The Multi-Cylinder Approach contributed by D. Napier & Son Ltd to Piston Engine Development, 1898 – 1950.

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D. Napier & Son Ltd, Engineers of London founded in 1808, were led from 1896 by second generation Engineering Director Montague S. Napier, who both designed and developed internal combustion piston engines with two, four or six cylinders, for automobile and marine propulsion, but by 1920 had produced a first sixteen-cylinder Napier 1000 bhp aero engine. During his twenty-year search for improved volumetric efficiency M.S. Napier utilised multiple poppet valves, with operation ranging from Atmospheric Pressure to Double Overhead Camshafts. Development of the twelve-cylinder "Triple Four or Lion" aero engine from 1917 with new 20 type series spanning a twenty-year period led by designers Napier, Rowledge and Wilkinson, will be analysed, as the power output rose from 450 to 1350 bhp when supercharged. Its airborne achievements included two Schneider Trophy successes, these being followed by powering many British World Records in the air, on land and on water. Design of M.S. Napier's twenty-four-cylinder diesel aero engine preceded his death in 1931, after which the multi-cylinder, air-cooled designs of Frank Halford appeared, these having poppet valves, as the high revving sixteen-cylinder "Rapier" and twenty-four-cylinder "Dagger" aero engines. Capt. George Wilkinson continued with diesels, the six-cylinder aero "Culverin" having twelve opposed pistons – built under license from Junkers – these anticipating the Napier eighteen-cylinder "Deltic" opposed piston marine diesel engines, to be reviewed from 1946. Conversion by Halford of Napier's water cooled sleeve valve diesel into the big petrol-fuelled twenty-four-cylinder aero "Sabre" between 1935 and 1942, will be covered in detail up to its final two-stage supercharged and inter-cooled "E122" version of 1947, this to give 3350 bhp.

The Turbo-Compounded Diesel, twelve-cylinder "Nomad I" aero engine will be reviewed in all its complexity, this progressing to a simplified "Nomad II" version from 1949 onwards, which was to almost end half a century of Napier I.C. design innovation.

KEYWORDS: Design Diversity, Induction Ingenuity, Record Reliability, Turbo-Supercharging, Turbo-Compounding

Designed with Precision

It would be hard to think of any British company other than D. Napier & Son founded in London in 1808 by a Scot, David Napier, for which the "Piston Revolution" conference's title is more relevant. Before the Great Exhibition at the Crystal Palace, Napier made his inventive son James his partner, so forming D. Napier & Son in 1847 (Figure 1). They built for the Bank of England the highly sensitive "Automaton" gold sovereign sorting machines, in addition to steam driven printing presses. This highly profitable combination led to the use of Napier double-platen printing machines by the Bank of England for printing Britain's bank notes from 1853 to 1880, hence the Napier telegraphic address of "Moneyer-London" in use up to 1960. The residue of this "official work" work came down to David's youngest Grandson, Montague S. Napier, following his father James's death in 1896. Montague utilised afresh the old Vine Street Works at Lambeth for internal combustion development.

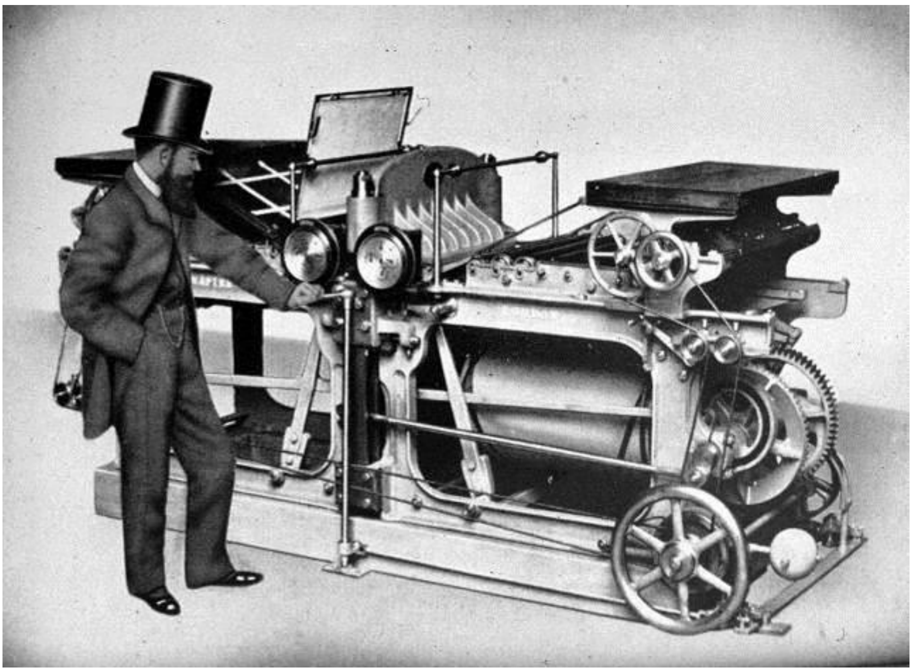

Figure 1. James M. Napier (the "Son" and partner within D. Napier & Son) seen in 1860 with a Napier double platen printing press, designed to print bank notes for the Bank of England.

D. Napier & Son could now move forward into the twentieth century with a new competitive British product, designed to meet the challenge from the Continent of Europe where the internal combustion engine was already established as a new prime mover for land and water transport. Montague having successfully produced his first four-stroke 2-cylinder petrol engine, installed in a light NAPIER motorcar, demand soon required a move to bigger works in Acton, West London from 1903. Here, an Engine Type Register was started from design "E1", this running unbroken for 75 years until 300 engines had been listed from Napier design offices. Of these diverse designs, more than 200 were piston engines, some being well into the Napier gas turbine era. This list contained engines having numbers of cylinders ranging from two to thirty two, while the many developments of each design were also given later type numbers. For example; there appeared 30 types of "Lion" during a twenty-year period, while no less than 90 "Deltic" variants were listed between 1946 and 1968.

From Lambeth Works in 1899 there came the sound of a new product under test, it being the first Napier four-stroke petrol engine of 8 HP, having an aluminium alloy block and crankcase. It comprised two in-line cylinders, each fed fuel-air mixture from a simple updraft carburettor via 3 suction operated poppet inlet valves, while ignition was by electric discharge from a trembler coil, this from the start being required by M.S. Napier and S.F. Edge. That pioneer 2.45 litre petrol engine design was the fitted to the first NAPIER motor carriage in 1900, which finished second overall in the round Britain "Thousand Miles Trial "of that year, this against the strongest continental motoring competition. By 1901, the sixteen HP, four-cylinder engined Napier model was capable of 60 mph, these being chosen by British racing drivers such as Charles Jarrott and Charles Rolls. A four-cylinder racing car, weighing just 1000 kg, with a 6.4 litre engine (Figure 2), now with induction via four atmospheric inlet poppet valves per cylinder, was entered and driven by S.F. Edge himself winning the 1902 international "Gordon Bennett Trophy Race" for Great Britain between Paris and Innsbruck.

