bore and 1500 mm stroke. Installed in the *Ernebank* in 1937

a total shaft power of 13 240 kW (18 000 bhp). The *Reino del Pacifico* will be remembered because of the severe crankcase explosion which was experienced on sea trials after a major overhaul in September 1947 when a group of H & W employees were killed or injured. This and other crankcase explosions were discussed by Pounder[6] who, according to his son, was devastated by this disaster.

The engines in the *Ulster Monarch* class of cross-channel ships, the six *Elder Dempster* cargo ships built in 1930 and the *Reino del Pacifico* all had airless injection. In the middle 1920s experiments had been carried out by H & W on airless injection on the engines of the *Lautaro* and *Lagarto*, engined in Finnieston in 1915 and 1917, and it was found that the elimination of the blast air compressors and bottles improved the engine efficiency by 5–6% and also reduced the engine length and weight. Originally a multiple-pump arrangement was used but by 1931 this had been superseded by a single pump for each cylinder. The engines for the *Britannic* and *Georgic*, completed in 1930 and 1932, respectively, were the last to have blast injection.

Double-acting crosshead engines

The success of the early B & W single-acting four-stroke engine led to the desire for higher powered and more compact engines. Following discussions between H. H. Blache, B & W's Technical Director and in the late thirties a Consultant to H & W, and Lord Pirrie, it was agreed that H & W should contribute to the funding of a prototype double-acting single-cylinder four-stroke crosshead-type experimental engine with a 840 mm bore and 1500 mm stroke.

This engine was based on patents granted to Blache, although there was a major contribution from V. Mickelson and F. E. Rebbeck of H & W to the design of the oil-cooled piston rod sleeve and the oil-cooled piston. The experimental engine was running in 1923 and it developed 736 kW (1000 hp) at 125 rev/min. Figure 7 shows a cross-section of the engine in which the chain-driven camshaft operates inlet, exhaust and fuel valves in both the top and bottom combustion space.

The experimental engine formed the basis for the introduction of the large double-acting four-stroke engine in 1926. These were the first diesel engines to be built in the Belfast Works of H & W. There were two cylinder sizes, 840 mm and 680 mm, but with varying stroke depending on application.

The programme at Belfast began with the large double-acting four-stroke engines of the twin-screw ships *Asturias, Alcantara* and *Carnarvan Castle*, with two eight-cylinder engines of 840 mm bore and 1500 mm stroke which developed a total shaft power of 10 665 kW (14 500 hp) at 115 rev/min for the first two and 8238 kW (11 200 hp) at 96 rev/min for the third.

The largest and last engines of this design to be built were those for the *Britannic* and *Georgic*, completed in 1930 and 1932. Figure 8 shows one of the engines of the *Georgic* which had ten cylinders of 840 mm bore and 1600 mm stroke giving a total shaft power of 13 607 kW (18 500 hp) at 102 rev/min. A total of thirty double-acting four-stroke engines were built in the period 1926–32 before being superseded by the double-acting two-stroke engine.

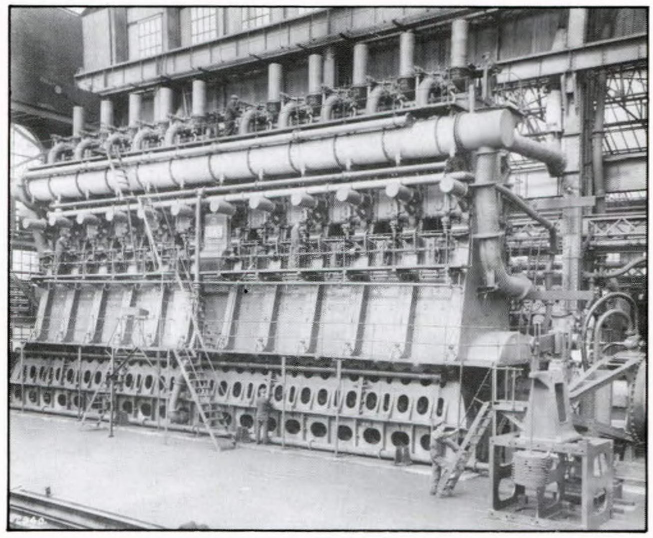

FIG. 8: Ten-cylinder, double-acting, four-stroke engine with a 840 mm bore and 1600 mm stroke. Maximum shaft power 8575 kW at 102 rev/min. Installed in the *Georgic* in 1932

DEVELOPMENT OF THE TWO-STROKE MARINE DIESEL ENGINE

When Pounder was appointed Chief Technical Engineer in 1933 the last of the double-acting four-stroke crosshead engines had been completed, though he inherited some in-service failures such as the cracking of the bottom cylinder covers. This is discussed in Ref. 5. Pounder was involved with the continuous manufacture and up-grading of other four-stroke designs including turbocharged engines and the under-piston-charged engines. However, his main contribution and interest was in relation to the two-stroke diesel engine.

Referring in particular to the double-acting four-stroke crosshead type of engine, Pounder[5] stated: 'As was only to be expected, having served a useful purpose these leviathan engines gave place to smaller, more advanced forms'. During the late 1920s B & W had evolved two distinctive two-stroke engines. For small powers the engines were of the single-acting trunk type, with a central poppet exhaust valve in the cylinder cover. For larger powers the engines were of the double-acting crosshead type, with central exhaust pistons arranged in the top and bottom cylinder covers.

Double-acting engines

With the emergence of the shipbuilding industry from the great depression, which started in 1929 and lasted through to 1932, a new level of technical advance was made by the introduction of the two-stroke double-acting engine. The range of shaft power of these engines extended from 3678 kW (5000 hp) in single-screw ships to more than 22 065 kW (30 000 hp) in twin-screw passenger vessels.

Figures 9 and 10 show the general arrangement of the single-acting two-stroke trunk-type engine with a central poppet valve and the double-acting two-stroke crosshead engine, respectively. An important aspect of both designs was that they incorporated uniflow scavenging with tangentially inclined scavenge ports, which has remained an essential characteristic of all B & W two-stroke designs up the present day. Uniflow scavenging, according to Pounder,[7] gives better breather characteristics than loop or cross scavenging, allowing higher specific outputs to be achieved. It is claimed that this more than offsets the greater complexity and higher capital cost.

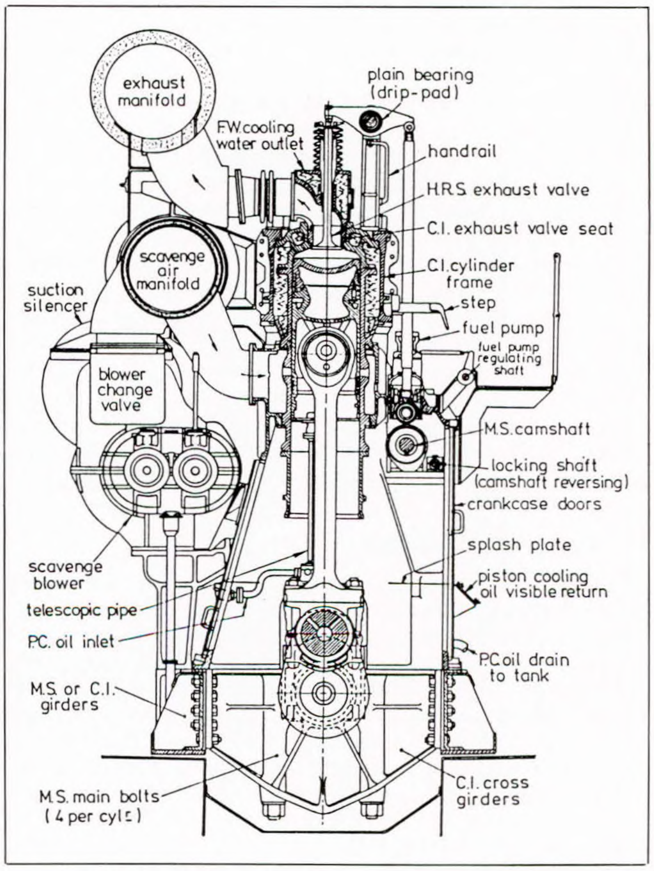

FIG. 9: Single-acting, two-stroke trunk engine

In the double-acting engines the scavenge ports were controlled by the main piston while the exhaust ports, top and bottom, were controlled by smaller diameter exhaust pistons. These pistons were originally operated by a secondary crankshaft chain-connected to the main crankshaft, but this soon gave way to an eccentric drive from the main crankshaft. These exhaust pistons developed power but because of their small size it was only about 10% of the engine power.

The mild steel piston rod was protected from the hot gases by an oil-cooled cast iron sleeve. The complete piston rod assembly passed through the stuffing box in the lower exhaust piston with an assembly of six twin rings and a bottom ring. Below this the piston rod passed through the scraper box, which was fitted with scraper rings to ensure that most of the oil was removed to leave an oil moist rod and prevent excessive oil being transferred to the stuffing box, where it would have caused ring sticking.

All the pistons were oil cooled. In the case of the main piston, oil was fed through a telescopic pipe to the annulus between the mild steel piston rod and the cast iron sleeve to the lower crown of the piston, and up to the top crown, back down the hole in the centre of the mild steel piston rod and from there to a spout and back to the suction tank.

Oil was fed to the lower exhaust piston through one of the two mild steel exhaust piston rods from a guide sleeve, up to the lower exhaust piston crosshead and thence to the lower exhaust piston. It was then transferred by a pipe clipped to the adjacent side rod up to the top piston, then back down a second pipe connected to a hole in the second mild steel exhaust piston rod, and thence to the guide sleeve where it was returned to the suction tank. The cylinder and the top and bottom covers were water cooled.

Lubrication was fed to each of the main bearings and from there through passages in the crankshaft to the crank pin to lubricate the big-end bush, and thence through the connecting rod to the small-end bush of the connecting rod where it found its way back to the crankcase. The eccentrics were lubricated by the cooling oil fed to and from the two mild steel exhaust piston rods. Oil was fed to the top-end bearing of the eccentric rod and thence down a hole in the rod to the eccentric, where it found its way back to the crankcase.

The first of these double-acting two-stroke engines were fitted to the *Australia Star*, delivered in 1935, which had twin-screw engines each having six cylinders with a 620 mm bore and 1400 mm stroke developing a total shaft power of 8826 kW (12 000 hp) at 98 rev/min. The largest of this early design of engine were those built for the *Stirling Castle*, the *Athlone Castle* and the *Capetown Castle*, completed in 1935, 1936 and 1938, respectively. These had twin-screw engines each of ten cylinders with a 660 mm bore and 1500 mm stroke, which at 80% of full power developed a total shaft power of 17 652 kW (24 000 hp).

Problems with the design

The double-acting two-stroke engine was not introduced without some problems.[5] Perhaps the most serious of these problems was the failure of piston rods after some years in service. Figure 11 shows the crosshead and piston rod arrangement. As stated by Pounder, it was a very compact design with not a millimetre of space to spare anywhere and the upper piston rod nut especially was of scant thickness. In many cases the threads stripped on the piston rod end above the crosshead block, in other cases the piston rod end fractured above or below the crosshead block, and in two cases fracture occurred through the rod and nut. No entirely satisfactory explanation of all the failures was forthcoming.

There was no possibility of increasing the diameter of the piston rod, and so the original forged carbon steel piston rods were replaced by a manganese molybdenum steel, which was all that was available during the days of war. However, some of these replacement rods failed within a couple of months, but if they survived for a few months then they did not break even after ten years of service. Eventually, as a result of experience, shipowners were advised periodically to renew their mild steel rods after a reasonable service life. In new installations the design was modified to accommodate a 15% increase in diameter, which appeared to overcome the problem.

