# PROSPECTS FOR A MARINE STIRLING ENGINE

BY

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## Introduction

About 1816 an engine design was suggested that had no boiler, no valves, no water and no internal explosion hazard. Obviously a remarkable device and one which could apparently offer financial savings. It is not surprising then that the co-inventors were Scotsmen, one a church minister, Robert Stirling, the other, his brother, James, an engineer. Although it seemed highly unlikely that such an engine could ever be constructed, the first successful engine was built in 1827 (see FIG. 1) and for a number of years Stirling engines enjoyed much commercial success with many thousands being manufactured. In general these devices were less than 10 kW but a Swedish engineer, Ericsson produced a form of Stirling engine which developed 250 kW at 9 rev/min. This engine was the main propulsion unit of a 2000 tonne ship and consisted of four cylinders with a bore of just over 4 metres and a stroke of approximately 2 metres. That the ship sank was perhaps indicative of the consequent demise of the Stirling engine, which by the start of the twentieth century had been completely superseded by other prime movers, namely internal combustion engines and electrical motors.

However, in the late 1930s just prior to the Second World War, the Dutch Company NV Philips Gloeilampenfabrieken's research engineers sought a heat-driven power source for radios and similar equipment for use in those situations where fuel was easier to obtain than batteries. Their choice was the Stirling

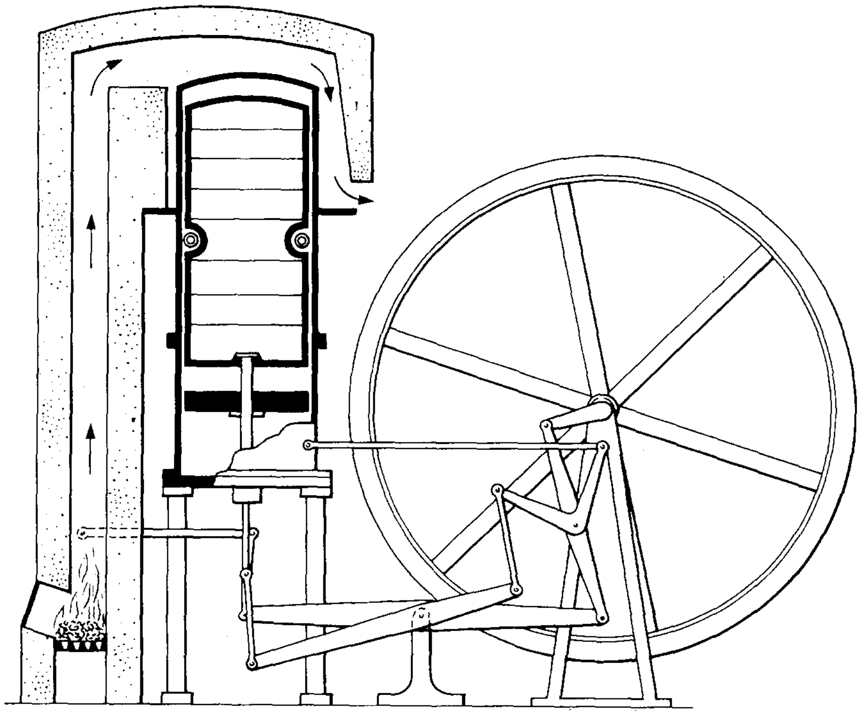

FIG. 1—THE 1827 STIRLING ENGINE

engine. Although this originally intended utilization eventually disappeared, Philips turned their attention to prime-mover applications after finding that higher efficiencies than those obtained with diesels could be achieved. From 1939 up to the present day, Stirling engine research has been carried out by Philips and their engines have found applications both in the United States Army and Navy. But before discussing this and other development work, the working principles of the engine are described.