The major development at Acton Works in 1903-1904 was the design and production of the world's first six-cylinder engine car (Figure 3), being shown at the 1904 Crystal Palace Motor Show. Such a Napier was comparatively quiet and smooth in acceleration, it having three twin cylinder-blocks mounted above a single crankcase containing a six-throw crankshaft, and had overhead inlet valves, now mechanically operated. This six-cylinder engine had Design Type No. "E 1" in the register, so setting the innovative multi-cylinder engine course at Acton, which was to be continued with increasing effectiveness for over half a century. Two other six-cylinder engine designs are noteworthy over the next twenty years, during which Napier had adopted time the "L-Head" design of valve arrangement for high performance cars, these having cam driven rocker operated overhead inlet valves, while exhausting via side valves.

Firstly a racing machine, known as "L48 – Samson", had such, with six cylinders of 6¼ in. bore by 6 in. stroke, this leaving Acton Works for a World Land Speed Record attempt in 1905 on Daytona Beach, Florida. Napier Works Driver MacDonald did achieve Britain's first record at 104.65 mph, this made against

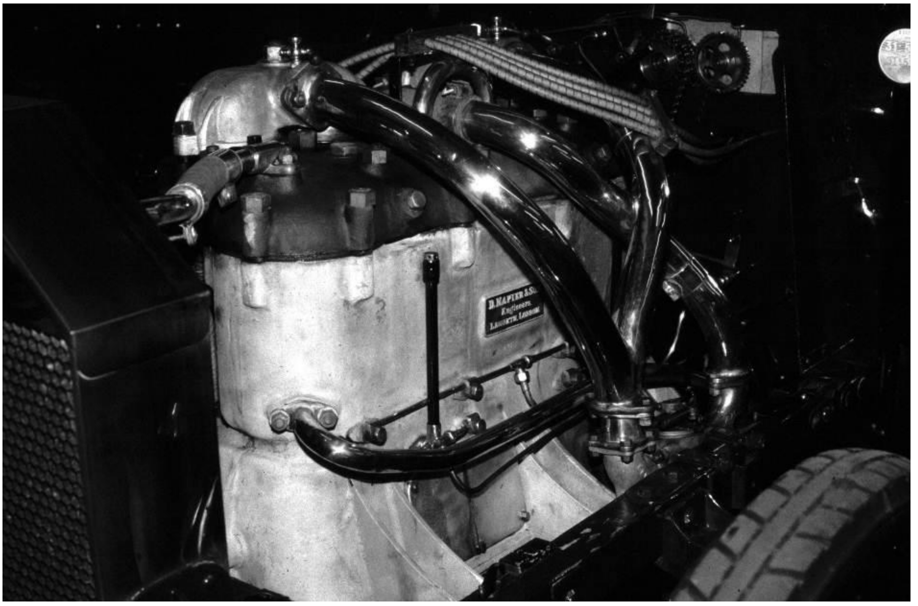

Figure 2. A 4 cylinder, 16 inlet valve NAPIER Gordon Bennett race car engine of 1903.

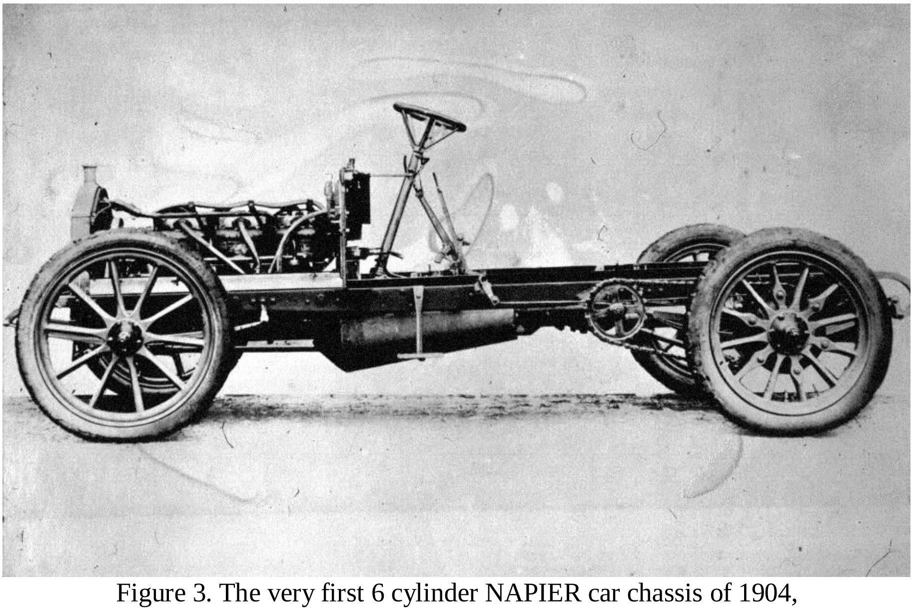

Figure 3. The very first 6 cylinder NAPIER car chassis of 1904,
having engine Type No. E1.

strong Mercedes and Fiat competition. A replica of “Samson” now runs in Australia having that actual “E10” engine, the three fine Daytona silver trophies now being on display at Brooklands Museum. More such records awaited a Napier aero engine from 1927.

Eleven years later, and designed to aero engine standards of lightness and reliability, the last Napier “E52” six cylinder car engine was introduced to power the “T75” car chassis. This 6.1 litre unit of 4 1/8” bore by 5” stroke had a 4.8:1 compression ratio, induction being by single overhead camshaft operating inlet and exhaust poppet valves. It produced 82 bhp at 2000 rpm, giving that final model of Napier motor carriage a top speed of just 60 mph. Its strong, but only rear-braked chassis, offered for both limousine and coupe cars, did not sell well to 1924, when car and commercial vehicle production at Acton was curtailed by M.S. Napier their Governing Director, he being determined to move the company towards an all aero engine business.

New Power for Flight

Wartime experience at Acton had by 1916 convinced M.S. Napier that there was both a need and an opportunity for the development of an aero engine of medium power, having greater strength and reliability than those currently available to the Royal Flying Corps, batches of which Acton works had dutifully manufactured under Ministry of Munitions contracts since 1914. With the departure of S.F. Edge in 1912 and constant repeat military orders for existing Napier vehicle types for the forces, designing was welcomed by Napier and Rowledge for an unusual Napier “Triple Four” aero engine incorporating advanced new features ahead of the existing types. Design, prototype build, and ground test proceeded apace during 1917-18, so that an engine was submitted ready for flight-testing at Farnborough before the armistice late in 1918. It had a robust four-throw forged “slab” crankshaft running in roller bearings, set under three banks of four cylinders arranged in “W” configuration, with a vertical bank and two side banks set down at 60 degrees, this requiring four master connecting rods, each with a pair of hinged side rods, these masters working on crankpins. Three sets of overhead valve gear were driven by bevel gears from off the crankshaft rear, their shafts reaching up to three pairs of double overhead camshafts (Figure 4). These operated two inlet and two exhaust valves in each cylinder, so giving sixteen poppet valves per bank and forty eight valves per engine. The cubic capacity of this “E64 Lion” engine was almost 24 litres, from twelve cylinders of 5½ in. bore by 5 1/8 in. stroke which, combined with a compression ratio of 5.8:1, gave an output of 450 bhp at 2000 crankshaft rpm, into a single reduction gear to the propeller shaft. Carburettors were both single and double Napier-Claudel updraft units, positioned up front, while BTH magnetos were positioned to the rear, this being standard for all service “Lions”. Later, triple carburettors were also placed at the rear end, as in the “E89 Series 11” of 1928, with a 6:1 compression ratio giving 530 bhp at 2350rpm. That engine type was the power unit of John Cobb’s “Napier Railton” car, the holder at 143.4 mph of the Brooklands lap record since 1935, which went on to average

150.5 mph for 24 hours in 1936 on Bonneville Salt Flats, USA. This car still runs today with its original “Lion” aero engine.

