THE DEVELOPMENT OF THE DIESEL ENGINE FOR NAVAL PURPOSES.*

The following remarks on the development of the Diesel engine for naval purposes should be of interest to Engineer Officers as illustrating the types of early engines fitted, with some of the difficulties encountered, and the different considerations that have been given from time to time to forward the development and a more extensive use of such machinery.

The first experiment afloat was the fitting of electric generating engines of Hornsby-Ackroyd type in three battleships as peace dynamos. These were virtually additional engines as far as the normal load requirements were concerned, and were placed on the upper deck, *not* under protection.

These engines were fairly satisfactory only when using clean fuel oils, such as shale or gas oil, and attempts to use the same fuel oil as that supplied for use under boilers were successful only for a very limited period.

However, the obvious advantage of the use of oil engines in being able to provide electric light when steam was down for executing repairs, or in the event of the steam service being put out of use during action, was demonstrated and caused these engines to be further considered for electric generating purposes.

Great efforts were made to enable them to use Texas fuel oil, by warming the oil, and passing it through cloth filters which virtually amounted to supplying the engine with a clean refined oil. On account of these very special precautions, the experiment could hardly be regarded as satisfactory, and further the output was reduced with the heavier oil.

Owing to the height of these dynamo engines, special arrangements had to be made in a later class of ships, in which the engines were placed below decks, to allow of withdrawal of parts, virtually raising the protective deck, and even with this additional head room, the dynamo engine compartments were undesirably hot, due principally to the exhaust pipes and silencers. These engines had three cylinders 15 inch diam. and 15 inch stroke and ran at 400 revs. per minute.

The oil consumption was about 0·9 lbs. per B.H.P. per hour and the lubricating oil consumption about 4 per cent. of the fuel oil consumption.

At the end of 1904 the boilers of Torpedo Boat 047 required extensive repairs, and the machinery also required considerable overhaul; it was therefore decided to see what could be accomplished in obtaining reversible oil engines to replace the steam machinery which developed 740 I.H.P. on one shaft at full power.

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* Substance of a paper read in Glasgow by the Engineer-in-Chief on 18th April 1922.

Three firms who had the most extended experience with the marine oil engines were invited to tender. Of these, one regretted their inability to do so, the second offered less than half the power desired on the weight available, and the third proposed an engine with which there was no experience and the machinery would have introduced vibratory forces which were of about the same magnitude as those in a vessel of the "Topaze" Class. The cost of the installation was considered too great for the practical results that were likely to follow. The results guaranteed were also disappointing, and it was eventually decided not to proceed further with the matter, as development had then evidently not reached the stage when manufacturers could confidently recommend their offers.

In 1905 when the designs for the Dreadnought were being prepared, it was decided that this ship should be provided with two Diesel dynamos each of 100 K.W. capacity, and that she should carry two 50-ft. pinnaces fitted with Diesel engines of 120 B.H.P. running at 400 revs. per minute. At the time these Diesel engines were ordered there was no experience in this country with any Diesel engine which had been run at a speed greater than 200 revs. per minute. The oil engine makers were quite prepared to design the Diesel engines to run at 400 revs. per minute, which was an important step forward in the development, but hesitated to run the air compressor at the same speed, so the air compressor was run at one-half the speed of the engine by a chain drive from the engine crankshaft, and the result was, as is often experienced, that the scheme introduced to avoid trouble was the means of causing it. The chain frequently broke and later the compressor crankshafts broke; the chain drive was eventually replaced by a spur gear drive which proved more satisfactory.

The engines were designed with the four cranks all in the same plane as in a four-cylinder car engine; the secondary vibratory forces resulting from this arrangement were primarily the source of much of the trouble which arose, and it was not until wooden shores were fitted by the ship's staff in the compartment under the engines, to give more stiffness to the engine bed, that better results were obtained. One of these engines was later replaced by a steam engine. This is not the only case where the failure of a Diesel engine could be fairly attributed to want of stiffness in the foundation. Designs of foundation structures for Diesels have often been based on those for steam engine practice, and sufficient consideration has not in many cases been given to the very different nature of the loads and of the fluctuation of the loads from those of corresponding steam engines of similar power. Even now the importance of this point is sometimes overlooked and the failure of Diesel engines is attributed to the engines themselves, when the foundations and not the engines are at fault.