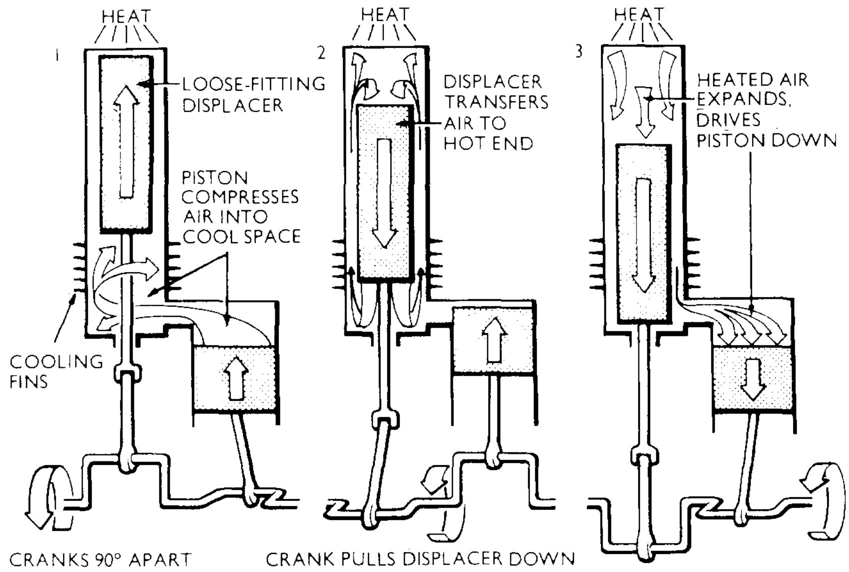


FIG. 2—THE BASIC PISTON-DISPLACER STIRLING ENGINE

## The Working Cycle of a Typical Stirling Engine

FIG. 2 shows a Stirling engine in its simplest form. On starting or by flywheel action during running, the power piston compresses the working fluid (usually air but sometimes helium or hydrogen) into the finned space below the displacer. The latter has a sloppy fit in the upper cylinder so that when the power piston has reached top dead centre in the lower cylinder not only has the displacer been moved half-way down but some of the intruding fluid has been transferred to the top end of the upper cylinder. At the top end, a heat source is located and fluid reaching this source receives heat energy and thus expands driving the power piston out and the cycle begins again using the same fluid charge. From the thermodynamics of the cycle, it may be shown that its ideal efficiency is the same as that for a Carnot engine.

In practice, however, the working process is different from that of the idealized engine. For instance, it is virtually impossible to make the cylinder glands completely gas-tight and therefore a replenishing device often has to be fitted for continuous operation. However, re-considering the idealized engine, if the heat source is removed but the movement of the piston-displacer arrangement continued in the same sequence, the fluid expansion will still occur but since there is now no heat transfer to the fluid its temperature must decrease. The heater has now become a cooler and the engine a refrigerating machine. Since the heat source is external to the engine its removal may be easily arranged, and has been in practice.

Thus, the Stirling engine may be a prime mover or a refrigerating device with, in theory, efficiencies and coefficients of performance comparable to the Carnot and reversed Carnot cycles. If such potential could be realized in practice then the Stirling engine could once again enjoy substantial success.