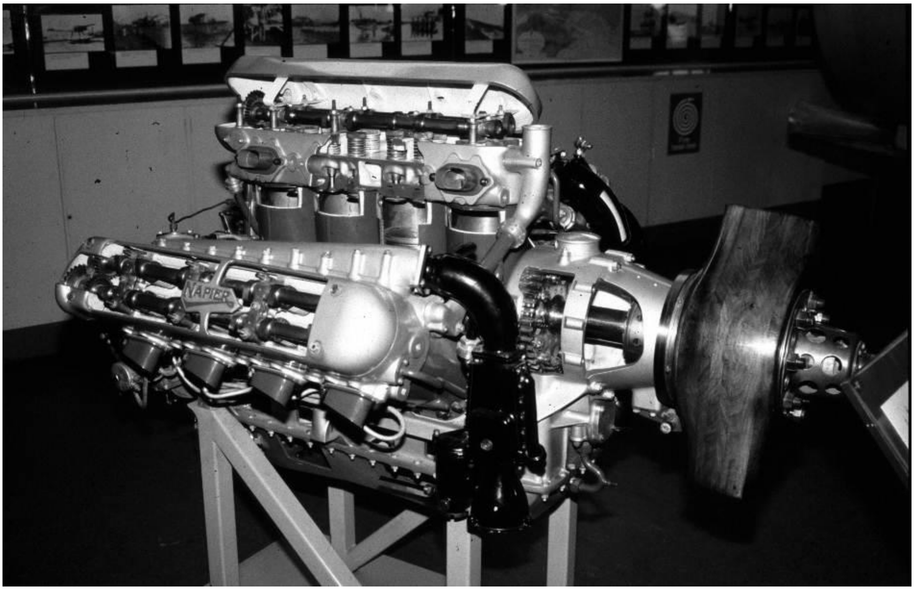

Figure 4. A part sectioned “Lion 5A” engine showing the triple DOHC for its 48 valves.

A.J. Rowledge having left by 1921, lion engine development at Acton continued along two main directions; to produce more power and to maintain it at high altitude. The latter was achieved, but with loss of reliability, by Turbo-charging a number of standard “Lions” with 5:1 C.R, from 1925, when 500 bhp was maintained up to 30,000 feet at Farnborough, before turbine bearing failures occurred. Work was then stopped as the materials available were unable to withstand such exhaust turbine temperatures.

The Schneider Trophy races demanded ever more power, ever since a “Series 2 Lion” had powered a Supermarine Sealion II aircraft to victory for Great Britain in the 1922 event. Supermarine’s Reginald Mitchell and Napier’s George Wilkinson formed a successful team over six years, leading to Schneider progress in 1925 and an outright win again at Venice in 1927 for the “Supermarine S5”, with a “Lion 7B” engine (Figure 5). “E90 Racing Lion” redesign had been radical for this very purpose, involving shortening connecting rods by 1 in., increasing the revs, plus 10:1 C.R. needing “doped” fuels. Thus these “Racing Lions Series 7” engines had a much-reduced frontal area and much more power. The output of the normally aspirated “Racing Lion Series 7” engine was now 900 bhp at 3300 rpm by 1927, sufficient to give first and second places to the British RAF High Speed Flight, piloting “S5” float planes that year. With yet more power demanded by Mitchell for the 1929 races, Napier and Wilkinson then mechanically supercharged


Figure 5. The Schneider Trophy winning Supermarine "S5"in 1927, powered by a reduced frontal area "Racing Lion 7B" of 875 bhp.

the "Racing Lion" using a triple air entry double-sided impeller (Figure 6), while reducing C.R. down to 6.6:1 level. Despite some increase in weight, the power output had risen to 1360 bhp at 3600 rpm into the double reduction gearbox to the propeller. So, a threefold power increase in ten years had been achieved, while maintaining the original twenty four litre capacity, but with an increased weight by 200 lb, this still gave a weight/power ratio of 0.86 lb. per bhp. It was achieved in the face of the larger capacity "R" engine then selected by Supermarine for their 1929 "S6" aircraft. However, "Racing Lion 7D" power did briefly take the World air speed record at 336 mph in the "Gloster 6" floatplane in 1929, enough to establish it as the most compact reliable record making power unit, being also suitable for water and land records. Two years later it was to be utilised in the determined hands of such British speed champions as Segrave, Campbell, Cobb, Scott-Paine and Carstairs.

Hubert Scott-Paine, head of the "British Powerboat Co" successfully converted a "Lion Series 11" direct drive variant, fitted with three Amal carburettors and coupled to a marine ahead /astern gearbox, to form a lightweight 500 bhp marine engine from 1934 onwards. It became the "Power-Napier Sea Lion", usually installed in 1500 bhp groups of three into Royal Navy MTBs and numerous Royal Air Force Air-Sea Rescue Launches of world war two. Large numbers of these "Sea Lions" were built both at Napier Acton and Liverpool works to 1956, when

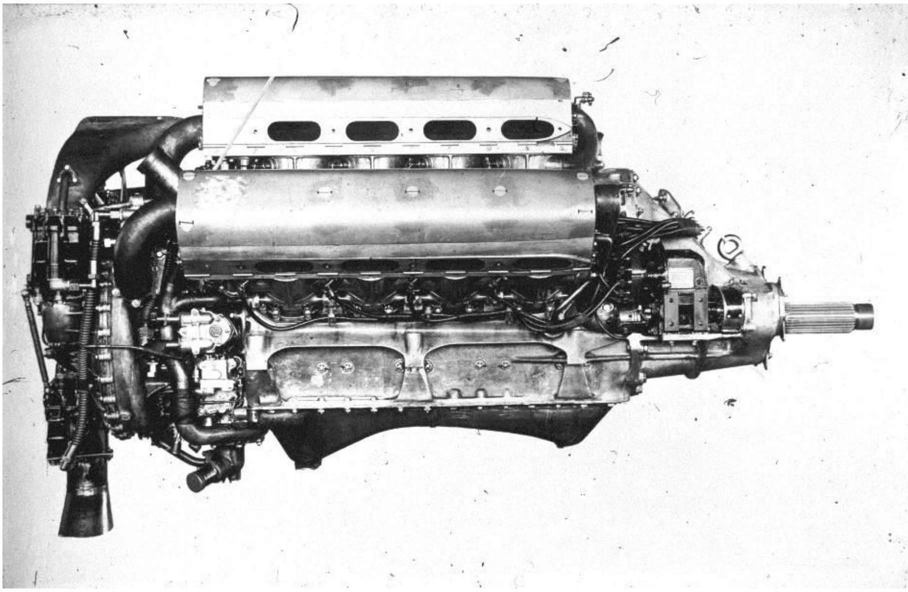

Figure 6. The supercharged “Racing Lion 7D” giving 1350 bhp, built for the trophy of 1929.

the last triple installations were made into new Vosper high speed launches. That was 40 years after the Triple-Four “Lion” design had first been conceived. Also noteworthy is that during this same period, the Napier “Lion” aero engine had been specified as the selected power unit for and then powering over 130 different military and civil aircraft types.

