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Stirling engines: potential applications in a marine environment

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SYNOPSIS

The Stirling engine was invented over 70 years before the Institute of Marine Engineers was founded. The engine enjoyed some commercial success in both industrial and marine applications from the 1830s until the turn of the century but was overtaken by technical developments in internal combustion engines and steam power plants. Interest in the engine was rekindled during the energy crises of the 1970s and today there are active research programmes in many parts of the world. The engine is particularly attractive for marine applications, as in the maritime environment many of the engine's inherent properties can be used to greatest advantage.

INTRODUCTION

The Stirling engine is a heat-driven prime mover which operates on a closed thermodynamic cycle, i.e. the engine receives its heat energy from a source external to the working cylinders and the same internal working fluid is used for each cycle of operation. The ideal Stirling cycle has the same theoretical thermal efficiency as the Carnot cycle and a larger specific work output. Potentially, therefore, the Stirling engine is the ultimate heat engine. So far this potential has not been fully realized and the best present day Stirlings offer little advantage in terms of maximum efficiency and power density over the latest diesel engines. However, under certain operating conditions the Stirling can have a superior performance (especially in terms of low levels of noise and exhaust pollution) and under part-load operation the Stirling is unrivalled amongst heat engines.

The Stirling can operate on any form of heat source and thus is not dependent on the primary fuel used. This is often referred to as a multi-fuel capability, which can, however, be misleading since not all Stirling engines will operate on any fuel. The range and variety of energy sources a Stirling system can use depend on the design of the heat exchanger used to supply the heat energy to the engine. For example, commercial Stirling engines have been built which at the turn of a valve can use over ten different liquid fuels without any significant performance degradation.

The modern development of the Stirling was begun in the 1930s by Philips[1–3], who continued their research in collaboration with, amongst others, General Motors and Ford for over 40 years. The technology developed during this period has enabled improvements to be made to the Stirling's performance over that achieved with the 19th century versions.

Although the Stirling has been considered for many applications over the last 50 years, its use in the marine field was considered almost as soon as the engine developments began. Marine engines were designed and built in sizes up to 300 kW for use in commercial motor cruisers, naval submarines and underwater weapon systems. However, when the Philips–General Motors marine Stirling was not taken up by the U.S. Navy in the mid-1960s, work in this area was significantly reduced.

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The main thrust of the Stirling's development has been towards automobile applications. In the U.S.A. during the 1960s automobiles were built by General Motors who used a combined heat-engine + electric-battery propulsion system based on the Stirling, an idea which is now regarded as advanced technology but which then was considered to be of little utility. Other licensees also considered the land transportation role but it was not until the oil and pollution problems of the 1970s that significant government funding became available to support private industrial development of the Stirling for this application, especially in the U.S.A. and Sweden. The ensuing U.S.A. research and development programme, which ends in 1989, was funded by the Federal Government and involved at least £100 Million of public money. The project has proved successful technically but it is unlikely that the Stirling-engined car will be available to the public for many years.

Attention in the U.K., Canada, U.S.A., West Germany, Japan, China and especially Sweden has once again turned to the marine applications of the Stirling engine. The applications considered cover a wide spectrum, from large coal-burning engines for main propulsion units in merchant ships[4,5] to high power density technologically advanced engines for use by navies in the subsea environment[6,7].

With all this interest and research and development work it may well be wondered why the Stirling prime mover has not been more commercially successful. The main reasons are the relatively high manufacturing costs and the need for the high power density Stirlings to prove their reliability. A lack of substantial research investment has not helped the situation but the technical failure of some ill-conceived projects has had an unfortunate effect on the attitude of many interested parties. Nevertheless, in the military environment where operational effectiveness is as important as purely financial considerations, the Stirling is seen as a viable power plant. The use of the Stirling as an underwater submarine battery charger is especially attractive[8] and the development of such a system has now passed the prototype phase[9]. Sea trials on the Swedish Stirling-powered submarine are due to be completed before the end of the decade.

There are many other marine applications for which the Stirling could be used, and it has often been said that the Stirling is an engine waiting for an application. To a large extent this is true when the prime mover version of the Stirling class of thermal machines is considered, but what must be remembered is that Stirling refrigeration engines have enjoyed considerable commercial success over the last 30 years and are likely to enjoy even more in the future as the use of micro-electronics and superconducting devices increases.