After recounting these experiences Pounder finally commented: 'This irksome and costly experience has been recounted in considerable detail as an example of the unwis-

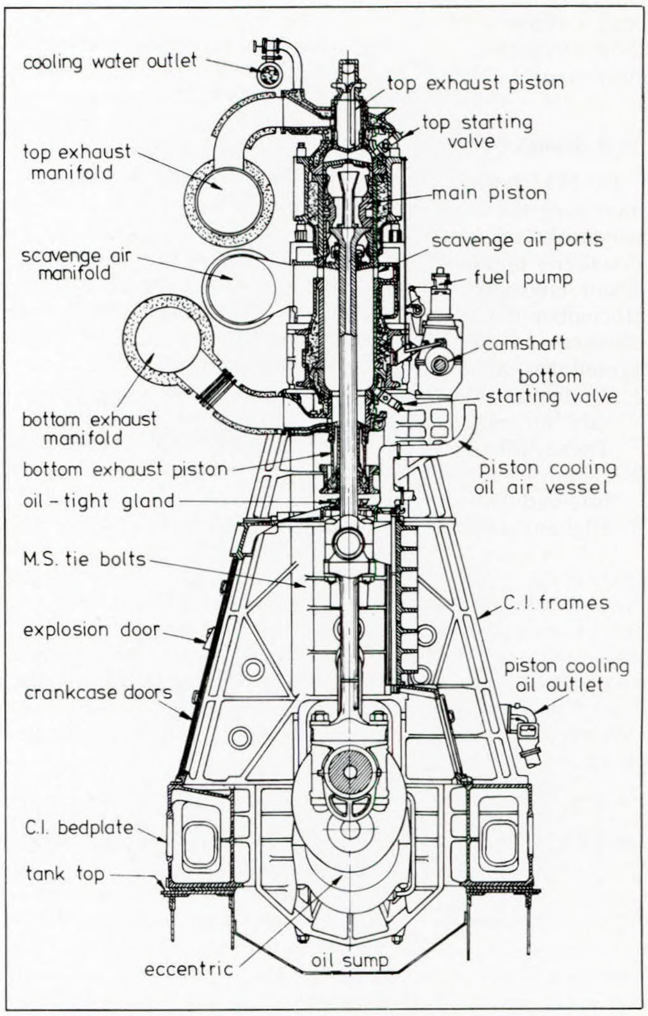

FIG. 10: Double-acting, two-stroke crosshead engine

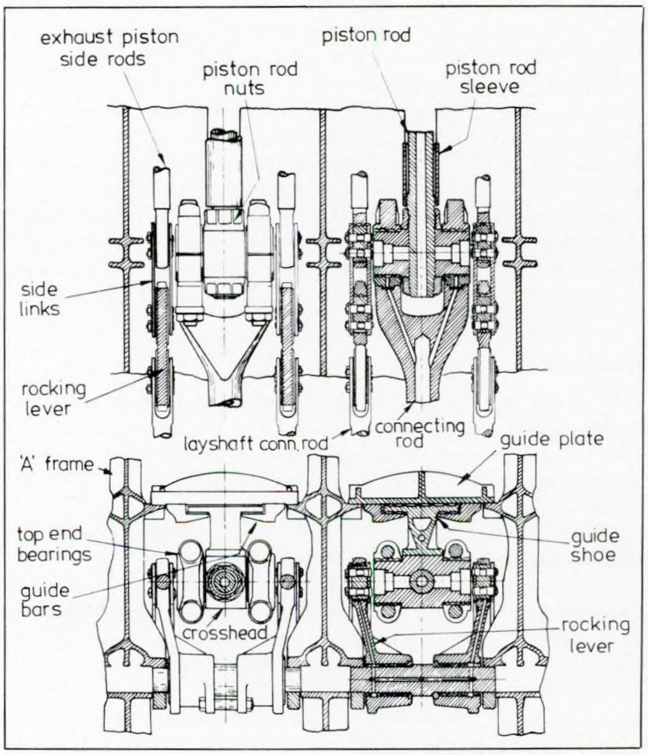

FIG. 11: Crosshead arrangement for the double-acting, two-stroke engine

dom, nay, of the arrant folly of making a design so tight at its crucial places that nothing can be done if expectations fall short of success. It is an outstanding example of the "over-cleverness" to which I earlier referred'.

New design considerations

By 1937 both B & W and H & W were contemplating increasing the exhaust piston diameter of the double-acting two-stroke engine to be equal to that of the main piston. Pounder's minutes[8] of a most interesting meeting between senior engineers of the two companies in Copenhagen in November 1937 give a clear picture of the reasons for these changes and the relationships of the two companies. They agreed that the main criticisms of clients were, to quote:

1. Difficulties of overhaul, due to the dismantlement necessary for exhaust pistons, cylinder covers, jackets, etc. These difficulties are absent in the Doxford design.
2. Disadvantages with chrome steel covers: (i) in manufacture and delivery and (ii) in service.
3. Higher cost of the engine generally.

H & W were for increasing the exhaust piston diameter to that of the main piston, and hence do away with the end covers and considerably simplify overhaul. They recognized that this would increase the power produced by the exhaust pistons and the cost of the exhaust piston driving gear. They proposed a reduction of the stroke of the exhaust pistons from 600 to 400 mm.

B & W were at that time designing a single-cylinder experimental engine with a main piston diameter of 530 mm and 1250 mm stroke and exhaust pistons of 530 mm diameter and 600 mm stroke, in which the exhaust pistons were driven by cranks and connecting rods rather than eccentrics. The H & W representatives pressed the considerable advantages of sticking to the well proven eccentric drives for the exhaust pistons. Ultimately B & W agreed to redesign their experimental engine with eccentric drives for the exhaust pistons and a reduced exhaust piston stroke of 400 mm. They further agreed to design a six-cylinder engine with this arrangement.

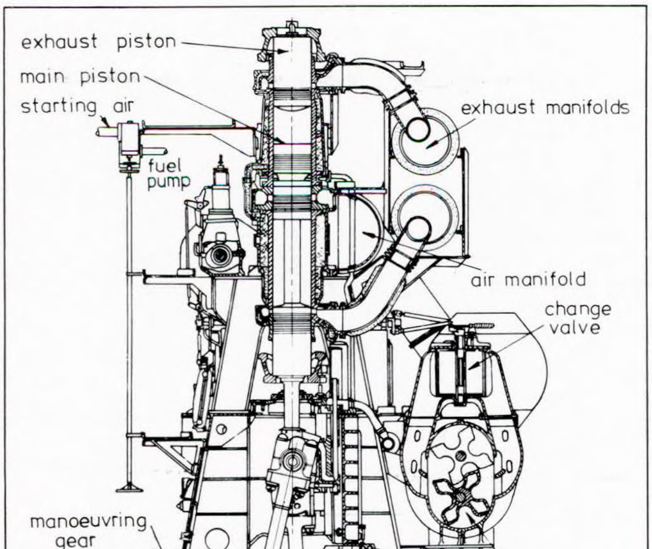

FIG. 12: Double-acting, two-stroke crosshead engine with full bore exhaust piston

In these minutes, the H & W representatives emphasized that they were primarily high-class ship builders and engine builders and the competitiveness and commercial success of a particular engine was as much a matter of production cost as it was design. However, though they emphasized their production role, it was apparent that they had a considerable influence on B & W in technical matters. It was at that time very much a partnership of equals.

In that same meeting, B & W informed the H & W representatives that for some years they were going to devote their attention to:

1. Double-acting engines: these will be cover-less engines with exhaust pistons of the same diameter as the main pistons and driven by eccentrics.
2. Single-acting engines: these will retain cylinder cover and poppet exhaust valves, and the design will be of the improved design not yet discussed between B & W and H & W representatives, and for which an experimental engine is being made.
3. Fast running trunk engines: these will be something like the engine running in the B & W shops but of a more commercial design.

The H & W representatives noted that at high revolutions the poppet valve engines were noisy and if the revolutions were reduced below the nuisance level then the engine became uncompetitive. It was also stated that it might be essential to depart from the poppet valve engine to secure an order. Perhaps Pounder was already beginning to think of the single-acting opposed-piston two-stroke engine.

Figure 12 shows the modified double-acting two-stroke engine with full bore exhaust pistons. The first of these engines was installed in the *Devis*, completed in 1944, although the experimental engine had run satisfactorily in 1938. This engine had six cylinders of 550 mm bore, a 1200 mm main stroke and a 400 mm exhaust stroke and it developed a shaft power of 4413 kW (6000 hp) at 115 rev/min. The largest installations built were the eight-cylinder engines installed in the twin-screw vessels *Port Hobart* and *Empire Star*, which gave a total shaft power of 11 033 kW (15 000 hp) at 116 rev/min. H & W built their last engine of this type in 1949.

It might be asked why the production of this engine lasted for such a short time. In 1949 Pounder[9] stated: 'At the present time for reasons which had their roots in the deterioration of overhauling staff at the repair ports, there is a tendency to favour single-acting engine types'. Later, in 1957, Pounder[5] further stated: 'As with all double-acting engines there were difficulties with the aggregate of bottom exhaust piston, piston rod and stuffing box. Periodic dismantling was necessary for survey purposes, apart from ordinary maintenance. One superintendent engineer told me 85% of his main engine-maintenance costs centred around the dismantling of the bottom end of the cylinder'.

There can be no doubt that although the four- and two-cycle double-acting engines were tremendous engineering achievements, they were complex and difficult and costly to maintain. It is increasingly recognised that, in general, simplicity is the hallmark of good design. It says a lot for the overhauling staff between the 1920s and the 1940s that they managed to cope with such complex machines.

Single-acting engines

While B & W were concentrating on single-acting two-stroke engines with a central exhaust valve in the cylinder cover, H & W were pursuing the single-acting two-stroke opposed-piston engine. Although there were some similarities to previous engines, the H & W engine was very much their own design, and Pounder[5] states that is was 'designed in Belfast which was the place of its origin'. Figures 13 and 14 show the single-acting two-stroke opposed-piston engine in both its crosshead and trunk forms.

The construction of the single-acting two-stroke opposed-

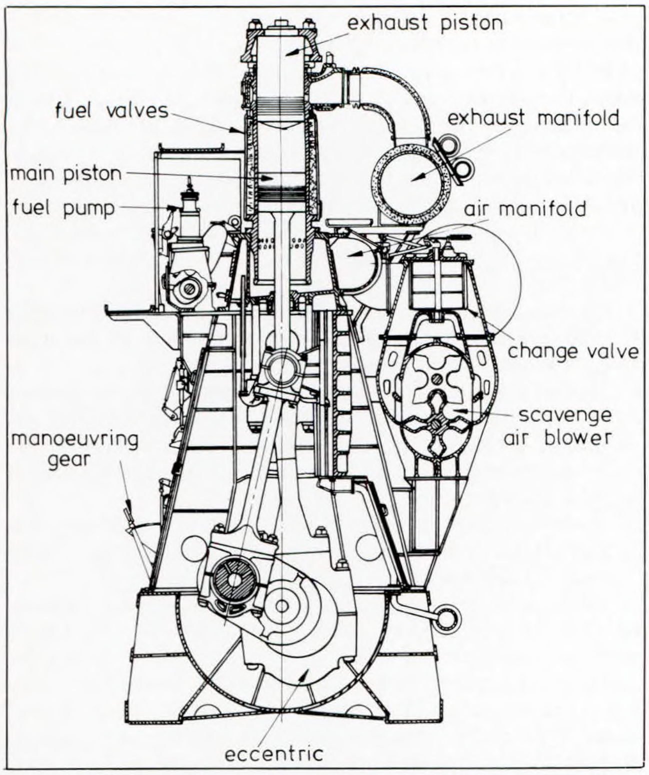

FIG. 13: Single-acting, two-stroke, opposed-piston crosshead engine

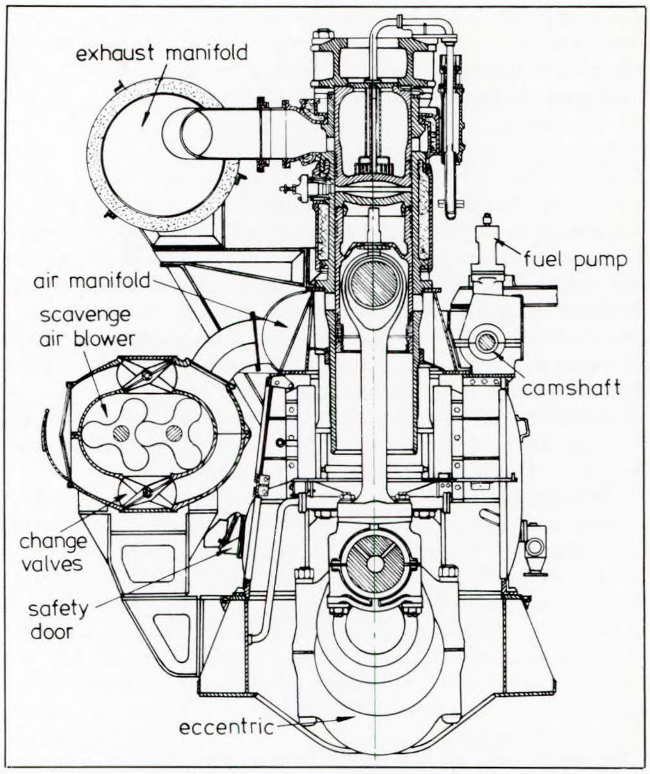

FIG. 14: Single-acting, two-stroke, opposed-piston trunk engine

piston engine was similar in many respects to that of the double-acting engine, the basis of the design being a short, rigid and compact crankshaft. The power produced by the exhaust piston was transmitted through eccentrics, which had been well proven in the double-acting engine and was the reason a short, rigid and compact crankshaft was possible.

As Pounder[9] stated: 'Some engineers continued to be sceptical of the value of an eccentric as an instrument for transmitting power' and he quotes experiments which demonstrated that the frictional losses in the eccentrics account for between 1 and 2% of the engine power, while loads much greater than used in engine design could be sustained.

Cooling oil going to and from the main piston entered and left via telescopic pipe connections to the crosshead, which also provided the lubrication for the crosshead guide shoes. Cooling oil going to and from the exhaust piston was provided by telescopic pipe connections attached to the exhaust piston yoke. Oil was supplied to the forked small-end bearings of the connecting rod through the crankshaft and big-end bearing, and oil was supplied to the small-end of the eccentric and the eccentric itself through the eccentric crosshead slides.