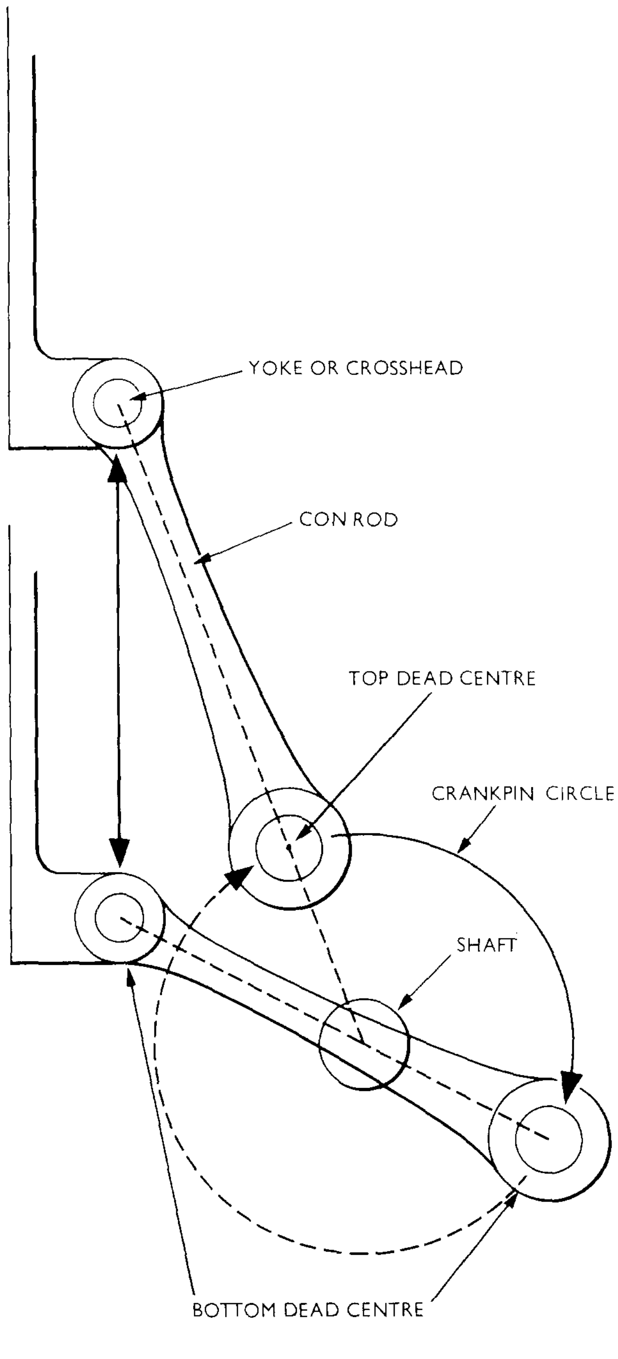


FIG. 3—THE MEIJER RHOMBIC DRIVE UNIT

**Stirling Engine Development**

Philips, since 1938, have developed a large number of engines for a multitude of suggested applications but they have published few details in open literature; perhaps this is not too surprising in view of their enormous investment of several million pounds in the engine's development. The data that have been published have, however, rekindled the interest of the engineering fraternity in the Stirling engine over the last decade especially now that alternatives to the Otto and Diesel engines are being sought.

Probably one of the most significant developments at Philips has been that of the Meijer rhombic drive which allows a single-cylinder engine to be perfectly balanced and the practical smoothness of running of this type of drive has been described as phenomenal. FIG. 3 is a diagram of such a drive. In this type of system, the power piston and the displacer both drive crossheads. Two connecting rods attached to these crossheads then drive two shafts but in opposite directions. These are geared together so that precise orientation is maintained ensuring that the crankpins follow opposite but identical paths. The piston is at top dead centre and bottom dead centre when the crank pin, crosshead, and shaft centres are in line. However, in this arrangement the angular displacement between top and bottom dead centre is not the normally encountered 180°. In moving from top to bottom dead centre the crankpin moves less or more than half a turn depending on whether the motion is clockwise or anti-clockwise.

The piston-displacer form of the Stirling engine has been the preferred form of a number of workers although there are other forms, for example, the Zwiauer-Wankel rotary Stirling Engine, FIG. 4. The power output of a Stirling engine is approximately proportional to the pressure of the working fluid; thus, the greater the pressure, the higher the efficiency and, since it is easier to deal with reciprocating seals in comparison to rotary seals, this in part explains the preference for the piston-displacer machines. FIG. 5 shows schematically the principles of the piston-displacer system. As previously mentioned, when the displacer moves upwards the fluid flows from the upper hot space to the lower