After the Dreadnought came the battle cruisers " Indomitable," " Inflexible," and " Invincible," and battleships of the " Bellerophon " Class, each ship being fitted with two 100 K.W. Diesel engines. In these engines, the air compressor was driven from the end of the crankshaft, and with well-stiffened seatings the difficulties due to vibration were practically eliminated.

As with all new propositions, difficulties were still quite of common occurrence, owing chiefly to a lack of experience and to the fact that the personnel had been educated on steam plants.

Eventually, however, after considerable running experience had been gained, the more serious troubles were gradually eliminated and fairly satisfactory results were obtained. Some ships returned reports which were quite satisfactory, while those from others were somewhat disappointing.

The cost of upkeep was, however, high, and in 1907, when the design of the " St. Vincent " Class came to be considered, it was decided to fit only one oil-driven dynamo. This was of 100 K.W. capacity and was an addition to the bare requirements for electric power.

Mention has been made of the two Diesel boats which were to be provided for the " Dreadnought "; these were delivered after much delay, and one was sent to the " Dreadnought " and the other to the " Lord Nelson." Difficulty was experienced in these boats with the reversing arrangements. Clutches and reverse gears were fitted and the clutches proved satisfactory, but the reverse gear, which was of a type in which several pinion wheels engage two wheels on the inside and outside rims, failed principally owing to the difficulty of making the pinions take equal shares of the load.

In addition to this trouble, the engines of these motor boats were not flexible enough to allow the boats to be easily brought alongside a vessel or a wharf, and were finally removed from the boats and used for experimental purposes on shore.

The engines were at that time blamed for failures which in the light of later experience, really should have been attributed to the reverse gears, as we have had many similar cases since with oil engines of other types, and it will generally be found difficult to transmit a heavy torque through clutches of this type in service boats, where the extreme available diameter is limited and the intensity of the load is therefore unusually high.

In the early part of 1911, it was arranged to fit a combination of oil engines and turbines in a torpedo boat destroyer. Two sets of two-cycle Diesel engines, each with four cylinders, were to be fitted immediately forward of the turbine engine-room, and geared to the corresponding turbine shafts, helical gearing being used. Clutches were to be provided for disconnecting when not in use. The maximum number of revolutions of the Diesel was to be 325, to be reduced by gearing to 260 revs. corresponding to a speed of 15 knots. The Diesel engines were to be used for cruising speeds. The power of each Diesel engine was to be 850, total 1,700 B.H.P.

• Unfortunately difficulties were experienced during the manufacture, although the very best help was obtained by the firm, and the engines were not fitted in the vessel.

The running portion of this machinery did not get beyond a single cylinder unit. The troubles experienced were breaking of the cylinder cover and difficulties with crosshead bearing and guide surfaces. After a time this unit developed full power for a short time.

Although unsuccessful this venture gave very useful information which was put to good account in future designs.

The Diesel electric generating engines previously referred to were not in all cases so reliable on service as could be desired and were not fitted in vessels built subsequent to the "St. Vincent" Class; it was not until 1911 that the question of again fitting oil-driven dynamos was considered. During the period which had elapsed experience was being gained with those already installed, and reports were, on the whole, becoming favourable. It was generally admitted if slight modifications could be made which would add to its reliability, the Diesel engine was undoubtedly an acquisition in a ship; its economy was beyond question.

The principal difficulties were the cracking of pistons and breakdowns of air compressors which were of the two-stage type. Complaints were also made of noise and vibration, and of the unsatisfactory leads of the exhaust pipes, which passed through living spaces and store rooms.