The two-stroke crosshead engine was first made with a 620 mm bore and a combined stroke of 1870 mm. The first of these engines, built under license by J. G. Kincaid Ltd in 1949, was a six-cylinder unit developing a shaft power of 3310 kW (4500 hp) at 115 rev/min. This was quickly followed by an engine with a 750 mm bore and a combined stroke of 2000 mm (1500 mm main stroke and 500 mm exhaust stroke). The first example, built in 1950 for a Norwegian tanker, was a seven-cylinder engine developing a shaft power of 5516 kW (7500 hp). Writing in 1957, Pounder[10] stated: 'Since 1950 engines of the type aggregating 514 850 kW (700 000 hp) have been built'.

Turbocharging

As was noted earlier, turbocharging of the B & W four-stroke engine had been introduced in 1929, although by 1926 the *Lochmonar*, built in 1924, had had turbocharging added. Experience had shown that the upkeep on these engines was

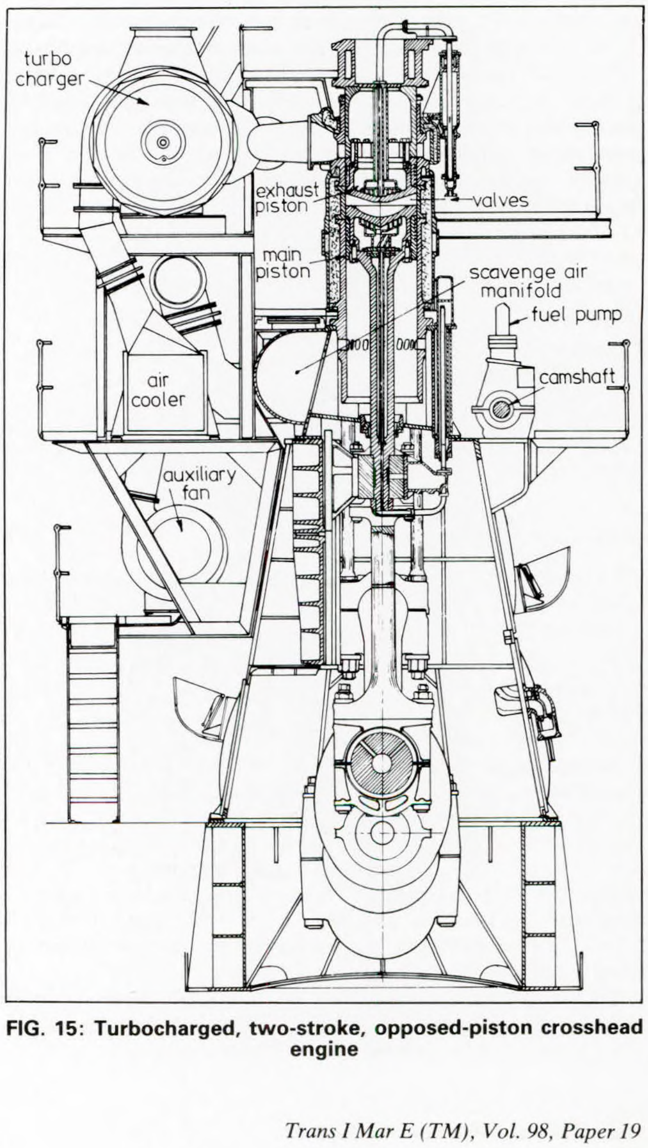

FIG. 15: Turbocharged, two-stroke, opposed-piston crosshead engine

surprisingly less than for engines having atmospheric induction, and in particular this applied to the life of liners. Pounder[10] attributed this to 'the higher temperature of the intake air, which was thus removed further from the region of the dewpoint'. So it was not surprising that by 1953 the first turbocharged two-stroke propelling engine was being manufactured, following successful preliminary work on a four-cylinder eccentric-type opposed-piston stationary engine of 370 mm bore and 825 mm total stroke.

The general layout of the engine, shown in Figure 15, was not vastly different to that of the non-turbocharged engine. Perhaps the main difference was in the use of a three-part liner with the upper and lower component parts being made of vanadium cast iron and with the centre section, which forms the boundary of the combustion chamber, being made of cast steel. However, there were some other modifications, such as stiffening of the crankshaft, which were made necessary by the increased loading.

The turbochargers were made by Napier and had an axial flow turbine coupled to a centrifugal compressor. They were located as close to the cylinder exhaust branches as possible to take advantage of the exhaust impulses. For slow running, when there was insufficient energy in the exhaust gases to drive the turbochargers, motor-driven auxiliary fans were fitted. With a modest supercharge of about 0.4 atmospheres, the engine power was significantly increased by 35% and the specific fuel consumption was slightly lower.

With an eight-cylinder engine of 750 mm bore and 2000 mm total stroke, a maximum trial trip shaft power of 10 297 kW (14 000 hp) or a continuous service power of 7943 kW (10 800 hp) could be produced. Pounder[10] noted that there was no difficulty in building a ten-cylinder engine, and with a 800 mm bore engine eight cylinders would produce 14 710 kW (20 000 hp), and with a higher level of supercharger could produce 17 652 kW (24 000 hp). In 1957 there was already 367 750 kW (500 000 hp) of pressure-charged engines delivered or on order. Figure 16 shows a typical example of a pressure-charged engine.

In the final years of the pressure-charged opposed-piston two-stroke engine a higher supercharge pressure was used and was provided by a new design of the Napier turbocharger. Two cylinder sizes covered the complete range of powers from 2942 kW (4000 hp) to 18 388 kW (25 000 hp). The smaller unit was of 600 mm bore and 1800 mm total stroke and provided a shaft power of 2942 kW (4000 hp) in four cylinders and 7355 kW (10 000 hp) in eight cylinders at 125 rev/min. The larger unit was of 750 mm bore and 2300 mm total stroke and provided shaft powers of 6620 and 18 388 kW (9000 and 25 000 hp) in four and ten cylinders, respectively.

Problems with the design

Considerable troubles were experienced with the bolted connection between the three-component cylinder liner in the pressure-charged opposed-piston two-stroke engine. These bolted joints were within the water jacket, which had been successful in other designs, but on this occasion numerous cracks, both in the flanges and bolts, were experienced, as enumerated by Pounder.[11]

These cracks were attributed to corrosion cracking, which arose from an incorrect choice of the material for the bolt and the poor detailed design of the joint itself. Ultimately it was overcome by using an earlier design of B & W in which the centre section of the liner was rigidly trapped between the upper and lower sections by the circumferential row of alloy-steel studs, as illustrated by Pounder.[12] There were no bolted connections in the water spaces and the combustion chambers were unusually sturdy steel castings.

Other problems arose with the eccentric strap and the white metal bearing. Cracking in 10 out of 1600 eccentric straps in service was noted by Pounder[12] and they were attributed mainly to the quality of the steel castings. However, this problem was overcome by using forge steel in the form of slab steel. Some problems involving cracking of the white metal were experienced, but Pounder stated that this did not occur when they were produced within H & W. With white metal bearings great care is needed to ensure adhesion of the white metal to the steel. Later designs incorporated white-metal-lined steel inserts, which were apparently satisfactory.

Improvements over 50 years

The development of the marine diesel engine from the first B & W reversible four-stroke engine to the H & W pressure-charged single-acting two-stroke engine within a period of fifty years demonstrates the never ending quest for greater power in a reduced space with decreased specific fuel consumption. Pounder[5,6,12] showed outlines of engines of the same power output, to demonstrate the great reduction in length and volume with corresponding reduction in weight achieved by the progression from the original four-stroke engine through the double-acting two-stroke engine to the highly supercharged opposed-piston two-stroke engine.

For example, the overall length for a single-acting four-stroke engine developing a shaft power of 2942 kW (4000 hp) was about 18 m, whereas the length for a low supercharged opposed-piston two-stroke engine was about 8 m. For an engine with a shaft power of 8826 kW (12 000 hp) the length of an unsupercharged two-stroke engine built in 1946 would have been just over 20 m, whereas for a supercharged two-stroke engine built in 1962 the length would have been just over 12 m. Pounder[13] compared two engines, an eight-cylinder single-acting four-stroke engine built in 1919 which delivered 4.41 kW/t (6 hp/t) and a highly supercharged single acting opposed-piston two-stroke engine with ten cylinders on offer in 1960 which would deliver 19.1 kW/t (26 hp/t), to demonstrate the great reduction of weight achieved in the period.

Improvement in fuel consumption figures are less easy to come by as test-bed figures on marine propulsion engines are not entirely meaningful. As Pounder[10] stated: 'But the author dislikes citing figures of this order as if they accorded with everyday practice, because too often they are apt to be quoted by managerial and non-technical men to the discomfort of operating engineers. The log abstract, recorded on the high seas, must necessarily have a different criterion than that of the test log dexterously compiled on an engine works test bed'. In 1957 Pounder[10] quoted a figure of 210 g/kWh

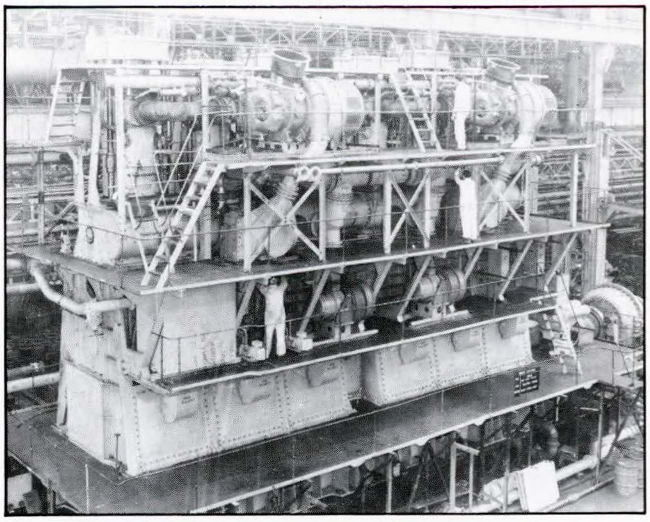

FIG. 16: Six-cylinder, turbocharged, single-acting, two-stroke, opposed-piston crosshead engine with a 750 mm bore and 2000 mm stroke. Shaft power 6250 kW at 110 rev/min. Installed in the *Ulster Star* in 1959

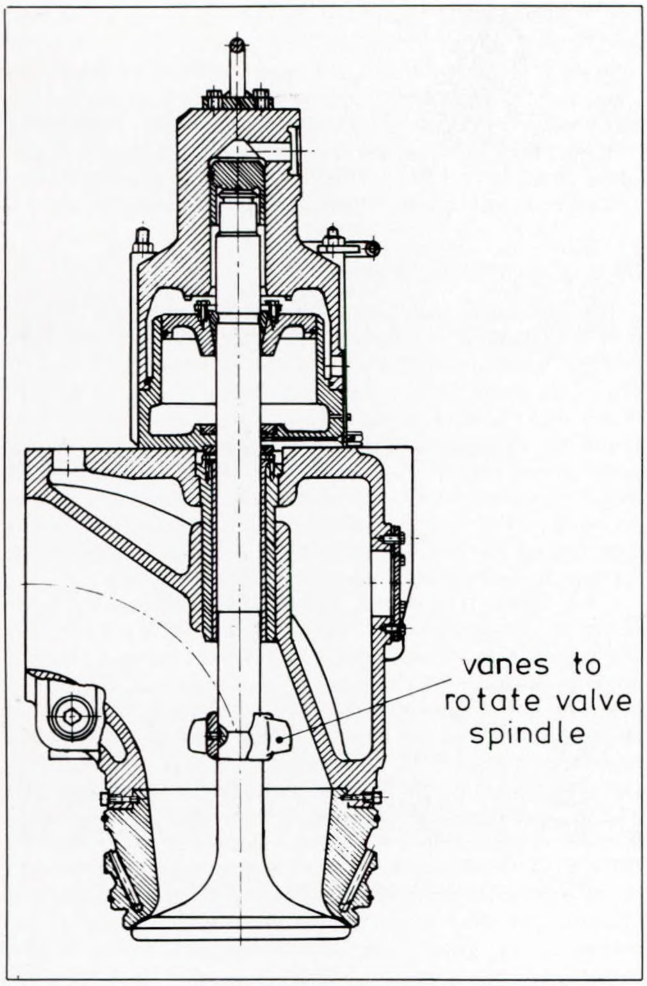

FIG. 17: Hydraulic actuated exhaust valve

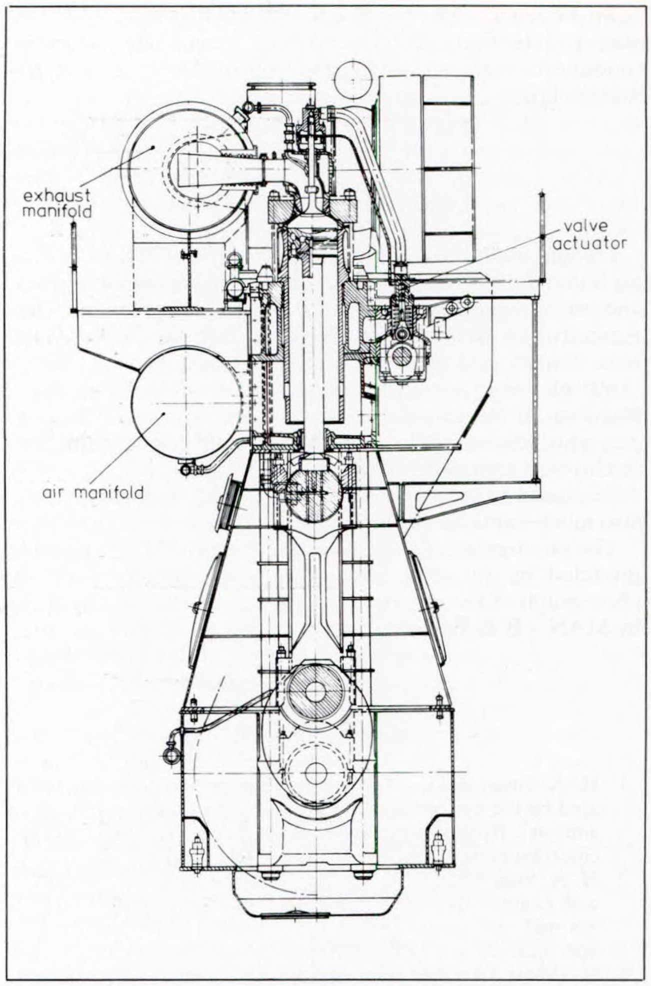

FIG. 18: Poppet-valve, two-stroke crosshead engine

(0.34 lb/hph), which is little different to that quoted by Pounder[6] in 1939 for double- and single-acting two-stroke engines.