The Stirling, unlike other heat engines, can be truly reversed, mechanically and thermodynamically, to become a refrigeration engine and temperatures below 10 K can be readily achieved. This very successful application of Stirling machine technology is often overlooked.

In a paper such as this, it is not possible to discuss all the potential uses of the Stirling engine in a marine environment. Therefore, after a general overview of the major development work to-date, it is intended to provide an insight to current and future research work .

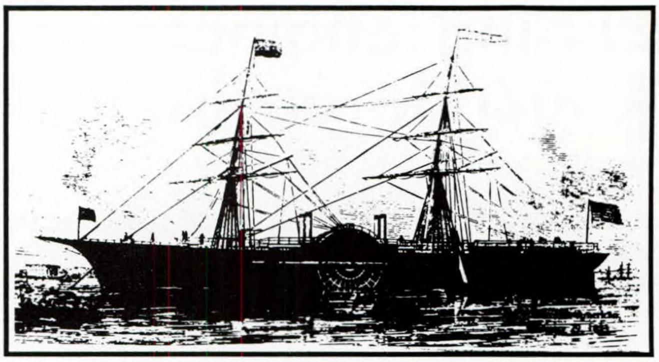

Fig. 1. *Ericsson* in 1853

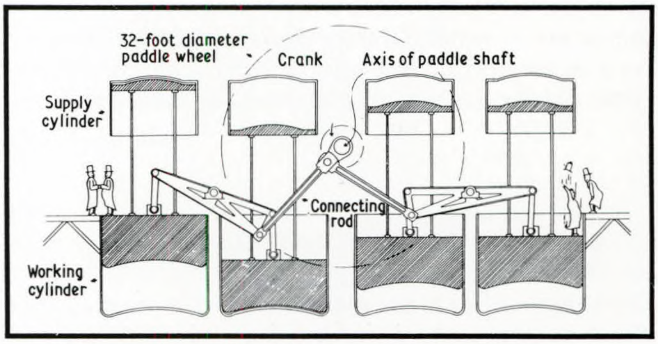

Fig. 2. The press riding on *Ericsson*'s pistons

DEVELOPMENT OVERVIEW

In the latter part of the 19th century the Stirling was just one of many available variants of the 'hot-air' engine; indeed the name 'Stirling' was not used until the 1940s to identify the particular type of hot-air engine invented and patented by the Stirling brothers in 1816[10]. The use of hot-air engines in a marine environment was investigated as early as the mid-1800s and the Swedish-born engineer Ericsson installed a 340 kW hot-air engine in the passenger vessel *Ericsson* in 1852. This engine had four 4.2 m diameter cylinders with a 1.5 m stroke and a shaft speed of 9 rev./min. The engines developed 225 kW, but were replaced by steam engines when the ship was rebuilt after capsizing in a squall off the approaches to New York harbour[11]. The ship is shown in Fig. 1 and the engines in schematic form are shown in Fig. 2 with members of the 'press' riding up and down on the large pistons! The early history of Stirling engine development is well documented in ref. 11.

The demise of the *Ericsson* was perhaps an omen as by the turn of the century interest in large hot-air engines was moribund, although small hot-air engines could be bought 'off-the-shelf' for most of the early part of the 1900s. These historic engines can now be seen in collections in the major science museums of the world and there are a number of organizations who still make and sell them for educational and novelty purposes.

The development of the modern Stirling engines began in the Philips Research Laboratories in Eindhoven in the mid-1930s. At this time there was an expansion of the use of radio communication and in areas not serviced by an electric grid system it was necessary to power the radio sets using inefficient and low power density lead–acid batteries. The researchers at Philips were looking for a small heat engine which could power an electric generator set using any available indigenous fuel and could provide the mechanical power quietly to avoid interfering with the radio operations. The two identified candidates were the hot-air engine of the type invented by the Stirlings and the steam engine[1].