It is of interest to note that as the personnel became better acquainted with the Diesel generating engines, the desire for them was in some cases so great that they were preferred to the reciprocating steam generating engines; the economy was very marked, one ship giving in comparison 35 tons of oil for the Diesel engine against 350 tons of coal for a reciprocating steam engine doing the same work.

As a result of the more favourable reports, it was decided to fit one oil-driven dynamo of 150 K.W. capacity to the ships of the 1911 programme, and generally since that time, two Diesel generators have been fitted in capital ships; during the war, however, some ships were only provided with one engine, and others with no Diesel engines, but this was often a question of obtaining machinery of this type in sufficient time.

To-day, although it cannot be stated that the oil engines are as reliable as the steam turbo plants, the results are on the whole satisfactory. The upkeep, however, is greater but the gain in economy outweighs the other disadvantages, as already indicated.

There is no doubt that the advent of the steam turbine caused the development of the oil engine to be much retarded, and the increase of power demanded with limited weights has become so enormous that it is impossible at present to consider oil engines for the propelling machinery of large surface warships.

For moderate power and comparatively low speed of revolution, such as are required for many merchant ships where head room and space are not so limited as in warships, there has been considerable development and the large number of Diesel engined ships now in use and building is an indication of the increased reliability expected and being obtained.

The manufacture of Diesel engines demands in many respects a higher standard of workmanship than the reciprocating steam engine, and what is even more important, a better education of the personnel.

Undoubtedly there has been, and there still exists, some prejudice against the Diesel engine, and whilst some of this may be due to lingering doubts as to its absolute reliability, it is also largely a prejudice against reciprocating engines which quickly developed when steam-driven engines of this type were displaced by the steam turbine, the relative advantages of the latter being enhanced by the advent of oil-fired boilers.

During the sitting of the Royal Commission on Fuel and Engines consideration was given as to what might be accomplished in various types of ships fitted with oil engines and combinations of oil engines and turbines for propulsive purposes. It was in view that the comparatively low powers required for economical speeds could be obtained by using oil engines, and the powers required for higher speeds obtained by using the less economical turbine plants. In a vessel designed for four propeller shafts, oil engines would have been fitted on two of the shafts, and steam turbines on the others. During this period the powers of the capital ships " Queen Elizabeth " Class had risen to 70,000 S.H.P. at full speed, making the problem of fitting oil engines very difficult, and still more difficult when the power was further increased in later vessels, although the reduction of power for the " Royal Sovereign " Class made things easier. It is of interest to note in the combination arrangements that the oil engines, if designed to be utilised for the full power requirements of the ship, could not obtain their full power at lower speeds if used alone, the revolutions being reduced even if the mean pressure obtained in the cylinders were the maximum.

These considerations, together with proposals to drag the idle screws of the turbine shafts, very considerably reduced the speeds which could be obtained with oil engines only on two shafts.

Owing to the outbreak of war the proposals were not persevered with, but proposals were made, however, in the design stage of the " Hood " to fit an oil engine of 1,200 H.P. on a centre shaft. This was increased later to 4,000 H.P. (to develop 3,000 H.P. at 185 revs.) and the final proposal was to fit two sets of eight-cylinder engines each of 4,500 H.P. running at 185 revs.

on the wing shafts with three sets of turbines on the centre shafts. These proposals were subsequently abandoned.

About the end of 1911, in view of the oil fuel requirements of the Fleet, it was decided to build a number of oil tank vessels, and arrangements were made to fit Diesel engines in five of these ships, the brake horse powers of the various types of engines being 450, 1,500, and 2,500 respectively.

Many serious difficulties with these engines presented themselves from time to time but valuable information and experience were obtained as regards the nature of the problems to be solved both as regards material and the training of personnel.

The machinery equipment of these vessels was arranged so that first-hand experience should be gained of the suitability of different types of auxiliary machinery for Diesel propelled vessels. The two smallest vessels had steering and other engines designed to use compressed air from compressors worked from the main engines. This system gave very little satisfaction. The next two vessels were fitted with steam auxiliaries and they were, of course, reliable, but as was well known would be the case, they were expensive in steam consumption.