EPILOGUE

With this apparently successful development of the H & W opposed-piston two-stroke engine the obvious question is, why did it come to an end during the 1960s? There are several reasons for its demise. In 1964 Pounder retired at the age of 71. Without doubt he had been a considerable driving force and had been in a senior position for many years and so had a strong power base. However, more importantly, his retirement coincided with a period of severe decline in shipbuilding in the Western World, and H & W suffered along with the rest. Under these circumstances it was no doubt difficult to justify continuing research and development for a rapidly declining market, especially when as licensees they could revert to being completely dependent on B & W for every detail.

Pounder[12] appeared to regard the poppet-valve two-stroke engine as inferior to the opposed-piston two-stroke engine on the grounds of the complexity of the poppet-valve operating mechanism, the need for a cylinder cover, with which he had bitter experience in both the double-acting four-stroke and double-acting two-stroke engines, and the noise and vibration associated with the valve gear. However, with the introduction of hydraulic actuation of poppet valves, shown in Figure 17, the complexity of push-rods, rockers and cams and their associated noise and vibration were largely overcome. Valve leakage with poppet valves was also reduced by fitting guide vanes to the valve spindle which rotates the valve.

It was also possible with a poppet-valve two-stroke engine to achieve optimum timing for running ahead or astern, which was not possible with the opposed-piston engine. Looking at the poppet-valve and opposed-piston designs objectively, there would appear to be no doubt as to the essential simplicity of the poppet-valve engine compared with the complexity of the eccentric drives, crossheads, side rods etc. of the opposed-piston engines.

There is, however, an alternative view that the demise of the H & W engines, and later the Doxford opposed-piston engines, was caused by a lack of understanding of the merits of the design. The apparent additional complexity of the design is partly offset by a simpler structure as the force on the upper piston is transmitted through the side rods and eccentrics, whereas with a cylinder cover the load is transmitted through the structure. There is an advantage in relation to balancing of three- and four-cylinder layouts, which makes these more acceptable. In the later Doxford design the cranks for the upper and lower pistons were 180° apart, so the engine developed the same power ahead or astern. The opposed-piston engine also gave a greater flow area of the exhaust ports compared with that of the poppet-valve, and also there was less obstruction to flow. Lastly, it is claimed that as the power is divided between the upper and lower piston a narrower, lower and lighter engine is obtained.

Whatever the truth, the poppet-valve two-stroke crosshead engine (Figures 18 and 19) has displaced the opposed-piston engine. With the largest B & W engine, with a 900 mm bore and 2916 mm stroke, the maximum continuous power per cylinder is 3710 kW (5040 hp) at 74 rev/min, which is more than double that of the first six-cylinder four-stroke engine of 1910. A twelve-cylinder engine of this latest design can develop 44 520 kW (60 480 hp). Even at the time of writing, a further extension of the B & W programme has been announced with a further power increase to 45 668 kW (62 040 hp).

ACKNOWLEDGEMENTS

I would like to thank Mr Rafton Pounder, who loaned me his father's collected papers and who has given me every help and encouragement, Mr John Parker, Chairman and Chief Executive of Harland and Wolff plc, and Mr Robert Harkness, Director of the Engineering Division of Harland and Wolff plc, who provided considerable assistance, and Mr R Milliken, of the Engineering Division of Harland and Wolff plc, who, amongst other duties, looks after the Engineering Archives. Comments on the first draft of this paper, which were passed to me by the Institute of Marine Engineers, were also much appreciated.

The photograph of the 1897 experimental diesel engine was provided by the Deutsches Museum, Munich, while the photograph of the engine room of the *Selandia* was provided by MAN – B & W Diesel A/S.

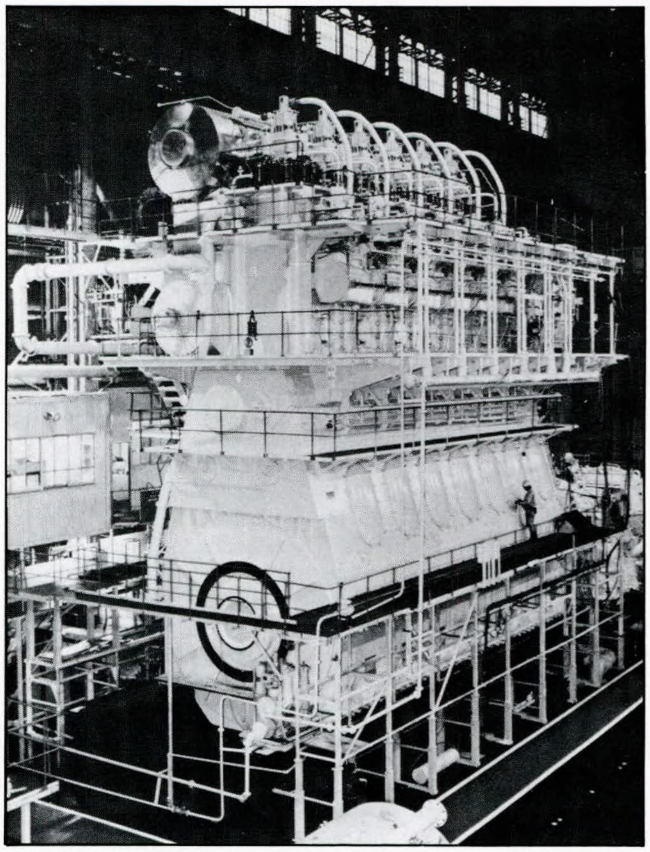

FIG. 19: 6L9OMC M.A.N. – B & W engine with a 900 mm bore and 2916 mm stroke. Shaft power 22 260 kW at 74 rev/min

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Discussion

J. McNAUGHT, FIMarE: As a member of the technical staff of Union-Castle, I knew Mr Pounder, and many of the other personalities referred to in the paper, very well. I think it is also worth mentioning that Mr A. Hammer sailed as Fourth Engineer on the maiden voyage of *Selandia*.

No doubt we can allow ourselves to indulge in a little nostalgia, but more importantly I believe that even today we can learn much from the experience gained in the operation of these engines and use it to avoid problems with more modern engines.

Although Union-Castle had a good selection of H&W–B&W engines, I shall concentrate mainly on the double-acting, two-stroke engines and our experiences with metal fatigue in them. Union-Castle operated this type of engine from 1935 to 1971 and I had experience of it for 32 of these 36 years, both seagoing and as a superintendent.

This machinery, despite fractured piston rods etc., served Union-Castle well and was fitted in mail vessels, intermediate ships and refrigerated and general cargo vessels. The total number of engines delivered to Union-Castle between 1935 and 1954 was 35, the total number of cylinders being 308 (1232 fuel injectors). Of these, seven engines with 54 cylinders were lost during the war. Again, 10 of the 35 engines were of layshaft design and were in three sizes of bore/stroke: 450/1200, 620/1400 and 660/1500 mm. The remainder were fitted with eccentric drive for the exhaust pistons and of two cylinder sizes: 620/1400 and 660/1500 mm.

Prof. Crossland has referred to fractured piston rods. Unfortunately, we suffered 33 or 34 such fractures and in many cases the crankshaft was damaged and required removal from the ship for repair. The change to EN16 steel for piston rods was a disaster, as stated in the paper, and mild steel rods were fitted as soon as practicable.

Many things were tried in conjunction with research bodies to alleviate the problem, eg rolled threads, hydraulic tightening of piston rod nuts instead of the heavy sliding tup, increased cross-sectional area of rod by reducing bore, introduction of articulated crosshead, ie gudgeon pin between crosshead and slipper, magnetic crack detection of rods and threads. Of these measures, the only one which counted was the crack detection.

When *Bloemfontein Castle*, a passenger ship, was built in 1950, the design was changed to a large outside diameter of piston rod and this design was repeated in two later general cargo ships. I do not remember a fractured rod in any of these 32 cylinders, measuring 620/1400 mm. The last fracture I recall was in one of the 660/1500 mm engines in 1959. The crankshaft was damaged and one journal had a 'throw' of 3 mm. It had to run in this condition for about a year before the ship could be withdrawn from service for repairs to be made.

What else fractured by fatigue? There is a long list, but strangely what appeared to be a disease on one engine size generally missed the other sizes. Exceptions to this were piston rods and exhaust piston driving rods.

On the 450/1200 mm engines, the layshafts fractured but this did not happen on the 620/1400 and 660/1500 mm engines. On the 620/1400 mm engines, the bolts securing the bellcrank bearings of the exhaust piston driving gear fractured with serious results. Again, this fault was confined to this engine size.

On the 660/1500 mm engine, the layshaft chains fractured and occasionally came through the chaincase doors. Constant inspection was necessary to prevent these fractures, and the number of spare side plates, pins etc. for these 147 mm chains was large. Again, this was confined to this engine size. In 1946–47 these chains were renewed and three Renalds 4 in matched chains were fitted per engine. There was no more trouble for the following 20 years of service.

I remember Mr Pounder discussing the fractures in the 147 mm pitch built-up chains with James Gray, who was Union-Castle Chief Superintendent Engineer, and referring to 'polygon action' as the cause of the fractures. His statement was that if the pitch of the chain was not an exact multiple of the distance between shaft centres, acceleration and deceleration took place as the link engaged with the sprocket wheel, causing an abnormal stress which initiated the fatigue cracks. I would like to ask Prof. Crossland if he has come across this phenomenon.

The use of cuttering to provide a good landing for bolts and nuts which interfered with the radius of, say, a keep on a connecting rod palm caused much fatigue trouble on the double-acting engine.

I think the most unusual fatigue fracture I have seen on a double-acting engine was through the bottom half of a bottom end bearing. The fracture had started in the corner of the dovetail for holding the white metal. Thereafter, we attempted to detect cracks when we were about to remetal and found cracks on a few occasions.

In conclusion, I would say how much I admire and wonder at the decision making of 1933 onwards when Mr Pounder, owners' representatives etc. had to design, build and operate brand new designs of engines with very little, if any, shop testing, and it says much for marine engineers that these engines operated for tens of years, and some are probably still operating. I contend that these engines were successful.

S. HANSEN (formerly Chief Designer, B&W): As I am the only person still alive who has been connected with B&W engineering since 1928, and thus have some inside knowledge of the last 56 years of the 72 year connection between H&W and B&W, I have been asked to comment on Prof. Crossland's paper and pay a tribute to the memory of the late Mr Pounder.

It was not until the war came to an end in 1945 that I came into personal contact with Mr Pounder, and we remained in contact after our retirements until a couple of years before Mr Pounder passed away. I came greatly to admire Mr Pounder for his common sense, for his practical engineering abilities, and for the way in which he, a master in his mother tongue, could make his long and wide experience live in his narrations.

Prof. Crossland is to be complimented for an excellent review of the types and sizes of the B&W engines built by H&W in the period from 1914 to 1964, when Mr Pounder retired. I have to admit that during my first reading it irritated me, because it gave me the impression of being unfair to B&W, which was also the reaction of some of my former colleagues. But on reading the title again and after studying the paper it dawned upon me that it was not intended to give a full story of some B&W engine types, but their story within H&W and some, but not all, of the irritation evaporated. The passages based on the memory and views of one person from one side can never be accepted as historic truth.

I shall only discuss a couple of the purely technical questions raised in the paper and in the references. We did not, at the time of issue, agree to all the statements in the references, but these points were discussed with Mr Pounder or with members of his staff while he was still a director in H&W. The present M.A.N.–B&W technical leaders in Copenhagen therefore find no good reason to blow new life into these old arguments, and I agree.