The best performance achieved by the Stirling engine until the Philips programme in terms of overall efficiency was 1–2%. The researchers at Philips reasoned that for an engine which theoretically could out-perform any other heat engine the scope for improvement was unbelievable, especially with the advances that had taken place in materials and technology since the start of the 20th century. The development of the engine was partially disrupted by the Second World War but by the late 1950s sufficient progress had been made for Philips to enter into a licensing agreement with the General Motors Corporation which continued for 12 years. During that time a 300 kW engine was built for testing by the U.S. Navy for use in both surface and subsea applications[2]. This engine, although only partially developed, performed as well as the then current diesels but this was not thought sufficiently attractive for any contracts to be placed for further development. Remarkably in the Navy noise trials it was shown that the Stirling was 15 times quieter than the equivalent diesel but in the subsea environment nuclear power was already taking over.

In 1959 a 30 kW engine was installed by Philips in a 10 m motor yacht *Johann de Witt* and remained in service until 1972. Many engine types and variants were built during the Philips' programmes and as early as 1956 basic engine efficiencies of 38% had been obtained with power densities in excess of 80 kW/litre. These performances had been obtained by increasing the mean pressure of the working gas inside the engines from atmospheric level to values exceeding 110 bar and by using lighter gases such as helium and hydrogen rather than air.

Conceptual designs for torpedo motors, submarine power plants and other subsea applications were proposed during the 1960s and hardware research on heat storage battery power packs and metal combustion energy sources was conducted as part of the Stirling engine research programmes[12]. Development of new heat exchanger materials, manufacturing techniques and power transmission devices lead to significant improvements in the operational effectiveness of the Stirling. However, the use of low-molecular-weight gases and high internal pressures imposed exacting design requirements on the sealing devices used to keep the gases in the internal spaces of the engine and the crankcase oil out of these spaces. The sealing problem associated with the high-technology high-speed Stirling was initially to prove the 'Achilles heel' of many of the development programmes and the problem has still to be completely overcome.

The Ford Motor Company, United Stirling of Sweden, and the West German diesel conglomerate MAN–MWM became licensees of Philips in the late 1960s and early 1970s. Initially all these companies appeared to be interested solely in land transportation projects. Ford developed a Stirling-powered Ford Taunus automobile with a 128 kW unit based on an earlier General Motors torpedo engine design. United Stirling eventually developed a new form of engine, in collaboration with the U.S.A. company Mechanical Technology Incorporated and Ricardo of the U.K., for automobile use.

Other applications began to be investigated by the mid-1970s. Apart from the West German developments, many of the research and development programmes carried out are well documented in the open literature (and it has been claimed[1] that the German companies have developed underwater engines of up to 750 kW). United Stirling of Sweden have investigated the use of Stirlings in a variety of applications and have made progress in many fields. Ford and other North American companies have concentrated their Stirling developments on space power modules, solar power electrical generators and cryogenic applications[13], while Mechanical Technology Incorporated have been actively involved in the Federal Government-funded automotive Stirling programme[14]. Many of the American programmes have been supported by the Government research laboratories at Cleveland, Ohio (NASA–LEWIS), Pasedena, California (JPL), and Argonne, Illinois (Argonne National Laboratory), for example. In Sweden, China and Japan, Governments have also contributed to various research programmes involving the Stirling.