The largest ship was fitted with electrically-driven auxiliaries, the generators being worked by separate Diesel engines. This system was very expensive in first cost and the auxiliary machinery gave considerable trouble which was associated with the working of the main engines to be referred to later.

The trials were much interfered with by the war and left this important question still an open one, and probably the solution will be found in a mixed system, but it was made evident that in connection with new types of machinery, it is not wise to attempt too many things at one time in the same ship, and that it would have been better to have given the trial to the main engines alone, leaving the question of the auxiliary engines to be dealt with under more favourable circumstances at a later stage.

In one of the oil-tank vessels of intermediate size, 6-cylinder engines of the M.A.N. 2-stroke cycle design were to be fitted. They were, however, fitted instead in the monitor "Marshal Ney." These engines gave considerable trouble, chiefly due to errors in design, but although they were of the two-cycle type, it is considered that the want of success was not in any way due to the fact that the two-cycle principle was involved.

For another tank vessel the machinery was made by Messrs. Vickers and the engines were fitted with the Firm's solid injection system of fuel supply to the cylinders. No arrangements were made for cooling the pistons.

Two independent air compressors were fitted to charge the reservoirs for the main engine starting air.

As in the previous installation, all the other auxiliaries were steam driven and two Yarrow oil-fired boilers were provided for this service.

During the early trials it was found difficult to realise the guaranteed fuel consumption: this was due to the measuring device which controls the supply of oil to the cylinders being fitted at too great a distance from the actual inlet into the cylinder and admitted of what is often described as "dribbling" and the consequent effect "after burning."

These engines were designed to use Texas oil fuel as usually supplied under the boilers.

After the shop trials the engines were placed on board the oil-tank vessel "Trefoil." The vessel was practically complete and ready for trials when the machinery was ordered to be removed and fitted in a second monitor, the "Marshal Soult."

Satisfactory sea trials were made, although the speed obtained was only about 5 knots: the engines were running at maximum revolutions, but could not develop the full horse-power. When the design of the propellers had been altered the full power was obtained with the result that the speed of the ship was increased to 6½ knots.

On the whole, the machinery would be described as reasonably successful, and probably few ships have been so often under fire as this monitor.

These monitors were manned by naval ratings with R.N.R. Engineer Officers. There is no doubt that the liberal engine-room complement provided and the opportunities for repair were factors facilitating the upkeep of this machinery.

As the result of the experience in the "Marshal Soult," certain modifications, principally in the arrangement of the fuel oil spray valves, were made on the replace set of engines for "Trefoil," an oil-tank vessel, with the result that there was an improvement in the oil consumption on the trials, averaging 0·47 lbs. per B.H.P. against 0·55 on the original set. Other mechanical details were modified, but are hardly of sufficient interest to mention in detail.

Experience on service so far has shown that a considerable amount of work is necessary to maintain the machinery in good working order, although the fact that this ship did her first eighteen months of hard war service without being laid up and without developing any defects except those that could be made good by the ship's staff may be regarded with great satisfaction. The subsequent cost of refitting has been heavy compared with steam engines of similar power, but this must be expected in an installation where there are 16 cylinders to the main engines besides Diesel-driven compressors and the steam plant. These additional costs have, however, been far outweighed by the saving in fuel, in personnel, and other advantages.

The machinery for a larger twin screw oil-tank vessel was made by Messrs. Vickers and consisted of two sets of eight-cylinder, four-cycle engines of a total power of 2,500.

The trials and subsequent service of the main engines were generally satisfactory.

The defects which probably caused most trouble occurred when the ship was working, during the war, in the sandy water of the Persian Gulf, for which service she had not been designed, and were due primarily to leakage from the glands of the piston-cooling pumps, and sometimes breakage of the pump parts; these pumps were of the trombone type.