In 1937 eccentrics on the crankshaft were not new to B&W, as they had from 1930 been used on a number of 150 mm locomotive engines, 220 mm auxiliary engines, and 500 mm propulsion and stationary engines, and the end of their era came in 1935 with the delivery by Kincaid of two eight cylinder, 620 mm engines. In these engines exhaust pistons of smaller diameter than the main piston were connected by means of oblique rods to one eccentric movement. The engines were expensive to build and resulted in the poppet-valve engine in 1935. Eccentrics were also used in the second generation of 620 mm, double-acting engines.

In 1937–1938 I was stationed in the USA, and letters and documents in the engineering files were destroyed by fire in 1943 following bombardment by Spitfires. I thus do not know why B&W should have intended to connect the top pistons of the experimental 550 mm double-acting engine to a layshaft with cranks. It might have been in order to obtain better balancing by using a longer top piston stroke and so avoid the reduction in mechanical efficiency associated with the large diameter eccentrics and full diameter exhaust pistons. A 1–2% decrease in mechanical efficiency meant just that much in fuel consumption where it had to complete with existing loop- and cross-scavenged engines.

Another reason might have been fear of the difficulties of producing satisfactory steel castings for the semi-built crankthrows, which were necessary for certain cylinder numbers. As a matter of fact a number of such roughly machined crankthrows, particularly for the 750 mm engine, landed on the scrapheap before satisfactory casting techniques were found.

The first 350 mm double-acting engines to be built were two eight cylinder units for Alfred Holt. They were shipped from Copenhagen in 1939, but unfortunately they were in Hamburg when the war broke out.

On page 9 of the paper Prof. Crossland notes that the cooperation was at that time a partnership of equals, and I wonder in what respect he means this.

H&W was by far the biggest firm in the family of licensees and, judging from the records from previous years, was most likely to build the largest number of the double-acting engines in question. Their views would therefore carry heavy weight as long as they were technically and economically justifiable.

I believe that the leaders of B&W at the time wished to end the era of the double-acting engine. By 1938–1939 the 620 and 740 mm, single-acting, crosshead, poppet-valve engines had been designed and featured a short piston which reduced the engine height. The diaphragm between the scavenging air box and the crankcase made the engines well suited for burning heavy oil, which was bound to come, and B&W four-cycle engines in the fleet of Compagnie Auxiliaire de Navigation of France had run on heavy oil since 1934 with good results. Furthermore, following calculations on the available energy, exhaust turbocharging of two-cycle engines had been suggested as a future possibility.

As for the single-acting, opposed-piston engines, it was H&W who during or right after World War II conceived the idea of cutting the cylinders of the double-acting engines in two and only use the upper part combined with the B&W short piston and diaphragm. Because of the success of the Doxford engine, Mr Pounder maintained, until 1959 when he seemed to be in doubt, that opposed-piston engines were the only type that would be accepted by owners in the UK. H&W designed the first 620 mm engine and B&W never had drawings of it.

A search of the M.A.N.–B&W files proved that B&W designed a seven cylinder, 750 mm engine in 1947 but it is not clear whether drawings were sent to H&W or only to Akers. Apart from Kincaid, who was a sub-licensee and thus unable to choose, Akers was the only B&W licensee to opt for this type of engine. H&W delivered the first unit in 1950 and Akers in 1953 to the same owner. Thus both might have used the B&W drawings.

As far as turbocharging goes, the picture is not quite so flimsy. From the files it is quite clear that in 1953 B&W made drawings of the 620 and 750 mm engines showing modifications for turbocharging. These drawings were then sent to Akers.

Following our presentation of the world's first turbocharged, two-stroke, poppet-valve engine in 1951, H&W, in cooperation with Napier, began turbocharging experiments on an existing small, uniflow engine. Napier were efficient sales people and convinced H&W that it should be the tail wagging the dog, with the result that H&W took a licence from Napier for turbocharging and construction of turbochargers.

Developments were thus following two slightly diverging roads, but as usual details and topical matters were discussed at numerous conferences in which never recorded drawings were exchanged between the two firms. We did not consider that timing of the ports was optimal and suggested changes, but H&W relied on their suitability with Napier chargers. We were also sceptical of using the gas pressure injection system which had been used on some previous engines. H&W insisted on its use but agreed to modify it to timed injection.

H&W had experienced vertical cracks at the fuel and starting valve pockets, but they had propogated so slowly that the majority of liners were in service at the time of discussion. H&W therefore retained this type of cylinder for the turbocharged engines. We had experienced cracks beginning at the outside because of casting difficulties. These were overcome by modified casting techniques.

As described at great length by Mr Pounder (Ref. 11 of the paper), it soon became obvious that these cylinders were not satisfactory and they were replaced by cylinders with a steel combustion chamber to which liners were bolted by flanges in the water space. This design also failed after a short time in service. We were not informed of this grave situation until members of the H&W staff came to Copenhagen to seek advice for urgent repairs of the flanged design in order to keep the ships in service.

We knew from experience confirmed by subsequent calculations in the late 30s that flanges of these dimensions were bound to fail in single-acting engines, where there were no compressive forces from staybolts as in double-acting engines with cylinder covers. We suggested and made drawings for provisional repairs and designed a cylinder with steel combustion chambers with joints outside the water space. The slightly modified design was adopted by H&W (Ref. 11 of the paper, Fig. 5b).

As similar quickly propagating cracks did not occur in the Akers engines, I believe that the very short lives of the two first cylinder designs were influenced by the aforementioned timing and the gas injection system, which produced an injection pattern different from that of the jerk pump.

On page 3, Prof. Crossland advances the view that Mr Pounder might have wished to sever the connection between H&W and B&W. This is not my impression, and more than once I heard Mr Pounder say: 'Copenhagen is our Mecca'.

At the time of his presidential address, Mr Pounder must have observed the faltering of the once so predominant British and European shipbuilding industries. He had experienced the tremendous investment that is necessary for the development of new engine types and for the production of drawings for all the cylinder numbers, even if it only consisted of modifications to other diameters or working principles. He must have seen the advantages of concentrating research, development and design by the licensor in a family of licensor and licensees working in close cooperation.

He knew that the idea of forming a single-acting, opposed-piston engine by combining ideas from the B&W double-acting engines and single-acting crosshead engines had not met wide acceptance outside UK, as was also the case for the Doxford engine. In spite of this B&W had introduced this engine to the family. Why Mr Pounder did not use this advantage to its full extent has puzzled many people within H&W.

The aim of the passage in his presidential address was probably to impress on the British critics that licensing was not

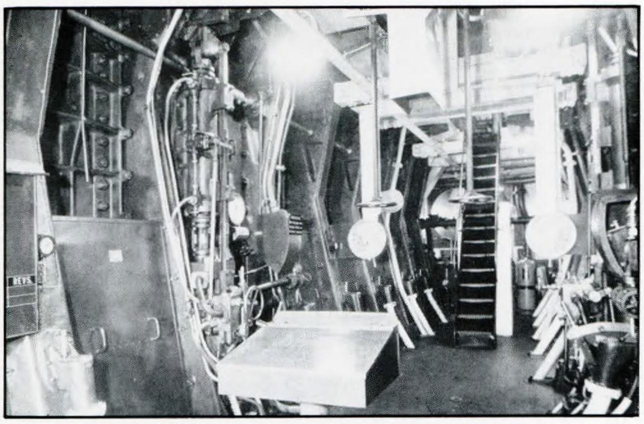

FIG. D1: Engine room of *New Zealand Star* showing starting platform

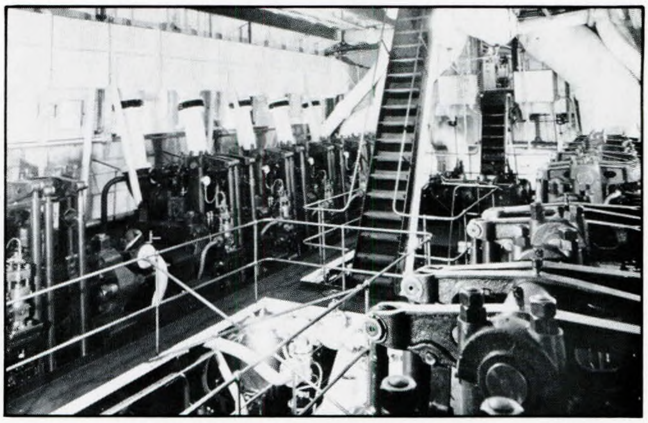

FIG. D2: Engine room of *New Zealand Star* showing top platform

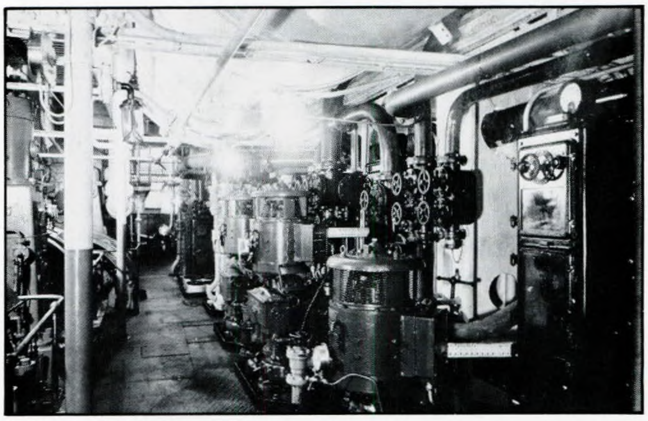

FIG. D3: Engine room of *New Zeland Star* showing bottom of main engine

caused by any lack of engineering knowledge and skill in UK engineers, a view with which in my opinion all other engineers in the world would agree. As a matter of fact, the connection still exists after 72 years, which may be a record for any branch of engineering. Considering B&W's financial crises of 1930 and 1972 we do not seem to have spun much gold as licensors.

Finally I have to thank Prof. Crossland for including an 'Epilogue' dedicated to the present day M.A.N.–B&W poppet-valve engine and thereby setting the previous part of the paper in relief. This engine system is now the only one remaining in the slow-speed, direct-coupled field, and is at the same time the world's most economical prime mover using combustible substances. It might be of interest here to note from the minutes of the 1959 meeting of B&W licensees that Mr Pounder said that the situation in the UK was changing and H&W was at a crossroad. The competition from Doxford was less keen and one firm after another had taken licences from Continental engine builders, including for the Götaverken poppet-valve engine. It was a perplexing problem to decide which way to go: poppet valve or opposed piston, but it is not difficult to guess what Mr Pounder would have opted for today.

H. E. TUNE, FIMarE: Prof. Crossland's graphic summary of Mr Pounder's involvement in and influence on the diesel engine scene of the 1930s to 1960s is of great interest, I am sure, to all those who had the fortune to be even in the smallest way associated with him and his developments. Many of the ships mentioned in the paper, and Mr Pounder's engines in them in particular, are well known to me as they formed a memorable part of my career involvement.

Of the original orders placed by Blue Star Line with H&W around 1933, the two ships *Imperial Star* and *New Zealand Star* preceded *Australia Star*, albeit by only a few months, on the contract programme. These two ships were fitted with the twin screw, ten cylinders per side 740 mm bore modestly pressure-charged, single-acting, four-stroke engines described by Prof. Crossland as the predecessors of Mr Pounder's double-acting engines. In these two ships pressure charging was applied by a Buchi blower.

Imperial Star was lost during the war but *New Zealand Star* survived to go to the breakers only in 1967. Figures D1, D2 and D3 show *New Zealand Star's* engine room in about 1962 when outward bound from London on voyage 61 to Australia and New Zealand and still very much in regular service.

These engines were truly leviathan but performed reliably and uneventfully for some 30 years. Having had 12 months experience on my first trip to sea in 1942 in Bibby's *Somersetshire* (also built by H&W in 1924) and with the twin-screw, single-acting, four-stroke installations noted by Prof. Crossland as the early 1920s generation, complete with blast injection and salt-water cooling, I can say no more than that on my first sight of the *New Zealand Star* I was suitably impressed by Mr Pounder's later improvements.

In the very short time from first placing orders for these Blue Star Line contracts Mr Pounder must obviously have persuaded my predecessor to join his march of progress and fit his new double-acting engine in *Australia Star*, which was the third ship of this programme, in 1936. As Prof. Crossland's figures show, the reasons are obvious. In physical terms the improvements in power against weight and space requirements meant an increase in pay load on these ships of some 25 000 ft^3, an argument which is always irresistable to Chairmen of any generation.

The increase in complexity, however, heralded quite another story. Prof. Crossland skims lightly over the exhaust piston driving arrangement in these first engines fitted to both *Australia Star* and *Sydney Star* and describes it as a 'secondary chain-driven crankshaft'.

In fact this arrangement was an expedient forced upon Mr Pounder by some nervousness on the parts of the Board of Trade and Classification Society to accept the increase in web span between main bearings which would have been needed to incorporate Mr Pounder's original proposal of main engine eccentrics. The driving arrangement finally adopted was a lay-shaft-driven oscillating bellcrank gear to provide the exhaust piston reciprocating travel. The twin bellcrank gear per cylinder weighed some 4 tonnes and incorporated a multiplicity of forklink/gudgeon bearings. In the tight design spaces later lamented by Mr Pounder the efficiency of locking devices was a nightmare and specific bearing loadings were relatively high.