The compact “H” engine

Undoubtedly the concept of having two “vertically opposed” aero engines operating “side by side”, each with its crankshaft, but these coupled via a gearbox to a common output shaft, would lead to greater design compactness. M.S. Napier working from France, but in contact with his newly appointed consultant designer Major Frank Halford in England from 1929, together designed two such “H” configured engines before Napier’s untimely death in 1931.

First was the small “E93” four-stroke, air-cooled “Rapier” engine (Figure 7), this type having 16 cylinders of 3 ½ in. bore and 3 ½ in. stroke, set in four vertically opposed rows, the pair of crankshafts delivering power via a gearbox to a common prop-shaft. The overhead poppet valves were push-rod operated via rockers, and induction was boosted from a mechanical medium speed supercharger feeding the 6.5:1 compression ratio cylinders. In time, after development, the “E100 Rapier 5” gave 360 bhp at 3500 rpm, a four-engine installation being used for Trans Atlantic mail delivery in 1939 in the Short “Mercury” aircraft.

Figure 7. Of “H” layout with two crankshafts and 16 air cooled cylinders, the lighter “E93” NAPIER “Rapier” 380 bhp aero engine of 1932 had 32 push-rod operated overhead valves.

In contrast, a big 24 cylinder 4 stroke “H” layout diesel, the “E101” was being developed at Acton in 1930 under Napier’s direction. This water cooled engine had single sleeve valves operating on the Burt-McCollum system, and 5 in. bores having pistons with 4 ¾ in. strokes. The sleeves were operated from 24 cranks driven by worm and worm-wheel at half crankshaft speed, that design then being patented by Chief Engineer Wilkinson after Napier’s death. Test units were built and run at the time, but the design was shelved until Halford used it in 1935.

Halford’s own next design was similar to the “Rapier”, but now with 24 cylinders in “H” configuration, in 4 air-cooled in-line vertical rows of 6 cylinders, these requiring strictly designed air ducts to cool the fins of the rear end cylinders. They used 4 in. bore by 3¾ in. stroke in the “E104”, “Napier-Halford Dagger” design of 1934 (Figure 8), with inlet and exhaust made via overhead poppet valves operated by 4 sets of single overhead camshafts. A rear double entry supercharger supplied the cylinders wherein the compression ratio was a high 7.75:1, giving this “Dagger” an output of 880 bhp at 3850 rpm. This was then increased to 1000 bhp,

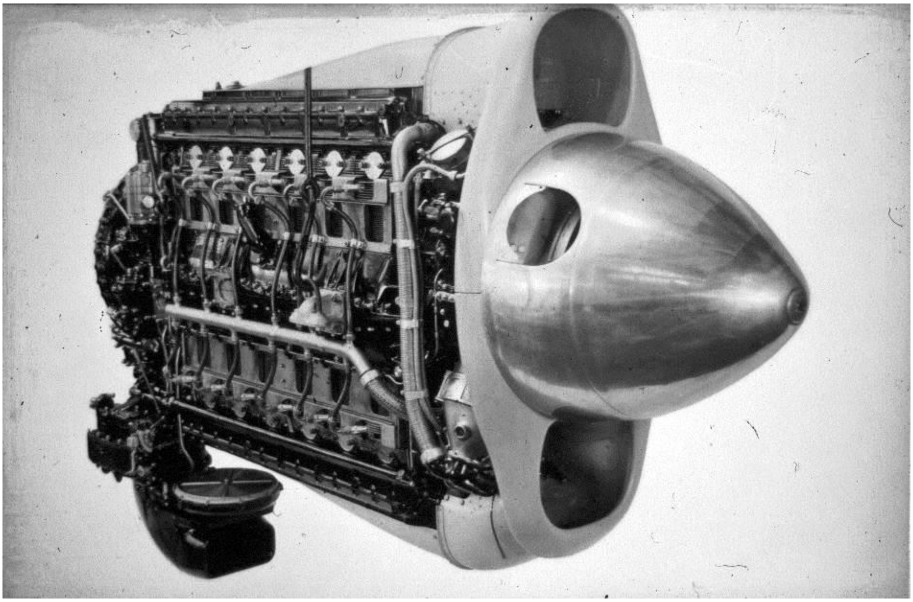

Figure 8. With 24 cylinders in "H" configuration, the E104 NAPIER "Dagger" of 1937, with 4 SOHCs operating poppet valves, gave 880 bhp at 3850 rpm revs from its pair of crankshafts.

by now running at 4000 rpm, from the "noisy E 108" powering the RAF's twin engine Handley Page "Hereford" bombers.

Enter the "Sabre"

A new challenge offered to Napier by the Air Ministry in 1935 was for a 2000 bhp aero engine for military use, this "needed in a hurry". Clearly the mechanical design work already done on the "E101" big "H"diesel could now be used by Halford as the basis for designing a new four-stroke petrol fuel, twenty four-cylinder sleeve valve engine having a high volumetric efficiency associated with sleeve valve ports. Retaining cylinders of 5 in. bore, it was now given the fixed compression ratio of 7:1, boosted from a large two-speed supercharger. The net result was the 36 litre "E107 Sabre" design (Figure 9) of 1937 onwards, this now having a revised "FLAT H" cross-section, which would house all auxiliary units on its top, while all pumps would be mounted beneath its crankcase, so giving a very compact engine layout. The "Sabre" was continuously developed in secrecy from this point on by a team of Napier engineers, initially spear-headed by Halford, later led by Ernest Chatterton, Chief Engineer Wilkinson and Designer Barlow, this before and throughout the duration of world war two, until a power output of 3000 bhp was achieved by 1945. How this was done holds great interest for engineers, for a variety of components had required strengthening as power output rose. Chief in its development would be an improved fuel supply into the engine induction system, this done by moving away from the early four choke updraft SU carburettor which, by 1941, had enabled 2200 bhp at 3700 rpm to be produced by the "Sabre 2A" engine, using just 9 P.S.I. of supercharger boost. This type was always the power unit for all 3,300 Hawker "Typhoon", 420 mph fighter-bombers that were constructed.