The salt water finding its way into the lubricating oil and containing a certain amount of sand, caused the piston rings to be gummed up and admitted of gas blowing past the pistons and gassing the engine-room staff. The gas blown past the pistons deposited carbon on the open type electrical machinery and as all the auxiliaries in the ship were electric, the trouble was cumulative. Little could be done in the circumstances, and it was only through great exertion on the part of the engine-room staff and the robust construction of the engines that the ship was kept running. Steam auxiliaries were afterwards fitted and the subsequent running of the machinery has been much more satisfactory.

About the end of 1911 arrangements were made for the construction of a single-cylinder experimental engine of 1,000 B.H.P.

The engine, which was of the 2-stroke cycle type, was made by Messrs. Vickers and intended finally to form part of a six-cylinder engine of 6,000 B.H.P. The diameter of the cylinder was 30 inches, stroke 36 inches, and revolutions 140 per minute. Compressed air was used for fuel injection. The auxiliaries were separately driven.

A considerable amount of experiment was necessary and the final trial took place about two years after placing the order.

The engine made a continuous run of 223 hours of which time 103 hours were run at full power, 90 hours at four-fifths, and 30 hours at three-fifths; the fuel oil used was Texas oil, having a viscosity of 137 secs. Redwood at 70° F.

The chief features brought out in connection with the experimental work were the difficulties of thoroughly scavenging the cylinder and getting rid of the products of combustion; in keeping the valves, pistons, cylinder liner and crosshead bearing cool, in designing the cylinder liner, piston and cover to stand the high temperatures and in spraying the oil so as to produce efficient combustion at the comparatively high mean pressure which was aimed at. These difficulties were all successfully overcome and the experimental work on this engine gave valuable information applicable to high power engines of all types.

The mean power maintained during the 103 hours' trial at full power was 1,044, and the fuel consumption of the main cylinder alone during this period was 0·405 lb. per hour per B.H.P. It was estimated that with the consumption for auxiliaries separately driven, for a six-cylinder engine would be about ·55 lb. of fuel oil per hour per B.H.P. In addition to this, the consumption of lubricating oil was estimated to bring this total up to ·6 lb. per hour per B.H.P. or just one-half the oil fuel consumption in a turbine installation. The total consumption of oil, including lubricating oil at four-fifths, three-fifths and two-fifths and one-fifth power based on the trials and other information, was found to be approximately per B.H.P. per hour ·6, ·65, ·70 and ·85 lb. respectively.

The engine at the completion of the trials was considered an efficient working arrangement capable of producing its full power for a further period, and that similar results could be expected if a multiple cylinder engine of the same type were designed for higher powers.

Moreover the experience gained during these trials indicated how a combination of units of this type, if used for propelling a ship at sea, could be utilised for a required endurance, while remaining efficient without important repairs.

Further experiments were made using Mexican oil, including a run of 90 hours, of which 30 hours were at full power and the remainder at four-fifths, and three-fifths power. A mean B.H.P. of over 1,000 was realised at full power and the engine worked satisfactorily.

It was necessary to stop the engine during the trials of this oil, not on account of the engines themselves, but owing to the failure of an auxiliary air compressor; on taking the opportunity of this stoppage to open out the cylinders of the main engine it was found, however, that there were hard carbon deposits on the piston rings and other parts, that one of the piston rings was broken and that the engine had practically reached its limit of work; if the stoppage had not occurred in the way it did the engine would probably have had to be stopped owing to the difficulties with the piston rings.

Considerable alterations were made in the spraying and oil supply arrangements during the preliminary experiments to adapt the engine to Mexican oil, and it was found that unless the combustion could be improved and the formation of the deposits prevented, working with Mexican oil would not be satisfactory.

Further experiments were being carried out raising the Mexican oil fuel to higher temperatures by placing electrical heaters on the discharge side of the pumps, and using solid injection, when the war intervened, and prevented any further experimental work in this direction.