Rapid bearing weardown throughout the system was a routine feature with all the consequent misalignment of the lower exhaust piston yoke involving gas gland blowpast and regular cases of piston sleeve firing. Dismantling of the whole

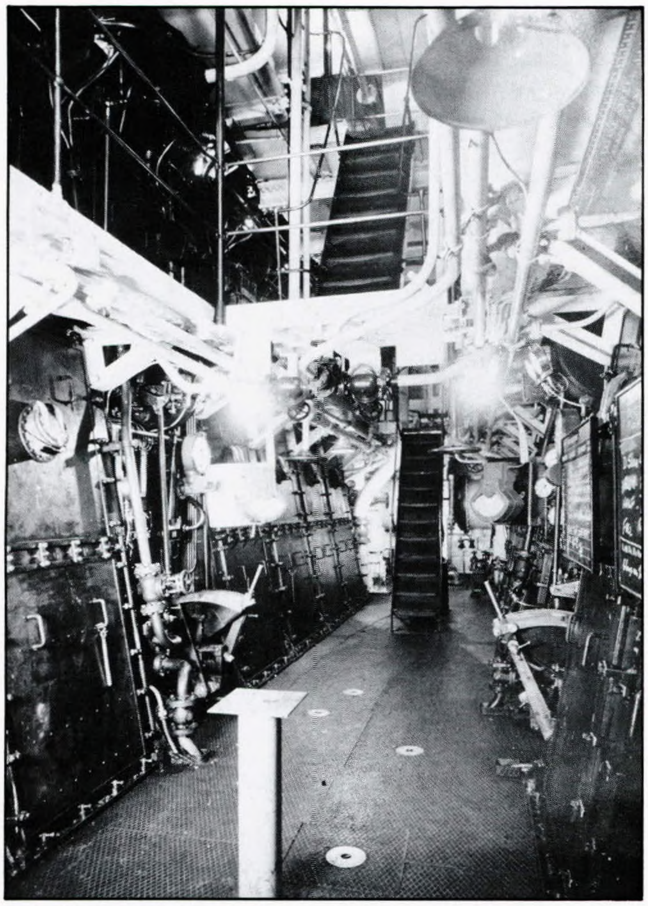

FIG. D4: Engine room of *Empire Star* showing starting platform

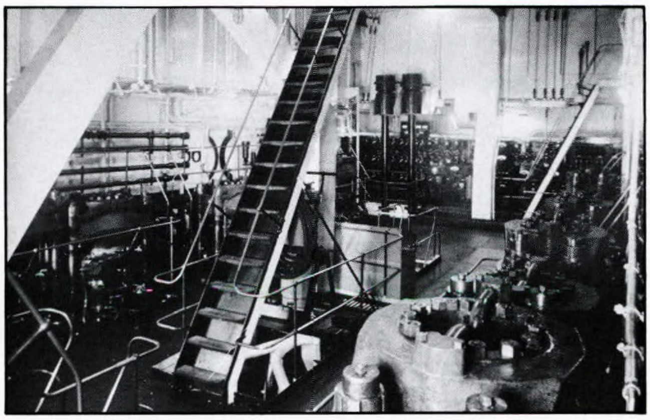

FIG. D5: Engine room of *Empire Star* showing top platform

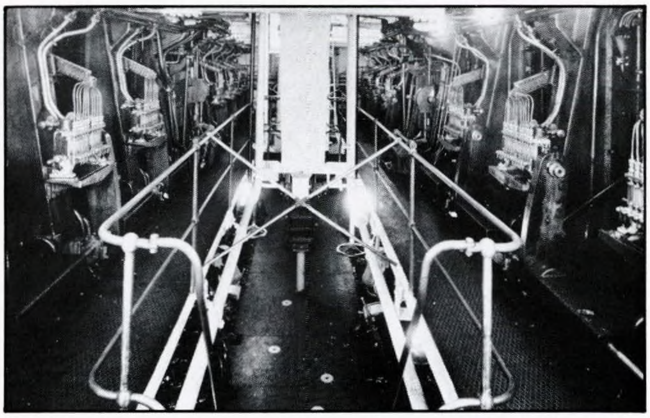

FIG. D6: Engine room of *Empire Star* showing lower middle platform

bellcrank complex for repair and refitting was a frequent occurrence. The dual roller driving chain, specially designed by Reynolds, weighed some 5 tonnes and at least twice in my experience broke unexpectedly in service at 98 rev/min and deposited itself neatly out of the crankcase and on to the main engine room platform.

As Prof. Crossland says, the arrangement was very rapidly disgarded for the totally reliable arrangement of eccentrics in this type of engine and in its successors, opposed-piston engines. Having got the bellcranks, however, in *Australia Star* and *Sydney Star* we managed to run them until these ships went to the breakers in the early 1960s.

Prof. Crossland has summarized all the problems of piston rod failure with which all operators of this type of engine will be totally familiar. The root causes have perhaps best been expressed by Mr Pounder himself.

A spate of lower cylinder cover cracking in these earlier engines together with the maintenance requirements of the bottom exhaust piston aggregate added to the problems of the management of these ships, as did the number of cylinder valves requiring frequent overhaul (96 in the *Australia Star* class). Nevertheless, these engine types did run and were run well by a generation of marine engineers who, in recognizing the challenge of Mr Pounder's innovations, contributed their part to the march of progress.

A welcome move to the full-bore exhaust pistons also arrived as a 'first' in *Devis*, and also in the largest installations of these types in *Empire Star* and *Port Hobart*. The engine room of the *Empire Star* is shown in Figures D4, D5 and D6.

The engines in these latter two ships had the first of H&W's fully fabricated steel bedplates. These had a serious defect, manifesting itself after a few years service as cracking of the main bearing housing welding attachments to the main bearing girders. *Port Hobart* reported this problem during a voyage homeward from Australia and returned directly to Belfast for a complete new bedplate to be fitted in both engines.

On arrival in the UK from Australia, *Empire Star* was examined and found to have a total of nine main bearing girders similarly affected throughout the two engines. These were repaired in Liverpool by rewelding on site with the subsequent distortion of the main bearing housings being controlled within certain limits. This was later accommodated by specially remetalled main bearing bottom halves. The repair took three weeks, the crankshaft alignment deflections being recovered to within + 5/1000 of an inch. Nine spare main bearings machined to the individual new crown thickness of the repaired main bearing girders were provided in the spare gear racks onboard but were never subsequently required.

The introduction of the single-acting, opposed-piston engines in the mid-1950s, together with increased supercharging, had immediate benefits in reliability and reduced workload, marred only in Blue Star Line by the initial stages of bolt fracturing in the tripartite combustion chamber. This has been noted by Prof. Crossland and appeared, at least within Blue Star Line, to disappear entirely once they had been modified as described. This exercise produced a considerable interchange between Blue Star Line and H&W with a number of experimental approaches until its final solution.

Mr Pounder did once confide in me at this time that he had 'begun to think that this had been his greatest problem'. Bearing in mind his style and his track record in solid accomplishment since 1933, I have always suspected some tongue in cheek histrionics for my benefit in that particular remark.

In summary, it is perhaps interesting to note the original prime initiatives of the 1930s to improve power against weight and space requirements and there is no doubt that Mr Pounder's double-acting, two-stroke crosshead engine was a major milestone in that direction. It is also worth noting that Mr Pounder's fuel figures of 1939 and 1957 (0.34 lb/bhp h) remained stable until around 1980, with fuel costs at that point then prompting the lead initiative.

As a final comment, I have sympathy with Mr Pounder's dislike of quoting operational fuel performance figures and not least I am grateful to Prof. Crossland for illuminating Mr Pounder's typical and, as always in my experience, most valuable earlier comments on this subject. His enlightenment might be helpful in some quarters as a refreshing contribution to much of the topical dialogue on fuel performance.

Fortunately those with the responsibilities of providing and running ships do not confine their choice of engine selection to the Yellow Pages, but it is interesting and at least comforting to learn that Mr Pounder, as an engine builder, was not unaware of the pitfalls in the lack of clear understanding of this complex area.

J. N. MACKENZIE, FIMarE: Along with hundreds of other engineers I have vivid recollections of the engines referred to in this paper. The first 10 cylinder, double-acting, two-stroke engine running on the test bed over 50 years ago was a magnificent sight I will never forget. However, I believe that we should look back with constructive assessment to avoid repetition of design weaknesses.

By the time H&W started diesel production in Belfast, about half the diesels afloat were B&W. Popularity must have been assisted by the reliability associated with the simplicity and robustness of the single-acting, four-stroke design.

Considering the choice of H&W-built four-stroke engines by many shipping companies, the close link between H&W and the Kylsant shipping group should not be overlooked. Many of the single-acting and all 30 of the double-acting engines were supplied to companies within the group at a time when Lord Kylsant was chairman of both the shipping companies and of H&W.

The double-acting, four-stroke engine with its blast injection and numerous exhaust valves for hand grinding was a work-intensive design but offered a better power:weight ratio and higher powers. It appears to have been B&W's answer to the Sulzer competition. Could Prof. Crossland please comment on the power:weight ratios of the competing designs.

The B&W double-acting, two-stroke engine was a complex and adventurous design and they were brave engineers who decided to adopt it. I believe that their decision was correct as these engines, despite their problems, had remarkably long and commercially successful lives, with less than half the fuel consumption of contemporary steam plant. My comments on problems may sound a dismal catalogue of failures but in normal running they were some of the smoothest diesels I have encountered and it was possible to balance a penny on edge on the cylinder cover when developing full power.

Piston rod failures were merely one of the more common breakages on those engines, my first experience of this being on my first voyage to sea. The most spectacular failure I witnessed was a broken exhaust piston tie rod and consequent disintegration of the top of the unit. Valve pockets being ejected from cylinder covers like mortar shells was not uncommon. As the engines aged there were examples of fatigue failures in a large proportion of components, except crankshafts and bedplates. Piston rod fatigue involved numerous variables and very wide varieties in life expectancy, from breakage at well under 50×10^6 cycles to complete freedom from cracks at over 500×10^6 cycles. Prevention by limiting life would have been both unsafe and uneconomic.

The successful life of these engines owed much to the dedication of Engineer Officers and Superintendents in conducting and devising preventative maintenance. Major factors included unit overhaul, improved alignment, strain measurement in tightening and non-destructive crack detection. Proprietary equipment failed to reveal cracks even on rods found to be seriously cracked when sectioned. Later, magnetic equipment of the owner's design was so successful in detecting cracks that there was a severe shortage of spare rods. Subsequently, developments in ultrasonics enabled the depth as well as the peripheral extent of a crack to be monitored. Piston rods were withdrawn when found to be cracked but non-dynamic components were monitored over years until the progress of cracking was considered to be excessive.

These engines were very difficult to work on and all aspects of inspection and overhaul were in marked contrast to the Doxford engine. Mr Pounder's 1937 note on this is interesting as nine years later he made a coastal voyage to observe our newly acquired single Doxford engine in a fleet of H&W engines, including about 220 double-acting cylinder units. His questions and remarks indicated that he was impressed with the accessibility.

My personal contact with the H&W opposed-piston crosshead engines was limited but the design appeared to be reasonably successful. This was also true of the trunk piston design used for driving generators. These were some of the most unsatisfactory engines I have encountered, in particular suffering severe wear of the eccentrics.

What can we learn from the engines? For anyone able to observe them and their records over a long period I believe that they provided an invaluable education in the problems of complexity, fretting and fatigue. Even today one sees features in new engines likely to create fretting and fatigue which critical observers of older engines might avoid. Owners are not consoled by a prototype that shows no cracks after 10×10^6 reversals, and their interest is in the engine when it is 10 to 20 years old.

During my association with these engines I had quite a lot of contact with Mr Pounder as I was sent to Belfast by my Chief Superintendent to investigate various problems. I was always courteously received by Mr Pounder who, considering he was thirty years my senior, lent a sympathetic ear to my awkward questions and attempted to assist.

His answers were sometimes enigmatic. After a paper at this Institute I asked him what he thought of the future of marine nuclear energy. He paused and looked at me with a wry smile before proclaiming emphatically 'that, Mr Mackenzie, will be your problem, not mine'. I am pleased to say that it was also not my problem.

R. HARKNESS, FIMarE: In Prof. Crossland's most informative paper he has skilfully managed to give a great amount of detailed information on the development of the slow-speed diesel engine in what we might call the 'Pounder era' in a most interesting way. If I may be permitted to add a little more detail, I think it is also interesting to look at the very rapid increase in the adoption of the diesel engine for ship propulsion by H&W and the numbers of engines produced during the time of Mr Pounder.

When he joined the Company in 1916, about 11 engines had been built at what became known as the Finnieston Works in Glasgow. By 1920, an average of 12 engines per year were being produced and by the mid-1920s this had increased to over 20 engines per year. To add to the technical and drawing office workload in support of this level of production, in 1921 the Greenock firm of J. G. Kincaid became a sub-licensee for the H&W–B&W engine programme, which was also supported from Belfast. In 1926, when the first engines were built in Belfast, the technical support requirement for the three production works, including J. G. Kincaid, was for over 30 engines per year and in 1930 this had risen to an all time record of 73 slow-speed engines built during that year.