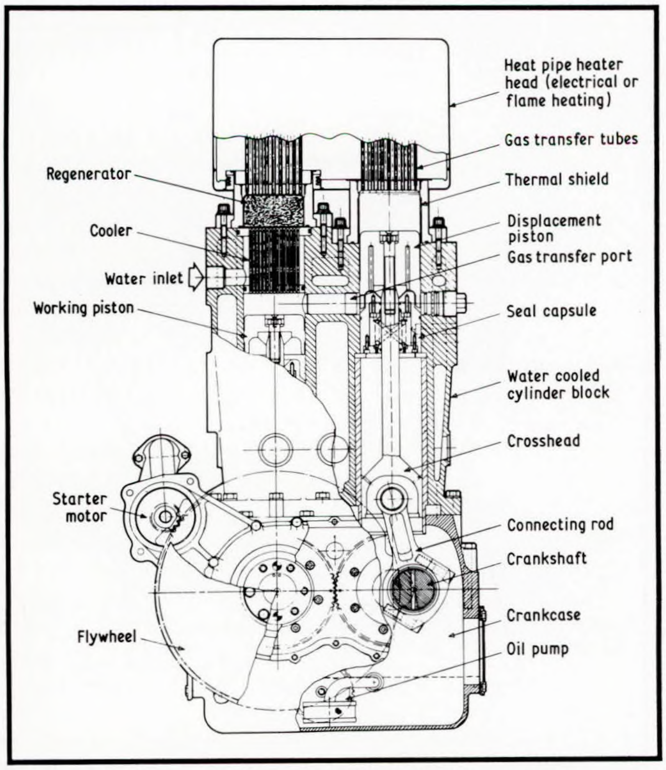

Fig. 3. The U.K. consortium Stirling engine

In the U.K. a consortium[15,16] of Universities and Industries began developing a 20 kW heat pipe Stirling in the late 1970s with funding from the SERC and the Department of Trade and Industry (see Fig. 3). This project ended in 1986 and a working engine was developed. In 1978 one of the originally proposed applications of the intended commercial version of this engine was as an electrical power generator for a motor fishing vessel. As previously stated, since the start of the 1980s increasing interest has also been shown in marine applications in China, Sweden and Japan. Conceptual studies of large marine engines and other marine Stirling applications have appeared frequently in the technical literature[17, 18]. All those interested in the marine applications have developed hardware as well as design and analysis software. Today the main areas appear to be 3-fold:

1. large coal-burning engines.
2. metal combustion torpedo engines.
3. commercial and naval submarine electrical power supplies.

There are, of course, a multitude of other possible marine applications and these will be discussed briefly later.

LARGE COAL-BURNING ENGINES

The 1970s oil crises were generated not only by the escalation in the price of crude oil but also by the uncertainties of its supply. It was not surprising, therefore, that other forms of fossil fuel, especially coal, were considered for use as primary energy sources at sea. A return to steam technology was considered, usually along with the use of fluidized-bed combustion. In North America and China much interest was shown in coal-burning Stirling engines of up to 1 MW for stationary power generation, marine and locomotive propulsion and for heavy off-highway rubber-tyred equipment in mining, agriculture and forestry[19]. In the U.K. some interest was shown by various members of the general engineering and shipbuilding communities and concept studies were carried out at the Royal Naval Engineering College (RNEC) and Associated Engineering Developments Ltd. on coal-burning Stirling engines for locomotive and ship propulsion[20].

Research in this particular area considered both the direct use of coal combustors and the indirect use of coal and fossil fuel slurries via fluidized beds and liquid metal heat pipes with the Stirling. Using air as the working fluid for low-speed operation it was shown that the use of coal with a Stirling was potentially cheaper, in the 0.5–5 MW range, than a Rankine engine and could compare with the cost of an equivalent diesel. However, in the more technically developed Western countries the end of the oil crises ameliorated the general energy problem and no very large coal-burning engines were built. Examples of the engines proposed for this type of application are shown in Figs. 4 and 5.

Stirling engines were considered by the Chinese as possible replacement engines for their 1700 kW Yangtse River passenger ferries. Some of the older vessels on this service are coal-fired but the majority use elderly diesels. The most recent development in this area has been based on the use of Bingham pistons and a special form of piston motion control which enables the shaft to be reversed without the need for a gearbox. The latter device was developed at RNEC under the guidance of Professor G. Walker[21]. The Bingham piston concept requires that the engine crankshaft passes through the piston rather than being attached to it in the normal manner. This usually means that some form of Scotch yoke mechanism has to be used. The general aim of such arrangements is to improve the compactness of the engine but unfortunately the use of the Scotch yoke mechanism also tends to increase the friction power losses and decrease bearing life. Nevertheless, engines have been successfully built on this principle[4] and a proposed design of a Bingham piston engine for marine applications is shown in Fig. 5.

The results from the simulation and costing exercise carried out on coal-fired Stirlings by RNEC and Associated Engineering Development are given in Table 1. The findings were that this form of Stirling engine could be an attractive and economical powerplant when diesel oil was not available. However, this work was not continued and other than the Yangtse River ferries there is little evidence of current research programmes on coal-fired marine Stirling engines, although there still appears to be a definite interest in the use of these engines for other applications.