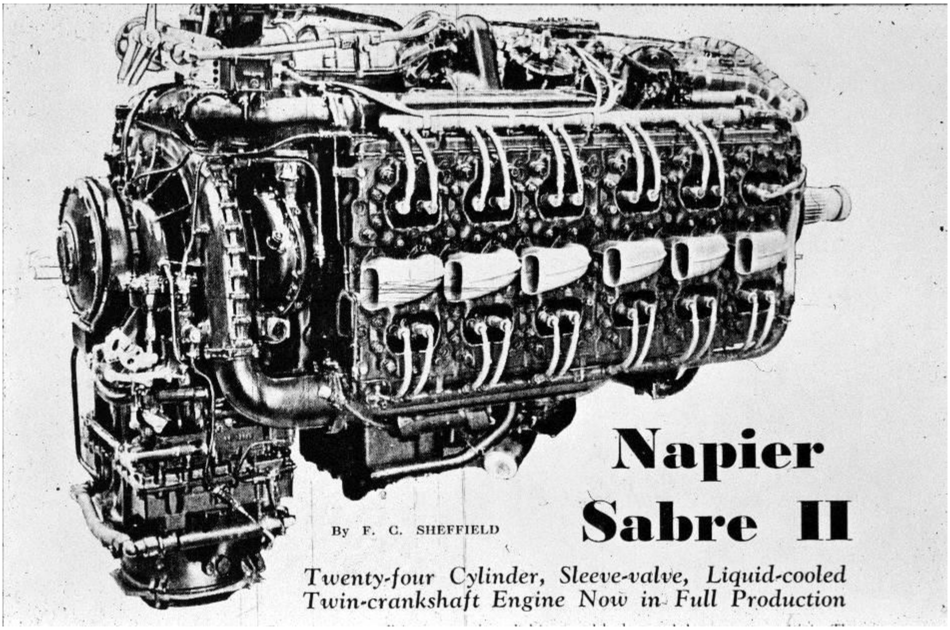

Figure 9. The flat lying "H" layout of the larger water-cooled "E107" NAPIER "Sabre", had 24 sleeve valve cylinders, seen here with an SU carburettor, and produced 2000 plus bhp.

From the end of 1942 the English Electric Co. Group acquired D. Napier & Son Ltd, Sir George Nelson becoming Chairman of the new Board, at which point Halford then resigned.

After sleeve valve seizure problems had been overcome, (this done after assistance received via the M.A.P. and courtesy of the more "sleeve" experienced Bristol Engine Co.), supercharger enlargement was pursued further, until a changeover was made to the Hobson-RAE injection carburettor, which supplied fuel directly into the supercharger eye, a system taking fuller advantage of the efficient sleeve valve induction design. The "Sabre 5A" was first to use this system, but was limited to less than 2600 bhp at 3850 rpm and 15 psi boost, due to higher power "detonation". This finally needed also the injection of Water-Methanol into an even larger supercharger to suppress the problem (Figure 10), enabling an unprecedented power of 3050 bhp at 3850 rpm using 17 psi boost, to be produced at sea level for Hawker fighters on take-off. The one ton "Sabre"

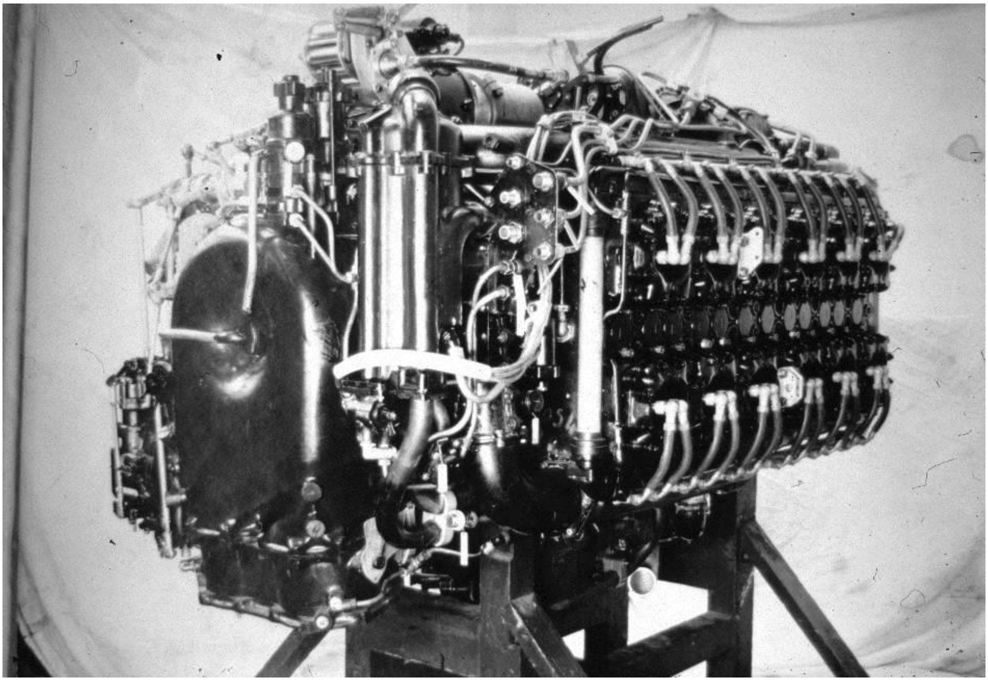
Figure 10. A 3050 bhp “Sabre” series 7 rear view, with RAE-Hobson Injection Carburettor and Water Methanol pipe-work entering the enlarged supercharger casing.

engine had finally achieved the very low 0.83 lb. per bhp weight-power ratio in the “Sabre 7”version in 1945, which gave that 490 mph speed in level flight to the prototype “Fury Mk 1”.

Design and development continued after WW2, with the “E122 Sabre” variant intended for civil or service use, this having contra-rotating propeller shafts, and 25 P.S.I. of boost from its two-stage supercharger, with inter-stage cooling, to produce an output of 3350 bhp at 3750 rpm. This project was “nipped-in-bud” while under manufacture at Acton, by the Air Ministry (along with a “well known rival company”), so leaving us at Napier to develop the multi-cylinder “Deltic” marine diesel, our new aero gas turbine designs, the “Nomad” Aero Compound, and today’s large, Lincoln based Turbocharger range, for the E.E. Co’s diesels.

The Coming of the Compounds

A wartime secret MO aero project was for a British higher power and high altitude, long-range diesel fuel aero engine, which would therefore necessitate a very low fuel consumption.

To achieve these objectives a gas turbine boosted “Compound Diesel” 2-stroke cycle piston engine was finally proposed by Napier in 1945. This design employed the exhaust gas from a simple thermally efficient 12 cylinder, horizontally opposed, loop-scavenge diesel piston engine of 41 litre capacity, with a 6in.dia.bore by 7 3/8 in. stroke. The gas was to be expanded through three gas turbine stages to extract most of the exhaust's residual energy. These turbine stages would firstly drive, through reduction gearing, an independent engine propeller, thus forming a compound power unit alongside the diesel driven prop-shaft and its propeller. The same turbine group also drove scavenge air compressors, which would feed pressurised air into the diesel cylinder inlet ports, much as now done by a turbocharger. Finally, after adding the exiting exhaust gas thrust out from a jet tailpipe, these all comprised the "E125 Nomad I" engine, which could produce 3100 effective horse power (ehp.) at 2050 crankshaft rpm, when being flown. At that time, the lack of axial compressor output pressure was boosted by adding a further centrifugal compressor stage, but despite its overall length of 10ft. 6in., a low fuel consumption of 0.35 lb. per ehp hour was attained by 1950 during test flights up to 25,000 feet in a Lincoln bomber, flown from the Napier Luton Flight Development Establishment.