When one remembers that engine development was a continual process and considers the complexity of the engines and the varied ship installation layouts, the required design and drawing office support was indeed phenomenal.

In all, during Mr Pounder's time with H&W, he would have had involvement with some 800 slow-speed engines of the types described by Prof. Crossland built either at Belfast or Finnieston and with a further 370 built under sub-licence by J. G. Kincaid. During this same period, H&W was designing and building shipboard generator engines and land-based power station generator engines, oil pipe-line pumping engines and even some 22 locomotive engines. The grand total is 2117 large diesel engines covering a wide range of designs, which may be said to have in some way come under 'the influence' of C. C. Pounder.

A. NORRIS, FIMarE: Mr Pounder belonged to the generation of design engineers with proven ability and the courage which expected new designs to work satisfactorily, first time, when an engine was built; he is remembered with respect by marine engineers. Prof. Crossland has produced an excellent paper reviewing early diesel engine history and the evolution of the H&W–B&W engines. To complement this it may be of interest to mention some of the characteristics of these engines as seen from the user's viewpoint.

My first introduction to the engines discussed in the paper was in 1932. The ship had formidable looking twin six cylinder 680 mm × 1400 mm DA4SC engines, of a total 7500 ihp/5700 bhp. They are shown in Figure 7 of the paper. These air-injection engines were very reliable and in 10 voyages, totalling more than 150 000 miles on a tight passenger liner schedule in the West African service, no stoppages at sea were necessary and there was only one delay in leaving port on time which was caused by a leak from a salt-water-cooled exhaust mainfold.

In my opinion this reliability was partly because of excellent atomization of fuel by 60 kg/cm^2 blast air in fuel valves which had been developed over two decades, and partly because of the ease of keeping such multi-cylinder normally aspirated engines in balance by levelling exhaust temperatures once the cylinder powers had been balanced. Such performance was only possible because of the expertise of the Engineer Officers (9 out of the 10 in that ship at the time were certificated) in their dealing with the many awkward and arduous jobs presented by changing the valves which served the bottom cylinders and the multitude of non-return valves in the three-stage main engine air compressors.

The earliest design I personally encountered was in MV *Aba* which had been built about 1918 and when completed was the first large diesel-engined passenger liner in the world. The twin 750 mm × 1100 mm SA4SC engines had round section cylinder covers, instead of the rectangular section of later years, and as the ship was 20 years old when I joined the engines had to be treated with great respect. After 'Full away' the fuel valve roller clearance had to be smartly increased before the engine was throughly warmed through, otherwise the exhaust valves would be burned out. The ship had some history of broken crankshafts on the main engine and on the 200 rev/min auxiliary engine. There was some vibration at sea which caused the mast heads to flutter towards each other and led the S.B. Naval Ratings on board to call her 'The Weeping Willow'! In retrospect this was significant but in such a riveted ship with heavy scantlings the vibration was not obstrusive in hotel or machinery spaces.

On page 6 of the paper Prof. Crossland mentions the six *Elder Dempster* cargo ships which were built in the 1930s with airless injection 740 mm bore SA4SC engines. There were early problems with cracked pistons which may have been accentuated by fuel atomization being inferior to that obtained with the earlier blast injection valves. The cracking was overcome by changing the material and making the piston in two parts, but the bolted circumferential joint provided was liable to leakage and required refacing after a year or so in service. As the bottom end of the cylinder was open the liner surface could be sighted for oil traces showing piston leakage, but if the observation coincided with a blow-past from the rings the viewer was liable to be sprayed with partly carbonized oil! The large diameter drive shaft to the fuel pumps was fitted with a multi-plate friction drive arrangement to avoid chattering of the line dog clutch which catered for timing correction when reversing; the plates were liable to wear and need unscheduled adjustment at sea.

A twin screw 620 mm × 1150 mm SA2SC poppet-valve engine (as shown in Figure 9 of the paper) which developed a total of 7200 bhp was notable for the extremely noisy Rootes blowers and the regular incidents of cylinder cover cracking, so much so that cylinder lift was measured by adapting the engine pressure indicator: if the lift increased it was necessary to reduce power on that cylinder. This particular passenger ship, built in 1935, was fitted with a Clarkson silencer-economiser in the main engine exhaust system to provide 500 lb/h of steam at 100 psig for hotel services.

Engines of the opposed-piston, turbocharged, crosshead type (as shown in Figure 15 of the paper) had, in addition to the problems mentioned in the paper, difficulties with white metal cracking in eccentric straps and, as with earlier B&W designs, in main crosshead pin bearings, but these normally only came to light when the parts were opened for survey. They also had a surprising incidence of scavenge belt fires if the specific air flow was reduced because of blower faults or falling shaft speed for a specific power following ship or propeller fouling. However, the engines were a robust and popular design and gave good service over their lifetime, but they were also rather heavier than the engines then available from competitors.

With reference to the 'Epilogue', other reasons for the poppet valve B&W engines (as shown in Figure 18 of the paper) supplanting the H&W opposed-piston engines during the early 1960s were the increased emphasis on savings in engine weight and engine-room length, which were necessary to increase the cargo space. A further factor was the very good reputation of the B&W engines then extant; however, the type K-EF which replaced them introduced some problems, but that is another story and no way detracts from the excellent results obtained from B&W engines over more than half a century.

J. BERRING, FIMarE: I do not think that it is right to support Mr Pounder's statement to the effect that the opposed-piston engine was designed in Belfast (page 9 of the paper). The original design of the opposed-piston engine came from B&W in Copenhagen. This development happened after pressure from H&W who had experienced severe trouble with cylinder covers and were feeling the competition from Doxford, who had overcome this problem by designing their successful coverless engine. The original drawings came from Copenhagen, but Mr Pounder was able to change details in every drawing without informing the licenser.

This can clearly be seen by the fact that B&W themselves have never been able to supply replacement parts to H&W opposed-piston engines. At the same time B&W did build a few engines of this design in Copenhagen, as did their licensees in Norway, Akers, who delivered a total of 54 opposed-piston engines with 391 600 bhp. The drawings for those engines surely did not come from Belfast.

In the 'Epilogue', Prof. Crossland asks why the opposed-piston engine came to an end in the 1960s. In my opinion this was an obvious development. The poppet-valve engine had been developed to a very high degree and Doxford had neglected to move into higher powers than could be installed at their own shipyard. The problems with cylinder covers had been solved and scavenge fires had become a serious stain on the reputation of the opposed-piston engine. Only British and Norwegian owners would accept this type of engine, and even they became fewer and fewer, and so H&W lost many orders.

However, the most important factor is that the poppet-valve engine was much cheaper to produce. H&W was in fact under great pressure from their sub-licensees, Kincaid, who knew this, and found it increasingly difficult to compete with the much cheaper Sulzer RND engine which had become dominant in the British market. They were also under pressure from B&W, who had seen their market share in Britain dwindle, and for whom I opened a London office in 1961. The purpose of this office was to provide the British market with a more popular and competitive engine, if the British licensees could not do so. Neither Sir Frederick Rebbeck nor Mr Pounder like this idea, but they were presented with it as a fait accompli.

This is all history now and I am pleased to see that Mr Pounder's name is again before us. By retiring as late as he did, he created friction with his co-directors, and as a consequence of this there was a tendency to blame him for everything that later went wrong at H&W. I believe that if he had retired a couple of years earlier he would have been a much happier man himself, and everybody else would have been glad to regard him as one of the most important and interesting personalities in British marine engineering, which he truly was.

J. E. H. APPLEBY, FIMarE: Prof. Crossland's historical review is of considerable interest and supplements one of the basic ingredients of good design, namely a good record of what has gone before.

The section entitled 'Early co-operation between H&W and B&W' is interesting to me as I served my Apprenticeship in Marine Engineering with Barclay, Curle and Company and was subsequently engaged on design in the main engine drawing office for a further 12 years. It was there that I learned from my older colleagues of the trials of the two B&W engines installed in 1912 in MS *Jutlandia* for the East Asiatic Company. Apparently there had been no shop test of these engines but only a protracted basin trial followed by sea trials, which seemed to have been hectic to say the least!

Moving on to the section entitled 'Double-acting crosshead engines', I suppose that such an arrangement probably gave at most a 40% increase in power allowing for the massive cross-sectional area of the piston rod. It is intriguing that combustion in the bottom end of the four-stroke engine cylinder was satisfactory in view of the enormous clearance volume necessary to accommodate the valves and their lift.

In the section entitled 'New design considerations' I am not surprised that 85% of main engine maintenance costs were incurred at the bottom end of the cylinder and get the impression that H&W were now motivated by the undoubted success of the much simpler Doxford LB engine, which was basically an extremely sound concept. Doxford claimed for this engine that the time to open up and examine a cylinder was 15 min, with only the upper piston and guide assembly bring removed.

I remember assisting in this exercise on the test bed to convince a doubting Superintendent Engine that this was feasible. It took us about 20 min to expose the line bore, notwithstanding the fact that we had all the necessary tools laid out rather like a cutlery set on a dinner table and a complete monopoly of the overhead power crane!

The Doxford concept allowed confident adoption as long ago as 1933 of one of the most successful welded engine constructions ever used. Following in Doxford's footsteps H&W were able to use the lighter welded structure upon adoption of the full diameter, short stroke, exhaust piston. Continuing with the double-acting concept meant twice the number of piston rings and piston crowns as required in the single-acting engine, plus the tormented stuffing box rings. Again the double-acting principle denigrated the design.

In the section entitled 'Problems with the design', eccentric straps are mentioned. I hark back to the IMechE Fifteenth Thomas Lowe Gray Lecture of 8 January 1943 when Mr Pounder made his memorable remark recollecting 'the old-time steam eccentric — grunting, in its trough of soapy water, as if in perpetual protest against its designer's violation of every law of lubrication'. The H&W eccentric must have presented some anxieties, particularly with regard to lubrication, because of the poor length to diameter ratio. Perhaps some of the cracking could have been caused by lack of stiffness in the plane parallel to the engine longitudinal centre-line. Nevertheless the design made a very compact, stiff and cheap crankweb possible.

A similar length to diameter ratio was adopted later by Doxford for the 'J' engine main bearing journals. I believe that some thought was given to the possibility of stiction in these journal bearings creating a high starting torque. Unlike the H&W engine, the bearings in the Doxford engine only carried the weight of the crankshaft and not any of the firing loads.

The Doxford three-throw crank had low torsional stiffness, which sometimes imposed barred crankshaft operating speeds because of torsional vibration reasonance. Such a crank arrangement did, however, permit the adoption of differential strokes for the upper and lower piston to give equal WR values (ie the product of weight of reciprocating parts and radius of crank), so achieving perfect rotary and primary balance for each cylinder. Such an elegant design was not possible with the H&W short-stroke, double exhaust pistons.

It is possible that the opposed-piston design for slow-speed marine engines reached its apogee on account of the limitations of mechanisms to harness the power of the upper/outer pistons. I think it would be difficult to sustain higher firing loads on either the eccentric or the three-throw crank with the white-metal bearing linings usually associated with such arrangements.

Other bearing lining materials with high load carrying capacity are less tolerant of difficult lubricating conditions, as in the eccentric, or of minor distortions of the crankpin of the three-throw crank under torsional strain. These potential restrictions are avoided with the conventional single-throw crank, which has generous proportions and large overlaps with the poppet-valve engine.

Moreover, I do not agree with Mr Pounder's opinion that poppet-valve, two-stroke engines are inferior to the opposed-piston, two-stroke engine. Indeed, some of today's most successful slow-speed marine engines are of a simple uniflow, poppet-valve design, and as Prof. Crossland says 'simplicity is the hallmark of good design'.

Skilful design and development work in the medium-speed engine field has shown that if thermal and mechanical strains are fully appreciated, highly rated poppet-valves and steel piston crowns and cylinder heads can be incorporated. This work has been extended by forward-thinking manufacturers of slow-speed marine engines. Such engines now incorporate bore-cooled cylinder heads and piston crowns along with poppet-valves and simple short and stiff single-throw cranks.

R. J. DAVIES, MIMarE: I found this paper to be compulsive reading, not least for the fact that I sailed as Fourth Engineer on one vessel fitted with H&W–B&W blast injection engines, the *Highland Chieftain*. Because of this admittedly short experience, I would like to make a few comments.

It seemed to me, as a steam/motor engineer, and in the light of limited experience of both blast injection and solid injection (surely 'liquid' injection would be more suitable?), that one of the most noteworthy advances in the progress of the CI engine resulted from the perfecting of the 'jerk'-type fuel pump, which rendered the air injection engine obsolete and made the 'solid' injection design practised. Bearing in mind the fact that while manoeuvring in and out of port the air compressor of the main engine was unable to cope with the task of supplying both starting air and blast air (thus necessitating the use of the auxiliary engines to augment the blast air), it seemed that the task of maintaining blast air pressure (and its eventual demise) was, to the operating engineer, one of the salutary differences between the old and the new systems. I note also that there is no reference to fuel pump design in the paper.