The trials strongly indicated that, when developments of this kind in the Diesel engine are in progress involving engineering consideration, thought and skill of a very high degree, the commercial idea of using cheaper oils probably unsuitable for such developments should not be simultaneously pressed from other directions. The field for the experimental use of cheap oils is in engines which have passed through the trial stage and the experimenting engineer should not be hampered and embarrassed while more important and high-class engineering trials are in progress.

At the end of 1912 it was pointed out that the close attention given by Continental engineers and manufacturers to the development of the Diesel engine for many years past had enabled them to accumulate a large fund of information from which, not only had there been a continuous development in size, economy, and reliability, but the methods of manufacture had also developed simultaneously, resulting in rapidity and cheapness of output.

Having little of this experience which could only be obtained first-hand by laborious and patient research, British manufacturers were handicapped in comparison with these Continental firms.

To be of effect in the competition they had to purchase licenses from these Continental firms at high cost, and although this provided them with certain standard working designs, it did not furnish them with the necessary experience to develop from these standards.

There were also indications that British manufacturers had not realised that a higher standard of workmanship was required for the essential parts of these engines than that for the ordinary types of marine steam engines, nor were many of them equipped with the special tools and appliances necessary for securing that higher standard.

It was confidently expected that they would overtake these arrears and eventually put themselves on a level or become superior to their Continental rivals in due course, but for some time they were at a disadvantage.

In these circumstances there was reason to believe that the Admiralty would derive considerable benefit by obtaining Diesel propelling engines for three 10,000-ton Tankers direct from the best of the Continental firms. The machinery would in this way be obtained in shorter time, and other advantages of considerable importance would accrue.

By the close touch of Admiralty Inspecting Officers with the detail design and the methods of manufacture of the several items, sources of information would become available and an accumulation of particulars would be obtained first hand that would be of great value to the Service and for future manufactures, and which it would be difficult to obtain in a short time in any other way.

The ordering of machinery from foreign makers, would undoubtedly have had the effect of stimulating the development of this newly started industry in Great Britain and would ultimately have been regarded as having been a beneficial step in its progress.

Arrangements were accordingly made to obtain from Messrs. Carels, Sulzer and the M.A.N. Co., machinery to the following requirements :—

Two sets, one right-handed and one left-handed, controlled from a position between the engines of two-cycle single-acting reversible Diesel engines of their own highest class manufacture for placing in a ship to drive twin screws and to develop in the aggregate about 3,200 B.H.P. (1,600 B.H.P. each screw) at about 120 to 130 revolutions per minute. The number of cylinders were to be as small as consistent with experience.

After delivery in this country, the engines were to be erected on board by the builders of the ship under the supervision of the engine makers' representative, who would also attend and supervise the trials in the ship, so far as the parts supplied by the engine makers were concerned.

Before delivery of Messrs. Carels' engines or those from the M.A.N. Co. could be made, war broke out with Germany, and neither of these engines were delivered. The Sulzer engines were delivered after satisfactory shop trials. It was hoped to find an opportunity to fit these engines in a suitable vessel; unfortunately this opportunity did not arise.

Extensive trials of these latter engines were made in the shops and included a full load continuous running trial of 48 hours. On this trial the engines developed a mean of 1,600 B.H.P., the fuel consumption per B.H.P. per hour being ·466 lb., and lubricating oil ·015 lb. per B.H.P. per hour.

It will be gathered from the foregoing brief survey, and it is not a complete one, that the Admiralty have not been apathetic in the development of the commercial Diesel engine, and although many of the schemes were not brought to a finish, mostly owing to the war itself, or the conclusion of the war, yet a great deal of valuable experience was obtained, and has been utilised.

As regards the Diesel engines used for propelling submarine vessels in the Navy, the earlier boats up to and including the "C" Class were fitted with petrol engines, and certain disadvantages of this type of fuel made it desirable even on the score of safety alone that arrangements should, if possible, be made to use heavier and safer fuel oil. This was carried out in the "D" Class Submarines, which were fitted with two six-cylinder 4-cycle Diesel engines, 100 B.H.P. per cylinder, with compressed air injection. A good deal of difficulty was experienced with the air compressors, and in the following classes of vessels, air compressors were dispensed with, and the "solid injection" of fuel (of which system Messrs. Vickers were the pioneers in this country), was employed, the fuel used generally being shale or a similar grade of oil.