By the time the pressure ratios of axial compressors from the Napier Research Station at Liverpool had increased towards 9:1, and the weight and length of the compound had needed reduction for ease of wing installations, a revised Nomad design was prepared for year 1951. This engine had a robust single prop-shaft, a larger axial compressor unit only, and had the provision of servo-controlled infinitely variable gear trains linking the turbine shaft and the rear of the diesel crankshaft. Any excess turbine power above that needed by the compressor could now be "tapped-off" in this revised compound engine, through gearing and transmitted directly to the crankshaft and thence to the propeller shaft. This more compact power unit was the "E145 Nomad 2" engine (Figure 11) that Napier continued to develop up until 1955, when the MOS finally withdrew its funding after fully 10 years. By then the power output of that shortened and lightened aero compound had risen to 4000 ehp, this with the expedient of water injection into the cylinders, while its fuel consumption had come down to 0.32 lb. per ehp hour. Regrettably, the complex, lean-burn Nomad engine had arrived almost too late to compete alongside even Napier's own propeller turbines, so leaving for many Napier engineers only the impressed memory of seeing and hearing their unique Nomad's subdued, deep-sounding flights at several Farnborough Air Shows.

Turbocharging – a Triumphant Finale

To end this paper we will approach the pinnacle of Napier multi-cylinder design, one that in the late 1940s was producing high power from a high speed compression ignition marine unit to have great versatility. This "Deltic" diesel, albeit one inspired by opposed piston two-stroke cycle technology for aircraft originating from Germany, contained many more innovative features that makes this Napier power unit still unique in the world today. At Junkers itself, any long

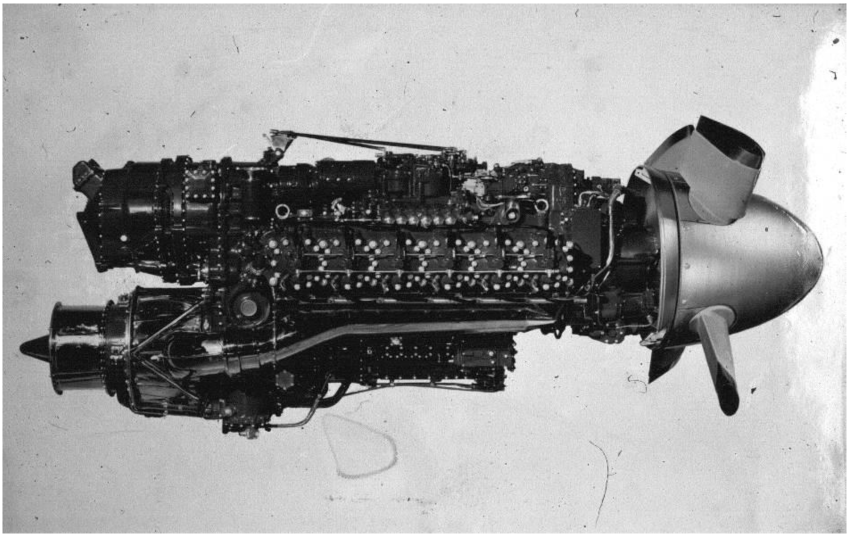

Figure 11. The simplified "E145 Nomad 2", now giving a 4000 ehp with water injection.

double-ended cylinder having a pair of opposed uniflow pistons, one controlling inlet ports, the other exhaust ports, was termed a "two cylinder" diesel engine. By the same reasoning, when at Acton no less than eighteen such long cylinders, each containing two opposed pistons, were arranged within one thirty six piston high output engine, that engine could equally have been termed a "thirty six cylinder". That would have formed the highest multi-cylinder engine number ever put into production at Napier, although a "forty eight cyl. Squartic" version had also been designed at Acton, having four crankshafts disposed at its four corners! The low inertia and overall weight of all the foregoing high revving power units over that 25 year period from 1930, was the result of the use of a multiplicity of working parts manufactured to a far greater degree of precision than those of our competitors in the aero and marine industry worldwide. The high power outputs obtained from these successful Napier multi-cylinder designs were, however, only gained at the expense of higher production costs within the company. It has, nevertheless, been rightly said that "Napier gave its customers more good engineering per pound spent than any other similar company"!

In the 1930s Napier had built their own two-stroke, in-line "six-cylinder", twelve opposed piston, compression-ignition, diesel-fuel, aero engines under license from Junkers of Germany, this Napier version being the "E95 Culverin" of 700 bhp. The engine had upper and lower crankshafts geared together at the front to a single prop-shaft, having a rear mechanical scavenge blower feeding air into its inlet ports. In 1946 after WW2 Napier had accepted an Admiralty contract to design and develop a lightweight, high output diesel engine to power Naval fast patrol boats and minesweepers. Their Napier eighteen-cylinder "E130 Deltic" opposed piston, two-stroke diesel design was then selected by the Admiralty, for development at Acton with an assortment of power outputs and service lives. By 1950 a prototype was on test with a marine gearbox and clutch, and boosted by a double-sided mechanical scavenge blower, this being well before the Series II later turbo-blown and "compound Deltic" designs.

"Deltic" Engines have an inverted "Delta" shape, the configuration forming an equilateral triangle made-up of three "Culverin" type six-cylinder banks (Figure 12), in each 60 degree corner of which there revolves a six-throw crankshaft, driven by pairs of connecting rods from the adjacent cylinders, via linked fork and blade big-ends. These eighteen-cylinder engines have eighteen steel, water cooled, open ended long cylinder "sleeves" containing machined inlet and exhaust ports, sleeves being sealed into water cooled cast aluminium alloy cylinder blocks. The three crankshafts are coupled into a phasing gear case at one end, where the lower crankshaft revolves in an opposite direction to its upper pair. These phasing gears maintain the correct inlet and exhaust timings for the two piston crowns in each cylinder as they open and close the sleeve inlet and exhaust ports. Exhaust ports are timed to be opened 20 degrees of crank angle ahead of the inlet ports placed towards the other end of the cylinder sleeve, this to ensure good scavenging in the cylinders. Working in 5 1/8 in. bores, the 36 opposed pistons have 7¼ in. strokes, to move them inwards across the ports, thus trapping a volume of air which is then compressed by the 15:1 compression ratio, this air thus heated causing the instantaneous "firing" of the diesel fuel injected between the piston crowns. Firing occurs once in all eighteen cylinders every revolution, at 20 degree intervals, so giving to the engine a very smooth output torque, while all the main reciprocating parts maintain near perfect balance.

By 1954, a pair of "E 130 Deltic 18-11B" engines would each produce 2500 bhp at 2000 crankshaft rpm, having 7.8 P.S.I. charge pressure, for powering 30 Royal Navy "Dark Class" M.T.Bs at 38 knots speed. This while similar pairs of de-rated type "18-7As" were installed to power the 110 Royal Navy "Ton Class" Minesweepers, these "Deltics" giving more hours between overhauls were governed to an output of 1600 bhp at 1500 rpm. Both types were built to the same standard as all the eighteen-cylinder "Deltic" range to follow, these early engine types having 88 litres swept volume, being fuelled via eighteen injection pumps, that is one to every cylinder injector, this to give the highest reliability in service.