METAL COMBUSTION TORPEDO ENGINES

The concept of metal combustion is not new and it has been known for some time that the heat energy release rates and energy densities available from the burning of metals rival that of nuclear reactors[2]. There was a great deal of fundamental research work undertaken in the 1960s on the use of metal combustion energy sources coupled with Stirling engines[12] and many chemical reaction were considered, the most favoured one being the reaction of lithium metal (Li) with sulphur hexafluoride (SF_6) as this reaction requires no air and does not generate a gaseous exhaust.

It was realized at an early stage in these developments that if the high rates of energy release could be harnessed to drive a heat engine then the complete system would make a particularly attractive underwater powerplant for a submarine or torpedo. The Li + SF_6 reaction temperature of 850 °C is ideal for use in steam generation or for use with Stirling engines. Studies of the concept were conducted in many countries with much of the basic chemical and materials research being carried out by Philips.

Actual metal combustion Stirling engine systems were built and high power densities were achieved but as far as it is known none of the developments ever passed the prototype phase. It is not difficult to show that a Stirling engine, using a swashplate-type drive mechanism, can be fitted into the modern torpedo and that such a unit could achieve the power levels required at present. However, several studies have shown that development of such a unit would require a high level of funding, and significant improvements to the predicted power-to-weight ratios of these systems would be needed if the performance of the powerplants currently available was to be bettered.

The speed limit of an underwater vehicle using conventional propeller propulsion is theoretically about 60 knots, and at this speed it is a matter of conjecture whether a metal combustion Stirling could deliver the power required to propel a torpedo. Work by the Philips licensee Stirling Thermal Motors of the U.S.A. on a proposed 825 kW engine suggests that the Stirling could meet this target[22] but studies by others are not so optimistic[23].

The present problems with this application are not with the engine itself but with the design of the metal combustion system and the overall packaging of the propulsion unit in the limited space available within a torpedo. There are in fact several conceptual and design difficulties to be overcome, for example the heat energy has to be transported to the engine from the reaction vessel and for such high energy densities a circulatory liquid-metal system of some description would normally be required.

The obvious solution to this particular problem would be the direct insertion of the Stirling's heat exchanger tubes into the reactor, but in practise this arrangement has not been wholly successful[2]. The use of conventional sodium heat pipes is another possible solution but it is questionable whether such

Table 1. Relative operating cost of Stirling and diesel engines

Nominal rating 1000 HP≈ (1000 x 33000)/778 ≈ 42500 Btu/min; $\eta_{ht\,tr}$ = Heat transfer efficiency of heat pipe system; η_{acc} = accessory losses due to fans, pumps, etc.

Type	$\frac{42500}{CV}$	$\frac{£}{lb}$	$\frac{1}{\eta_{comb}}$	$\frac{1}{\eta_{mech}}$	$\frac{1}{\eta_{therm}}$	$\frac{1}{\eta_{ht\,tr}}$	$\frac{1}{\eta_{acc}}$	$\frac{£}{min}$
Diesel	$\frac{42500}{18000}$ (oil)	$\frac{0.1}{1.0}$ (oil)	$\frac{1}{0.97}$	$\frac{1}{0.8}$	$\frac{1}{0.36}$	—	$\frac{1}{0.95}$	0.92
Stirling	$\frac{42500}{10000}$ (coal)	$\frac{0.02}{1.0}$ (coal)	$\frac{1}{0.97}$	$\frac{1}{0.8}$	$\frac{1}{0.28}$	$\frac{1}{0.6}$	$\frac{1}{0.9}$	0.67