This was the general position at the time of the outbreak of war, and at that period the Vickers' 4-cycle engine with cylinders 14½ in. dia., 15 in. stroke, and developing 100 H.P. per cylinder at 380 revs. per minute was the only available submarine propelling engine with which there was an extended experience in the Service.

At a very early stage in the war it became necessary to standardise engines as far as possible in order to obtain the maximum rate of production, and in these circumstances engines of the above-named Vickers' type became the standard for the propelling engines of British Submarines and were produced in large numbers, both by Messrs. Vickers themselves and also by other firms working under license. The only development, therefore, in this class of engine during the war period was as regards the number of cylinders employed, the engines in the earlier classes of submarine consisting of twin 8-cylinder units, those in later classes of twin 12-cylinder units, whilst in still another class triple 12-cylinder units were fitted.

It will be appreciated that, at least in the earlier stages of the war, conditions did not permit of experimental work being undertaken to any great extent, even if suitable facilities had been available.

In the last year or so of the war, however, following on the inauguration of the Admiralty Engineering Laboratory, a certain amount of experimental work was commenced. For obvious reasons, in order not to interfere with production, these experiments in their earlier stages were confined to endeavours to increase the power and improve the running of engines of the standard type, whilst departing from the standard design as little as possible.

It must always be borne in mind that for naval practice, the maximum power on the smallest possible size and weight must be obtained. The Diesel engine still compares unfavourably in regard to weight with the oil-fired boiler and steam-turbine combination, and usually the space available, especially in the direction of head room, is severely limited.

It is in the attempt to obtain the maximum power for a given size of cylinder combined with good efficiency and reliability that some important features have to be considered and on these features a large amount of Admiralty experimental work has been based.

As is well known the factors on which the power for a given cylinder size (*i.e.*, bore and stroke) depends are :—

(1) The engine revolutions.
(2) The mean pressure developed throughout the working stroke.
(3) The number of firing strokes per revolution.

When we consider (1) it has to be remembered that when the speed is increased beyond a certain figure the condition is arrived at where the inertia forces may actually exceed the loads due to combustion pressures, and as these latter pressures in general govern the scantlings of important details, the importance of keeping down the inertia forces can be fully appreciated. The solution of this problem led to the use of pistons of aluminium alloy instead of cast iron. By this means it was found possible to run an experimental engine of very similar design to a standard submarine engine at a speed approaching 500 r.p.m. (instead of 380 r.p.m. usual with a submarine engine), and to obtain in the experimental engine about 155 B.H.P. per cylinder (as compared with about 100 B.H.P. in the standard engine), without increasing the inertia stresses set up. The use of aluminium pistons enabled connecting rods of lighter section to be used and combined with the use of a rod of I-section instead of circular section enabled a very considerable reduction of reciprocating weights to be effected. From these reciprocating weights, assuming the same speed of 380 r.p.m. in the two cases, the bearing pressures were worked out for the experimental and the standard engines respectively. These were found to be considerably less for the experimental engine, and the speed being the same in both cases, the reduction is a measure of the increase of the mechanical efficiency, which is estimated to be about 2 per cent.

The use of an aluminium alloy for pistons carries with it also a further incidental advantage due to the high thermal conductivity of the metal. This is of considerable importance in connexion with pistons of large size, particularly where internal cooling by the use of either oil or water is necessary. There is in addition a large over-all saving of weight and the British 1,200 B.H.P. engine with aluminium pistons is the lightest engine per B.H.P. of all that are known.

Experience is also being gained with pistons under actual Service conditions, and their behaviour after a period of continuous service will be a matter of considerable interest.