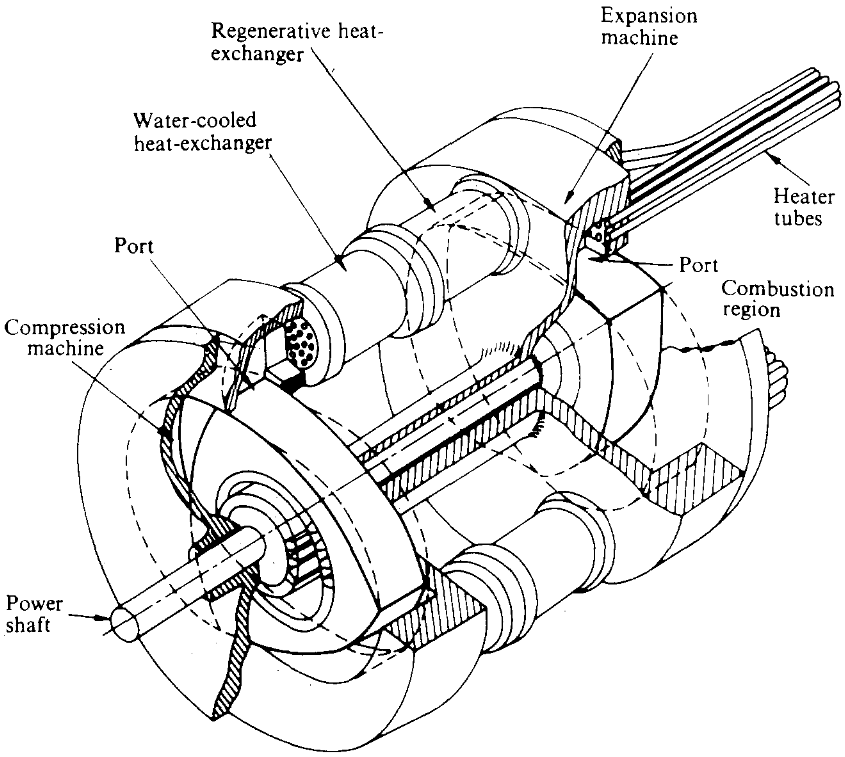


FIG. 4—THE ZWIAUER-WANKEL ROTARY STIRLING ENGINE

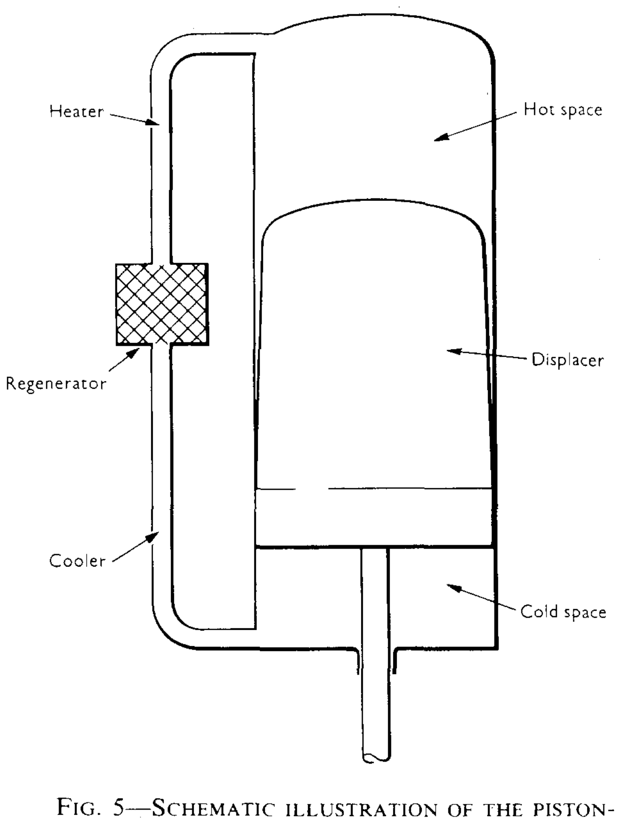


FIG. 5—SCHEMATIC ILLUSTRATION OF THE PISTON-DISPLACER REGENERATIVE STIRLING ENGINE

cold space and if this motion is reversed then so is the fluid flow direction. During the former motion the hot fluid will give up some of its heat energy which must be recovered during the latter motion. To ensure that the transfer of heat energy is efficient and that losses out of the system are kept to a minimum it is usual to insert a regenerator into the system, as shown in the diagram. The regenerator is a matrix of porous material, usually metal wires, to which the fluid transfers heat energy on its way to the cooler and from which the fluid re-absorbs the stored heat energy before entering the heater. The regenerator in a Stirling engine may thus be likened to a 'heat sponge' which alternately receives and releases heat. The foregoing is a brief description of the idealized piston-displacer form of the Stirling engine. Since the 1950s, much research work has been done on the performance of various regenerators but the optimum balance between aerodynamic and mechanical friction losses and heat transfer rates has still not been achieved. This accounts for the fact that the output and efficiency of