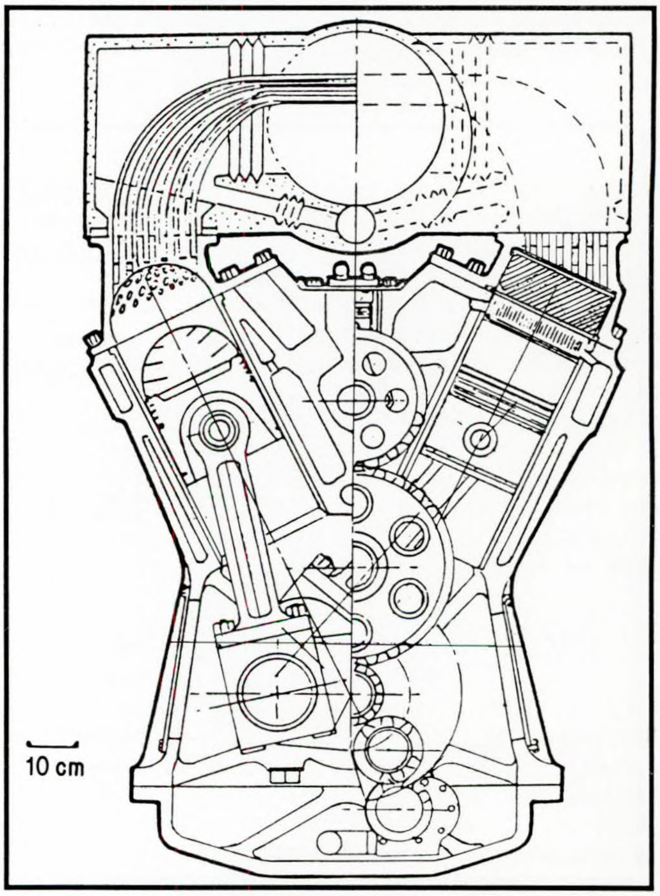

Fig. 4. The Manadon S engine

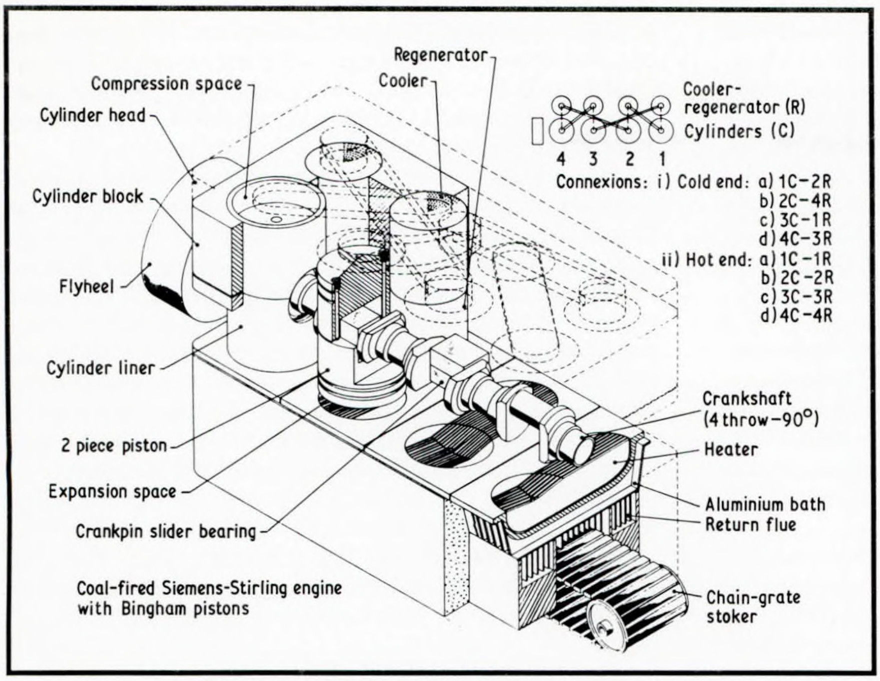

Fig. 5. The Walker–Tricorne marine engine

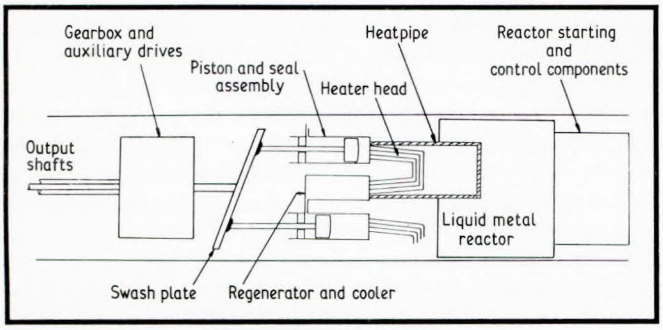

Fig. 6. The Stirling torpedo concept

a device could transport the required rates of energy flow without the help of liquid-metal pumps. If the latter were to be used then there are other better ways of transporting the heat energy.