At about the period when these experiments were reaching an advanced stage it became known that the Germans had under construction Diesel engines, suitable for submarine vessels, developing about 300 B.H.P. per cylinder, and consequently the next step decided upon was to proceed with the design of a single-cylinder unit of about 300 B.H.P. embodying as far as applicable the results of experience gained with the earlier experimental engine. The dimensions decided upon were 20-ins. diameter, 20-ins. stroke with full speed revolutions of 390 per minute, *i.e.*, a piston speed of 1,300 ft. per minute, which was a considerable advance on previous practice.

It was decided to fit a piston of aluminium alloy as in the experimental engine, but in this case arrangements were made to cool the piston internally by the circulation of oil. The engine has now been in use for experimental purposes for quite a considerable time and has run quite satisfactorily. In particular it may be mentioned that no trouble at all has been experienced with the aluminium piston although it has from time to time been subjected to high temperatures and high mean pressures up to as much as 150 lbs. per sq. in.

Also even at these very high mean pressures it has been recently found possible to obtain an invisible exhaust.

The reduction of inertia stresses is not the only question that has to be solved in high-speed engines. The efficient induction and scavenging of the exhaust gases involve difficulties in providing adequate valve or port area with more rapid and sudden valve operation; there are also the questions of cylinder cooling, a greater number of heat units having to be conducted away in a given time as the speed of the engine increases if trouble with the exhaust valves is to be avoided.

Further development in these general lines is, therefore, largely dependent on metallurgical research in light, high tensile alloys and materials possessing adequate strength, combined either with good heat-resisting or heat conducting properties as necessary.

As regards (2) the problem of obtaining the maximum mean pressure with efficient and smokeless combustion has occasioned a considerable amount of experimental work and much more is still necessary in this direction.

A consideration of (3) indicates that naval requirements will not be obtained unless the double-acting 2-stroke engine is developed, which, however, owing to limitations as regards spaces, especially in the direction of head room, opens up difficult questions. It is not the intention to expand on the question of 2-stroke versus 4-stroke engines, as this has been a well-discussed subject. If the 4-stroke engine is generally favoured at present it is because experience and practice are somewhat more advanced with this type and any natural disadvantages that the 2-stroke engine is recognised to possess are in general more accentuated when the discussion is confined to very high speed engines. It will be noted later, however, that experiments on the possibilities of trying out single-acting and double-acting 2-stroke units in addition to others working on the 4-stroke cycle are being carried out.

Concurrently with the design and construction of the 300-B.H.P. experimental engine for the laboratory, an experimental engine of approximately the same size and power was designed and built for the Admiralty by Messrs. Vickers, and this engine has run successful trials during the last twelve months.

A further experimental engine of 500 B.H.P. per crank, but of the "Vee" type, 250 B.H.P. per cylinder, was constructed for the Admiralty by Messrs. Beardmore, and the trials of this engine, although they are not yet completed, have given very promising results. There is no doubt, therefore, that should the necessity arise, British engineers will be able to design and construct submarine engines of at least as high power per cylinder as those used in the German submarines.

The possibilities of the 2-stroke type have also not been overlooked and an engine of this kind has been constructed by Messrs. J. S. White, and is now installed at the laboratory. This single-cylindered engine is designed to produce 400 B.H.P. at 390 r.p.m., and it is expected that experimental work upon it will provide very valuable data.

A good deal of attention has been directed recently to the possibilities of double-acting 2-stroke engines, and a large engine of this type, from which it is hoped that most valuable experience and information will be gained, is already being designed and under construction for the laboratory.

It is not possible to give a detailed description of the large amount of subsidiary work which has been and is still being done at the laboratory in connection with problems that have arisen from time to time in the course of the work with the experimental engines. As instances, however, there may be mentioned an investigation undertaken (with a view to elucidating some of the problems of fuel injection) to determine the influence of temperature on the "time lag" between the moment of injection and the moment when rise of pressure commences; also the trial of various methods of piston cooling, &c., and the determination of certain physical constants and heat data which will be of the greatest assistance in the design of engines of high speed and power.