I well remember one of a number of occasions (this particular one occurring whilst manoeuvring out of the River Tagus) when the blast air pressure was inadvertently allowed to fall below its safe limit of (I believe) 20 atm (working pressure 25 atm). The first indication of malfunction was a noise which struck me at the time as being like a sudden loud chord from a church organ. There was then a hasty scramble up the ladders to shut off fuel and air to the damaged fuel valve, which on removal appeared to have had the business end removed by means of an oxy-acetylene burning torch.

Those of us who manned the H&W engines were of the opinion that under-sized exhaust pistons were used (as also eccentrics) in order to avoid infringement of the Doxford patents. I was constantly surprised (as a steam 'up and downer' man) to see eccentrics being used to drive a crankshaft!

F. C. BOWN, FIMarE: I would like to congratulate Prof. Crossland on an excellent paper, which must have brought back both pleasant and unpleasant memories to many marine engineers.

I would, however, like to draw Prof. Crossland's attention to page 7 of the paper, where it is stated that the first diesel engines to be built at the H&W Yard in Belfast were fitted to the *Asturias, Alcantara* and *Carnarvon Castle*. It should be noted that the *Asturias* and *Alcantara* were both re-engined with steam turbine plant in the early early 1930s. The slide that Prof. Crossland showed of the *Asturias* must have been after 1939, as the vessels until that time had two funnels. I believe that she and her sister ship were converted to Armed Merchant Cruisers at the outbreak of World War II, when one funnel was removed. Therefore, the smoke which engulfed the *Asturias* in the photograph could not be attributed to the large double-acting, four-stroke engines, but to the three Babcock Johnson boilers.

J. McAFEE, FIMarE: In 1921 I joined Harland & Wolff as a pupil apprentice, my father paying the company for this privilege, and reading the paper evoked memories of my early days in the Belfast engine works, where in 1926 I witnessed the erection of the first main diesel engine constructed there. This was the massive double-acting, four-stroke engine illustrated in Figure 7 of the paper and based on the experimental engine constructed by B&W.

Professor Crossland has outlined the events from 1912 onwards which led to H&W acquiring a licence from B&W, but was there a skeleton in the cupboard? One morning I poked my head into a small power station within the shipyard and found it contained a six-cylinder Sulzer engine with a massive flywheel coupled to two generators. Sometime later I learned from Prof. J. H. Smith, a predecessor of Prof. Crossland, that this engine had broken more than one crankshaft, probably because of a severe torsional critical, and he had been asked to find a solution.

The decision by H&W to purchase this engine from Winterthur must have been taken sometime previous to the outbreak of war in 1914 and presumably to gain experience of the Sulzer type. It is briefly mentioned in one of Mr Pounder's papers but with no comment. Is it possible that at the time H&W had not yet come to a decision and but for a broken crankshaft might have taken up a different licence?

Shortly afterwards I entered the diesel drawing office, then under the control of those Danes who, like Vikings, had arrived in Belfast a few years earlier. I also met Mr Pounder, then a leading draughtsman in the pipe arrangement office. He had already shown his literary ability in a handbook on the balancing of engines in which I found an explanation of the high-sounding 'Yarrow, Schlick and Tweedy System', now of historical interest only.

Figure 4 of the paper gives me pleasure as it shows the very engine with which I first went to sea. I completed the maiden voyage and then joined a sister ship, where for a whole year we sailed leisurely about the world never exceeding 90 rev/min and 1900 bhp and without any mishap. Forty years later an engine of the same dimensions, except for a slightly increased stroke, was delivered by H&W to develop 10 800 ihp at 120 rev/min. After I left the King Line I was disturbed to learn that cracks had developed in the bedplates and these had to be renewed in all nine ships.

The massive double-acting, four-stroke engines for *Asturias* and *Alcantara*, which began the programme at Belfast, were apparently not satisfactory since after about five years in service both ships were fitted with steam machinery, causing an uproar at a meeting of the shipping company's shareholders. The similar but not so highly rated engines in *Carnarvon Castle* survived with the attention of the owners eminent superintendent James Gray. In retrospect it is easy to see that these massive and complex engines were in advance of their time. Mr Pounder himself wrote many years later 'in the evolution of marine machinery it is always the simple and commonsense design which ultimately prevails' but by then he had retired from the scene.

The 1920s spawned a number of British-designed large marine diesel engines of which only the Doxford type survived, in accordance with Mr Pounder's dictum. No one has written the story of the seagoing engineers who in those days had to keep some of these engines in operation. I had experience of two, one of which had twin Vickers engines so that, at sea, hopefully one engine would endure whilst we repaired the other.

Then there were the two ships with Beardmore/Tosi engines which all pilots boarded with apprehension. One had hit the quay in Liverpool with such force that a large crane fell over across the bows. With uneasy feelings I became Second Engineer on the other and for nearly a year, with a good team, managed to keep the machinery in operation until I decided to leave the sea. On my very last voyage, entering port one morning the engine controls failed to operate and to the frantic sounds of the bridge telegraph we ran full speed ashore, a shattering experience.

The great depression was now at its height with little work for marine engineers ashore, but I returned for a brief time to the diesel drawing office in Belfast and was occupied with engines for the Bank of England, which had ordered its own private electricity supply system in case of civilian unrest and disturbance.

When I departed for another career Mr Pounder, now Chief Draughtsman, helped me on my way. Our paths crossed often in succeeding years and I remember in particular an occasion during the last war when I happened to be in Belfast and he asked me how long should be the time to raise steam with a cold Scotch boiler. It was a question that any uneducated fireman could have answered but he smiled with content when I suggested about twenty hours. Later I discovered that new boilers of Scotch type had been fitted by his firm in some Admiralty ships and had developed cracks, claimed to be caused by bad design. It was typical of Mr Pounder's detective instinct that he suspected the real cause.

Mr Pounder was born towards the end of the Victorian age when the self-help advocated by Samuel Smiles enabled a man from modest beginnings to rise to the top. It is unlikely that we shall see his type again in the world of engineers where progress is now determined by academic qualifications.

Our last meeting was in Belfast after he had retired. Some time later he sent me a copy of his book *Healers from Another World*. When he died the local press, in an obituary notice, described this as 'a remarkable chronicle of psychic experience'. It was indeed, but then the eminent physicist Sir Oliver Lodge claimed to have been in contact with his son Raymond long after the latter's death. We who remain in the tents of Kedar (a phase of Mr Pounder's) can only wonder.

H. D. MAKINSON, FIMarE: The paper gives a neat synopsis of the history of the H&W–B&W engines and some ships. Mention of the *Lautaro* recalled my abiding image of white-haired engineers made old before their time on the 'L' boats.

The single-acting, four-stroke engine shown in Figure 4 of the paper was a big improvement on earlier engines. Readers may not realise that with regard to the head valves the term 'air' refers to both air inlet valve and air start valve. The arrangement for keeping the air start valve roller clear of the cam when not required was ingenious. The independent air compressor was hardly ever used because of its very high starting load and only resorted to in dire circumstances! The air reservoir pressure was normally kept up by leaking-off from the high-pressure blast air system at about 60 bar down to near 25 bar for the starting air. Alternatively the starting air was kept topped up from the generator blast air system.

I would be glad if Prof. Crossland could comment on some other milestones in the engine history, such as when the change was made from salt-water cooling of the cylinder jacket to fresh-water cooling on a closed system. Leaving Victoria Dock in London in January with the type of engine shown in Figure 4 of the paper often meant that the circulating water was like 'ice water' at 37 °F. There were steam heating connections to each cylinder, but they were all blanked off and never used.

I see that the double-acting, four-stroke engines were built from 1926 and, to the best of my knowledge, these were all fresh-water cooled, but MV *Gascony*, on which I sailed, was equipped with a 1926-built, salt-water-cooled four-stroke engine of the type shown in Figure 4 of the paper.

The *Britannic* and *Georgic* had unique engine rooms, each housing the two 10-cylinder engines. The blast air compressors were driven separately in the generator room by four four-cylinder diesel engines. It was probably the most complicated arrangement of blast air bottles and delivery pipes and leak-off arrangements ever designed.

It would be interesting to know if the piston rod fractures only applied to the double-acting, two-stroke engines, many details of which appear in the Thomas Lowe Gray Lecture of 1951 by James Gray of Union-Castle, or whether the double-acting, four-stroke engines had any similar difficulties. The double-acting, four-stroke engines did not have single slipper guides but had shoes on both column faces. Whilst in theory and practice the shoe operates in engines grossing a total of millions of kW (horsepower) without any defects, I wonder if the double-acting, two-stroke engine would have behaved better with a two-shoe arrangement.

Since so many old engines are being kept on land in mills and other places, and such a fuss is made over many lesser items, it is disappointing that not a single cylinder from a double-acting, four-stroke engine or a double-acting, two-stroke engine have been kept for posterity in the Science Museum. As Prof. Crossland so rightly says, the double-acting engines were 'tremendous engineering achievements'.

Amongst the features that can never be adequately recalled are the unenviable tastes left in the mouth from the various gas leaks from the glands or bottom exhaust pistons of a double-acting engine or leaky exhaust of the early single-acting engines.

I. R. MICHAELSON: One of the recollections I have is of the number of cylinders liners waiting at the repair berth to be changed for liners that cracked during the voyage. This reflected the ability of the ships engineers to maintain service schedules under very arduous conditions, a factor glossed over in the paper but well remembered by the Chief Engineers now watching over in the celestial control room. One cannot overlook the contribution by Lloyd's Register of Shipping surveyors who assisted in overcoming the many problems encountered with the double-acting engine during the period when the engine was a leader in the British shipbuilding industry.

It is not my intention to detract from the enormous research and energy Mr Pounder carried out to make his engines leaders in their class, but it is generally considered by Chief Engineers in Australia that the Doxford engine adapted better to conditions existing at the time now referred to nostalgically as 'the good old days'.

No doubt Mr Pounder would have been elated to know his brilliant career has been remembered by such a well documented paper.

Author's reply

I would first like to thank all the contributors for their immensely interesting comments and recollections. Any one of the contributors could, I am sure, have written a more authoritative, interesting and informative paper. They have the advantage of personal experience of these 'leviathan' engines, while I can only rely on what I have read and gleaned from talking with people.

These contributions provide a truly historic record, based on the experience of engineer officers and superintendents, and I believe this more than justifies the effort required to write this paper. For me what has come out of the contributions and verbal discussions is an even greater respect for the seagoing engineers, who were faced with the task of keeping these engines running while at sea, and for the superintendents ashore, who instigated modifications and developments aimed at improving their reliability. It does not surprise me that engineer officers and superintendents have been so much in demand throughout industry. They have experienced nearly every form of problem associated with machinery and they have had to make do and mend and modify and develop to achieve acceptable reliability.

Mr McNaught asked about failure of chains used in the secondary chain-driven crankshaft employed on the early double-acting, two-stroke engines. He mentions Mr Pounder referring to 'polygon action' as the cause of chain fractures. Despite much thought this mechanism of chain failure is not clear to me.

I particularly welcome the contribution from Mr Hansen. He is perfectly correct that I concentrated my attention on the collaboration between H&W and B&W, and particularly in the building and development of the double-acting, two-stroke engine, which led to the opposed-piston, two-stroke engine with which Mr Pounder was so deeply involved. To have presented a full story of the development of the B&W engine types would have required a book rather than a paper. I hope that somebody will take on this task before records are lost and memories fade.

Mr Hansen has added enormously to the information presented in my paper and he confirms that the single-acting, opposed-piston, two-stroke engine was conceived by H&W during World War II. On reflection, it may be that I read too much into Mr Pounder's statement about having to provide details of every change and improvement made during World War II to their licensor. There was no doubt that he had a great respect for B&W but I suppose it is natural for every licensor, especially when they have been by far the biggest licensee, to develop itchy feet and to contemplate if they can go it alone.

Mr McKenzie asked me to comment on the power:weight ratios of competing engines in the 1920s, but unfortunately this information is not readily available to me.

Mr Berring's statement that the opposed-piston, two-stroke engine was an original design from B&W seems at variance with Mr Hansen's statement. I think the truth of the matter is that Mr Pounder was instrumental in its design and development in Belfast, but obviously in many of its design features it relied on B&W practices. As stated by Mr Hansen, H&W 'conceived the idea of cutting the cylinders of the double-acting engines in two and only used the upper part combined with the B&W piston and diaphragm'.

Mr McAfee refers to a six-cylinder Sulzer engine in the power station in Queen's Island. According to Mr Pounder (Ref. 4 of the paper), licences had been taken out with other engine companies previous to the association with B&W. 'Also to obtain first-hand experience of Sulzer engines, an engine having six cylinders, 760 mm bore by 1020 mm stroke, delivering 2610 kW at 125 rev/min to direct-current and alternating-current generators, was purchased from Winterthur for the power station at Queen's Island. This engine which is still in use (1948) was at that time the largest Sulzer engine in the world and probably the largest diesel engine of any kind then existing'.

I would again like to thank all the contributors for their most interesting comments and recollections.

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