The next project using de-rated engines needed flange-mounted generating equipment driven by the phasing gear case output coupling, this where the marine "Deltic" ahead/astern gearbox had been attached. Such generator and alternator units were used by less accessible BBC transmitting stations, or when travelling within diesel electric railway locomotives to generate controllable DC traction motor current. The latter "Deltic" application became better known than any other in the UK from 1955, when a prototype" English Electric Co./Napier Co-Co locomotive, made its debut on British Rail, Midland Region, the 3,300 hp

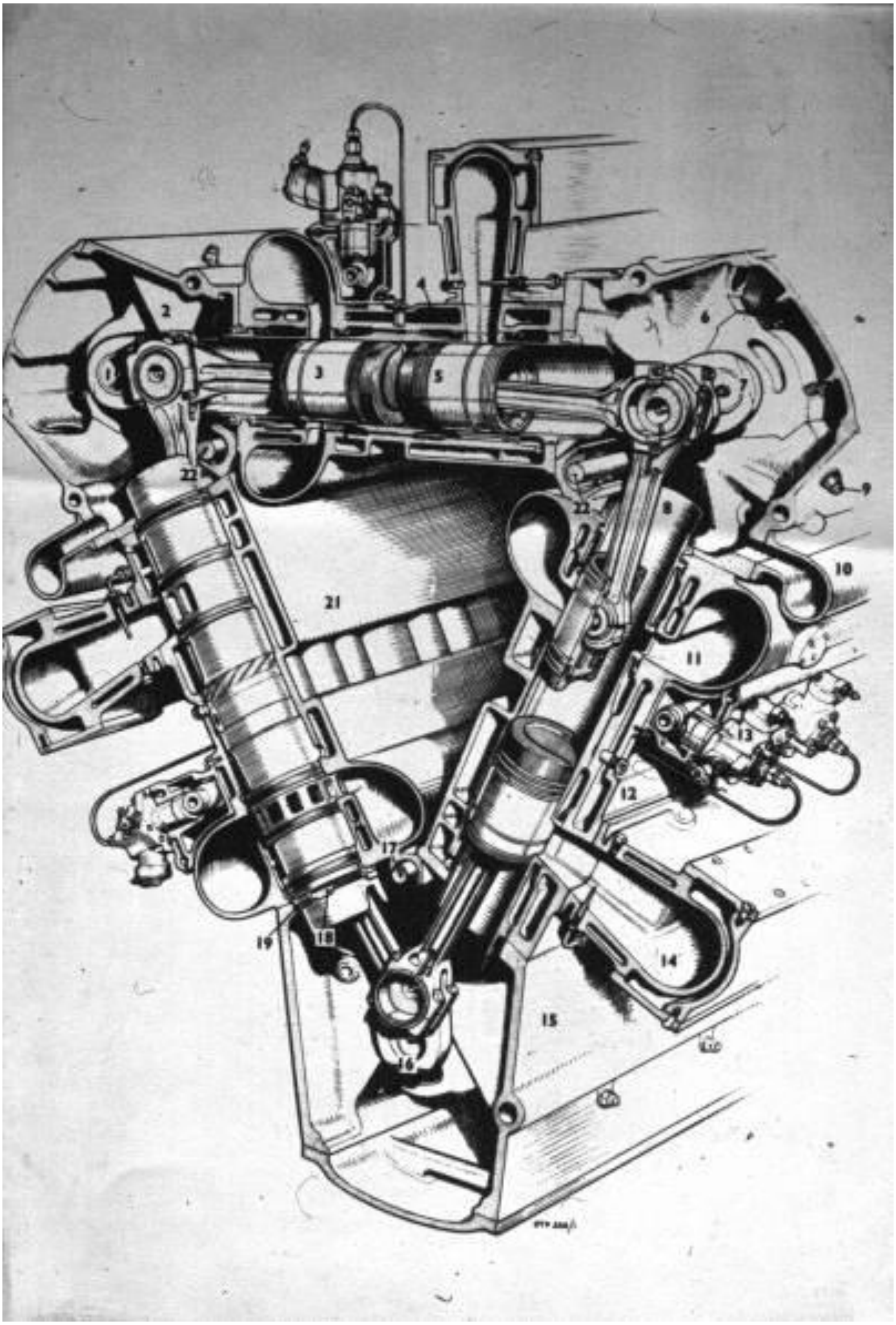

Figure 12. Cross-section of a “Deltic” triangular diesel, showing six opposed pistons in three cylinders.

"DELTIC". Their joint company management, under the Chairmanship of Sir George Nelson, privately decided to fit a pair of 1650 bhp "E 158 D18-12A" lightweight generating engines into the chassis of an E.E. Co. locomotive weighing only 100 tons, giving it more power available up to 100 mph speed than any locomotive before it on rails.

Another Napier development, concurrent with the aero "Nomad", was the "E 160 Deltic Compound" marine engine that similarly strove for the highest thermal efficiency, with high power output at low specific fuel consumption, aimed at future Royal Navy fast patrol boats. A compact design was achieved by introducing a large turbo-compressor unit into the centre of the diesel triangle, from which surplus rotational power could be obtained via its exhaust gas turbines. This power was delivered into the phasing gear-trains where it increased output shaft torque in the marine gearbox. This complex and heavier engine came up to expectations in 1956 on test at Acton (Figure 13) producing a peak of 5,500 bhp, this the highest reached by any Napier unit. But again, several lighter marine gas turbines had by then reached comparable powers, but with much higher fuel consumptions, nevertheless the Admiralty decided that all-turbine power should be "the way forward" for future light fast craft. So ended the now legendry Napier "Deltic Compound" development programme, there-and-then!

While locomotive haulage trials had continued on the Eastern Region, E.E. Co received a production order for 22 similar lightweight Type 5 locomotives, now with twin "E169 Deltic 18-25B" engines of 1650 bhp. Entering service from 1961, they heralded the start of the term "Inter-City Travel", then running consistently between Kings Cross and Edinburgh from 1962 over a period of twenty years. Today six of these heritage locomotives are preserved, most in operational condition.

Napier continued marine "Deltic" development at Acton works up to its closure in 1968, when the programme was transferred to Napier Liverpool works, where later more powerful Turbo-charged engines, from both eighteen- and nine-cylinder designs, were still under production. The chief component in the design that required most development was the piston, for combustion occurred between piston crowns trapping heat locally, and had earlier even caused some iron crowns to fail. The solution found was to manufacture the piston crown from a 96% copper-rich Hidural alloy, which permitted the heat above it to be rapidly conducted through down to the pressurised oil-flow beneath it, fed through the inner piston body holding the gudgeon pin. Within turbocharged "Deltics even higher temperatures were encountered and the reliability of their built-up opposed pistons remained critical throughout.