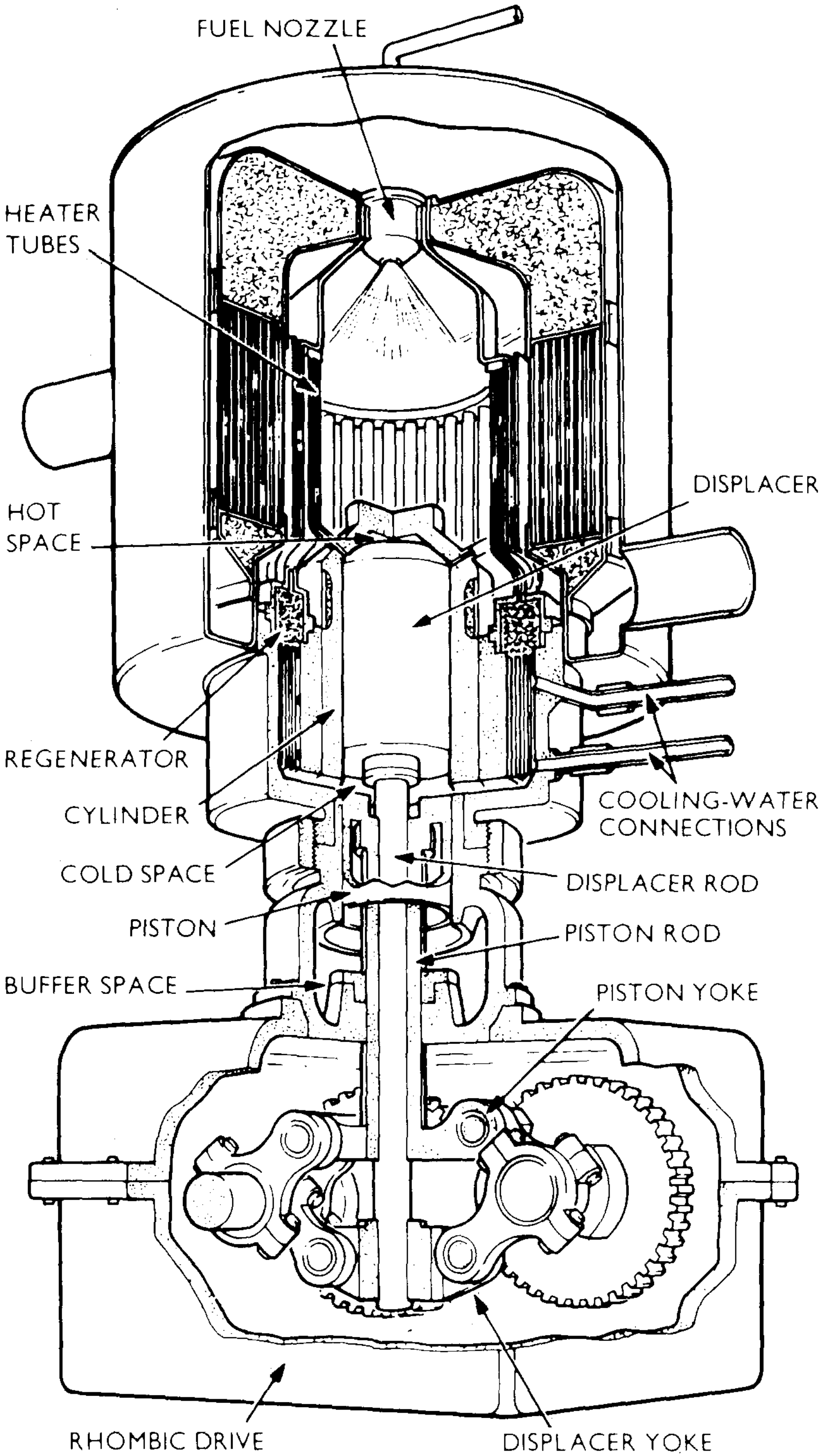


FIG. 6—THE MODERN STIRLING ENGINE WITH A RHOMBIC DRIVE

practical engines are only fractions of those ideally possible, but this is true for most mechanical prime movers.

In the modern Philips Stirling engine the working fluid is sealed in the cylinders and in a buffer space below the power piston. Because of this buffer zone, the power piston is pushed in as well as out thus giving two power pulses per revolution. The significance of this can be readily appreciated by the example that a four-cylinder piston-displacer Stirling engine with a rhombic drive would have twice as many power strokes per revolution as a V-8 automobile engine. A diagram of such a Stirling engine is shown in FIG. 6. The mean working pressure of these engines is in excess of 100 bar.

In the form of a prime mover, the Stirling engine is still in the development stage (particularly for powers in excess of 300 kW) but Philips have exploited the refrigerational uses of the Stirling cycle. Compound Stirling cycle refrigerators are now available that will produce 0·6 litres of liquid hydrogen per kilowatt and units have been produced which are highly efficient between 350 and 70 K and thus particularly useful in cryogenics.

**Possible Marine Engineering Applications**

Data on the performance of the Stirling engine prototypes have been released albeit without complete engine specifications. However, it is these data upon which the utilization of the Stirling engine in marine situations is to be discussed. The properties of the Stirling make it a direct competitor to the Diesel and so throughout the discussion comparisons will often be made.

*Fuel Insensitivity*

The Stirling engine has been shown to be equally effective using a number of fuels, namely:

(*a*) Dieso.
(*b*) Kerosene.
(*c*) Alcohol.
(*d*) Non-leaded petrol.
(*e*) Liquid petroleum gas.
(*f*) Liquid natural gas.

and it is claimed that a variety of fuels from coal and coal derivatives to camel dung are just as effective. This is perhaps to be expected since the combustion is external. The Stirling engine is thus insensitive to fuel changes whereas the Diesel's performance is altered with different fuels. At the moment, however, an equivalent Stirling engine is between 1·2 and 2 times the cost of a Diesel and it may be more economical to modify the Diesel to burn other fuels—the original Diesels were, after all, coal burning. Even so, it is obvious that fuel insensitivity will become increasingly important as the reserves of the more common fossil fuels are depleted.