More importantly for Napier, the turbo-charged "E 239 T18-37K" engine had reached a power of 3,100 bhp at 2,100 crankshaft rpm by 1960. It was finding several naval markets overseas, being universally selected as the power unit for fast patrol boats of the Norwegian designed M.T.B known as the "Nasty Class",

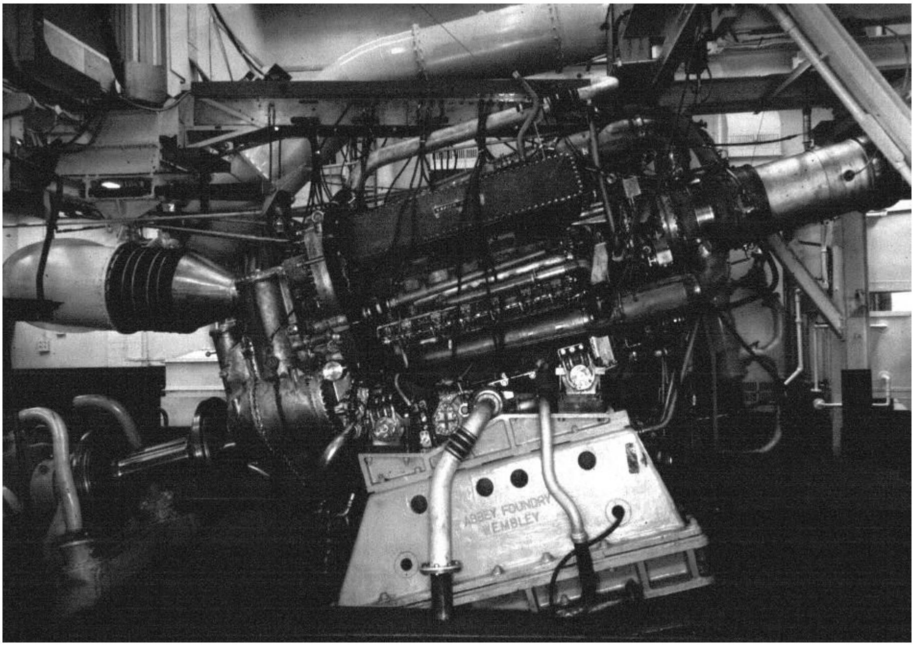

Figure 13. Prototype Deltic Compound seen giving 5,500 bhp on test at Acton during 1956.

capable of 47 knots. Pairs installed with Napier Vee-drive gearboxes gave 6000 bhp in the engine room of these boats for fifteen world navies, including the United States Navy who made there own boats and "Deltic" installations. A yet later type, the "E263 CT18-42K" engine (Figure 14), incorporated charge cooling from of its enlarged turbo-charger, giving high density scavenge air delivered at 19 P.S.I. charge pressure. This production batch of "Deltics", built for Indian Navy service, produced 4000 bhp on test, and was rated for service at 3,700 bhp.

Finally, in apparent contradiction to the Napier multi-cylinder tradition, their final remaining "Deltic" engines still in naval service, this fifty years after their initial design, operate with 9 uniflow, 2-stroke cylinders, having eighteen opposed pistons working within them. These smaller sized, nine cylinder units of 44 litre capacity, now have a mechanical scavenge blower. These were designed at Acton in the late 1960s, to function with many non-magnetic austenitic steel working parts, and were later constructed at GEC-Paxman Diesels of Colchester, by former Napier staff. They power the thirteen-strong "Hunt Class" inshore Mine Counter-Measures Vessels of the Royal Navy, built in the 1980s, having Glass reinforced plastic (GRP) hulls for "ultra low magnetic signature" mine-hunting duties, this achieved by the installation the three non-magnetic Napier engines in each one. For both electrical minesweeping supplies and hydraulically powered slow drive

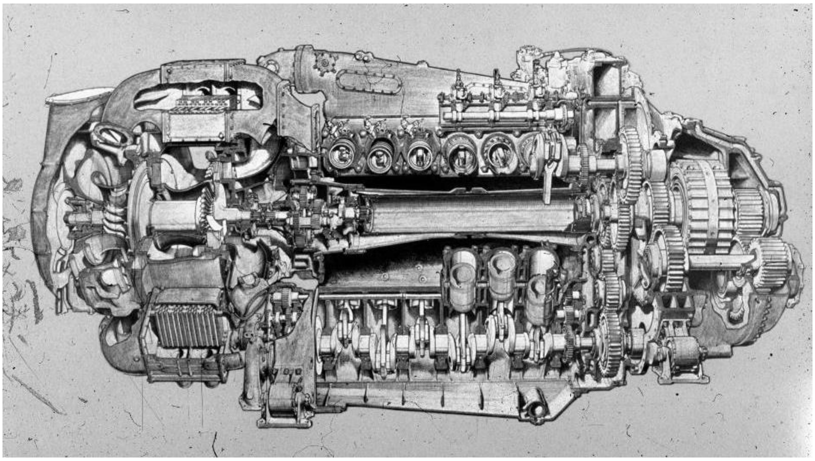

Figure 14. Section of an "E263" Charge Cooled "CT18-42K" engine capable of 4000 bhp.

manoeuvres of the ship, a single "E276 D9-55B" is employed, giving 750 bhp at 1400 crpm. Main ship propulsion power is provided by a pair of "E 280 D9-59K" Deltics (Figure 15), each with an output of 950 bhp at 1700 crpm. Both these much simplified engine types are still maintained for the RN by outside contractors.

This paper has traced some Napier multiple-piston engine developments through the first half of the twentieth century, these often enriched by eminent engineers, such as Sir Harry Ricardo. It ranged from types "E1" to "E280", with

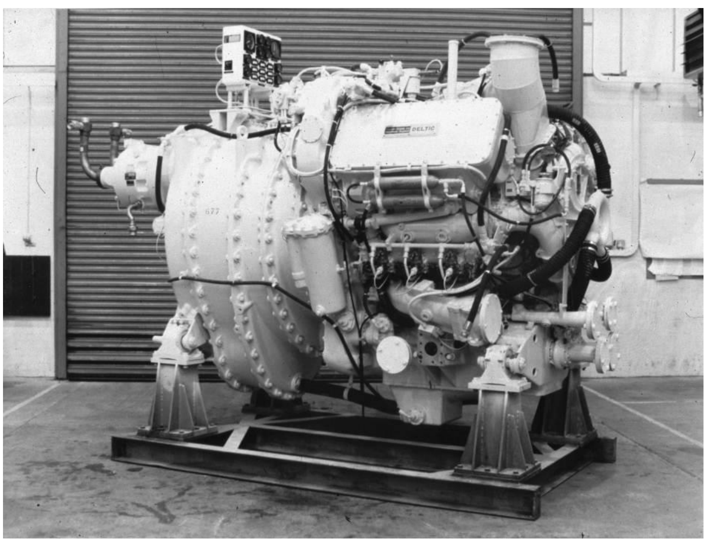

Figure 15. An E280 all non-magnetic parts, nine-cylinder propulsion Deltic, the D9-59K giving 950 bhp at 1700 rpm to Royal Navy Mine Counter Measure Vessels of the "Hunt Class".

from six to thirty six pistons and powers from 55 to 5,500 bhp. The Napier Power Heritage Trust has been recording these unique products of D. Napier & Son Ltd since 1991.

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