*Heat Source Insensitivity*

Since the Stirling is a heat engine with external combustion, any heat source may be used, i.e. burner flames, fluidized-bed combustors, fuel cells, nuclear-heat sources, heat pipes, and so on. All have been tried with varying degrees of success. Here once again the Stirling offers great flexibility in comparison with other mechanical prime movers. Also, a theoretical study of Stirling engine utilization with a nuclear power pack has shown that definite advantages can be achieved over steam turbine/nuclear combinations especially in ship propulsion.

*Low Maintenance Costs*

The new 'roll-sock' seal developed by Philips has greatly increased the time interval both between oil changes and working fluid replenishment. Philips claim that engines up to 350 kW required maintenance only every 20 000 hours. Although these claims have not been substantiated by detailed information, one of Philips' licensees, United Stirling of Sweden, have published more precise maintenance details for a V-4 prototype automobile engine. These are:

| | |
|---|---|
| Engine Life | 7500–15 000 hours |
| Component Life | 8500–17 500 hours |

| | |
|---|---|
| Major Overhaul | 7500 hours |
| Maintenance | 500 hours (working fluid replenishment every 3 months) |
| Reliability | > 2000 hours mean time between failure |

These data are very comparable with the ASR and Deltic ranges.

*Low Noise Pollution*

The cylinder-pressure/crank-angle characteristic of the Stirling engine is considerably more uniform than that of other piston engines, see FIG. 7. The consequence of this is that if a rhombic drive is employed then a torque/crank-angle characteristic comparable with a four-cylinder Diesel can be obtained from a single-cylinder Stirling engine. The smoothness of these characteristics ensures low noise pollution over a wide frequency spectrum. This is a very definite advantage in comparison with Diesels which in all warships are one of the main sources of noise and vibration. FIG. 8 shows a noise-frequency plot obtained by the United States Navy in trials on a 300 kW Stirling engine and on the same plot the characteristics of a comparable Diesel are shown.

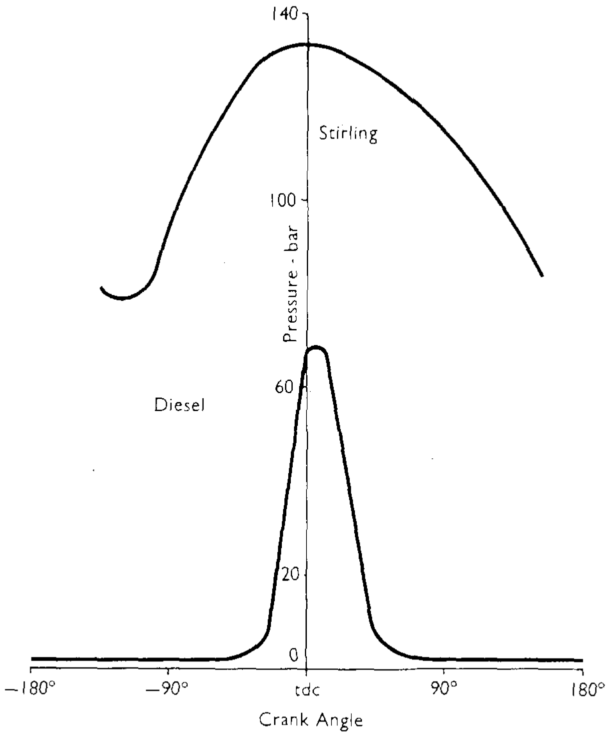


FIG. 7—CYLINDER-PRESSURE/CRANK-ANGLE CHARACTERISTICS OF A TYPICAL ENGINE

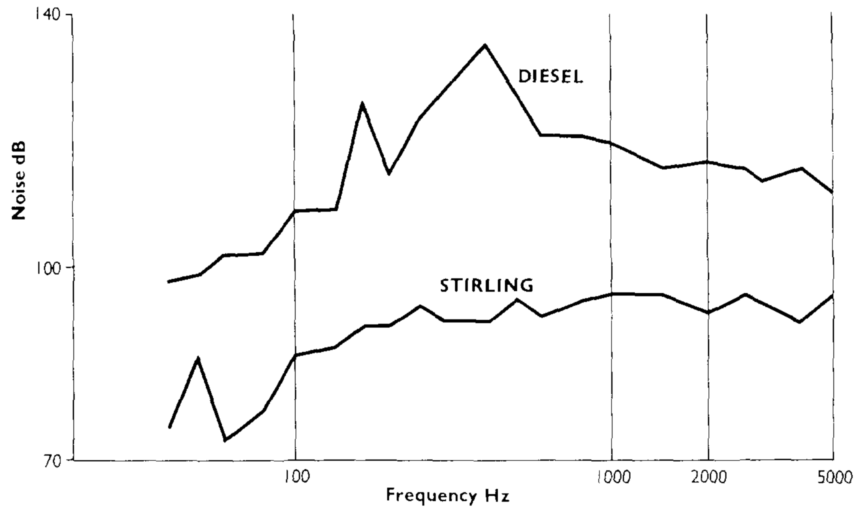


FIG. 8—NOISE SPECTRUM OF A 300kW ENGINE

*Low Exhaust Pollution*

As combustion in a Stirling engine is external, arrangements can be made to ensure more efficient burning than that usually encountered in piston engines and also lower temperature exhaust products. Consequently the exhaust pollution and $NO_X$ formation in a Stirling engine is considerably lower than in either a Diesel or petrol engine, see TABLE I. These data are based on a 65 kW power unit.

In comparison with a gas turbine, the Stirling has similar exhaust emissions on a ppm basis as shown in TABLE II. However, in a gas turbine unit, because of the requirement for large excess air flows, the actual amount of exhaust product is about eight times that of a Stirling. For this reason, the pollution comparison shown in TABLE III is perhaps more satisfactory.

TABLE I

| *Constituents* | *Pollution levels in ppm* | | |
|---|---|---|---|
| | Stirling | Diesel | Petrol |
| $C_xH_y$ | 1–2 | 200–4000 | 5000–40 000 |
| Soot | Nil | visible | |
| CO | 70–300 | 1000 | 4–10% |
| $NO/NO_2$ | 100–200 | 400–2000 | 600–2000 |

TABLE II

| *Constituents* | *Pollution levels in ppm* | |
|---|---|---|
| | Stirling | Gas turbine |
| $C_xH_y$ | 1–2 | 1·5 |
| CO | 70–300 | 200–250 |
| $NO_x$ | 100–200 | 90–250 |

TABLE III

| *Constituent* | *Pollution levels in mg/s/kW* | |
|---|---|---|
| | Stirling | Gas turbine |
| $C_xH_y$ | $2{\cdot}25–4{\cdot}5 \times 10^{-3}$ | $27 \times 10^{-3}$ |
| CO | 0·075–0·225 | 1·5–2·7 |
| $NO_x$ | 0·075–0·150 | 0·5–1·5 |

*Constant Torque over a Wide Speed Range*

FIG. 9 shows the torque-speed characteristics for a 30 kW Stirling unit between 250 and 2250 rev/min. It is remarkably smooth, although at higher casing pressures there is a high-speed droop. A comparison of torque/crank-angle characteristics for a fixed-speed Otto and Stirling engine is shown as FIG. 10, both units having a power rating of 75 kW.

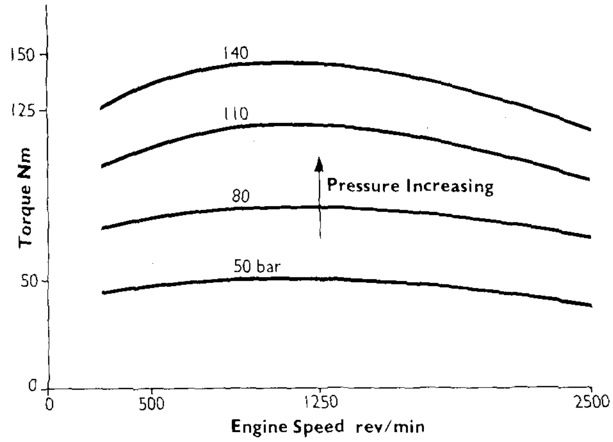


FIG. 9—TORQUE/SPEED CHARACTERISTICS OF A 300 KW ENGINE

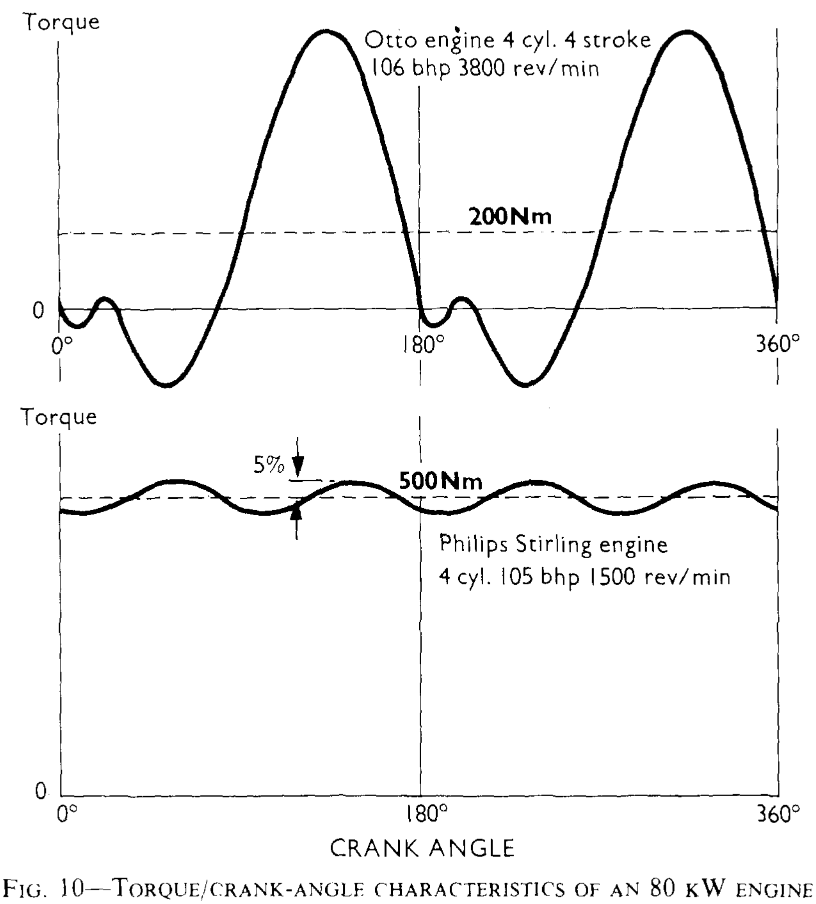


FIG. 10—TORQUE/CRANK-ANGLE CHARACTERISTICS OF AN 80 KW ENGINE

## Discussion

There are other advantages of Stirling utilization as well as those already given: for example, any Stirling engine may be overloaded by 50 per cent. for short periods and also starting is very reliable depending only on burner ignition. Furthermore, because of the external combustion system, the Stirling engine is not subjected to airborne dust erosion as are other piston engines.

The Stirling engine, although still in the development stage, has shown itself to be a serious challenger to the diesel. In the Royal Navy, diesels have two main uses: electrical generation (fixed speed) and propulsion for submersibles and small surface craft. The power ratings of these diesels vary in unit size from 200 to 2000 kW, the *Leander* Class using two 500 kW sets for generation whilst the new

MCMVs have two 700 kW main engines and three 200 kW main generators.

In terms of electrical power generation, diesels are very noisy, coke up at low B.M.E.P. and require a great deal of skilled maintenance. In all these areas, the Stirling has distinct advantages. Perhaps the most important virtue, however, is the low noise signature which would make the Stirling most appropriate for the proposed silent frigates of the twenty-first century. A minimum size of Stirling for this application would appear to be around 500 kW. However, at the moment, the cost of the development and manufacture of the Stirling is still too high to warrant it superseding the Diesel.

In terms of propulsion the gas turbine could not be replaced by the Stirling although a combination of the two might be useful (COSAG!). In small surface craft such as MCMVs, the Stirling would prove advantageous provided units of up to 2 MW could be produced. The low noise signature would greatly reduce sonar interference and weapon actuation. It is for this same reason that the Stirling engine may yet find itself in a patrol submarine. The low noise signature together with reduced maintenance, cleaner air in the working spaces, and low infra-red emissions (due to low temperature and cleaner exhaust emissions) have much to offer in underwater warfare situations, including torpedo propulsion.

Is all this speculation? Is someone trying to sell an old engine in new guise, or is there some substance to it? Well, the United States Navy, in conjunction with General Motors Ltd., have investigated the military use of Stirling engines. They built pilot plants which were almost silent and could operate in a submersible with eight times the endurance of a comparable diesel/storage-battery system. Furthermore, since the Stirling works on a closed cycle and is pressurized, its operating characteristics are independent of depth.

If the Stirling is as good as it is claimed, then why are they not in use today? One answer must be development cost: the diesels in present use do the job even with their shortcomings and in the present economic climate funds are not available in the UK to launch the type of programme required to marinize the Stirling. Funds are, however, now being made available for general Stirling development. The United States and Japanese car manufacturers are also investing heavily in the Stirling.

Although the open literature reveals only the advantages of the engine and none of the drawbacks, nevertheless the case for the marine Stirling engine is very compelling.

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