The sulphur hexafluoride has to be stored under pressure and transported to the reactor. The lithium has to be transported using thermoelectrodynamic pumps. All these requirements can be met, but as yet many of the components are not commercially available and require further development work. Nevertheless, if the potential of the metal combustion concept could be realized then it would be an extremely attractive energy source for general use as well as with the Stirling. A proposed layout of a typical Stirling-engined torpedo concept is shown in Fig. 6.

SUBMARINE ELECTRICAL POWER GENERATION

The advent of nuclear power enabled the naval submersible to become a true submarine and have underwater endurances limited only by the amount of food which could be carried for the crews. The research and development costs of nuclear-powered submarines were so large that for the Western nations involved little was left for the investigation of any other type of powerplant. Nevertheless the conventional diesel-electric submarine continued to be used by non- nuclear nations and some nuclear nations as well. Indeed there are still certain operational missions which can be adequately, and sometimes better, performed by these cheaper and smaller vessels.

By the early 1970s the submarine had become the capital ship of the world's major navies replacing the battleship and the aircraft carrier. This capital position was further enhanced when the submarine became the main platform for the transporting and launching of strategic nuclear weapons. Even so for the majority of nations the term 'submarine' still means diesel-electric vessels. The average size of these vessels is about 1000 t displacement, compared with nuclear vessels which have now been built with displacements up to 30,000 t.

In the 1940s the need to extend the submerged endurance of submarines was brought about by the increasingly effective anti-submarine warfare tactics developed especially by the allied navies and air forces. All submarines were then powered by diesel-electric systems. Underwater the electric motors were driven by lead–acid batteries which had to be re-charged daily, when on submerged patrol, by surfacing and running the diesel generators. This operation exposed the submarine to possible detection, visual and sonar, as well as interrupting its patrol. Only by extending the underwater endurance of the submarine could its chance of survival be significantly increased and its combat effectiveness thereby enhanced. The first step in this direction was taken with the invention of the snort mast which allowed a submarine to remain below the surface at periscope depth and still draw into the vessel combustion air for the diesel generators. This system is still in use.

Apart from the snort invention, other methods of increasing submerged endurance were considered and several heat-driven atmosphere-independent power systems were investigated. In Britain, after the Second World War, a captured German-designed turbine which used the chemical products of dissociated hydrogen peroxide (H_2O_2) and a hydrocarbon fuel was installed in the experimental submarines HMS *Explorer* and HMS *Excalibur* with some success, although H_2O_2 is a hazardous substance to handle and is a fire risk. In Germany the closed-cycle diesel engine was investigated but only reached a conceptual stage. Research on electrochemical batteries was carried out in many countries, but as previously stated the arrival of the nuclear-powered submarine caused all these developments to be severely curtailed. However, in recent years advances in sensor and weapons systems have made the low-endurance diesel-electric submarine increasingly, and in some cases unacceptably, vulnerable.

To minimize the possibility of detection it is crucial for the submarine to remain under the surface at a safe depth, which means it must have the capability for extended endurance, i.e. days rather than hours. The obvious route to achieving this is nuclear power but for many nations and navies this option is technologically unsupportable, not politically acceptable, or too expensive. Furthermore, in coastal waters and shallow seas present nuclear submarines are too large and it is not easy to design a small nuclear-powered submarine. Consequently there has been a resurgence of development effort towards extending the submerged endurance of conventional submarines. The impetus for this development work has not only come from the defence sector but also the commercial marine industries, who have shown great interest in the acquisition of extended endurance submersibles, both manned and unmanned, to carry out a variety of tasks associated with the offshore oil industries, under-ice cargo transportation and general ocean resource exploitation.

In addition to the military submarine avoiding detection, it must also be able to detect other vessels. In an environment where noise is the primary means of detection the submarine must be able to 'listen' for long periods of time without its own noise either masking its sensors or revealing its presence. Thus the powerplant that provides a submarine with enhanced submergence capability must be able to produce its power quietly, otherwise in many roles it will be of little use.

In the production of silent underwater power the electrochemical battery is unrivalled. The obvious answer to the problem of extended endurance would seem therefore to be improved batteries. There is no doubt that the present performance of lead–acid batteries can be improved from both power density and safety viewpoints. However the recharging of batteries is a potentially dangerous process. Apart from such obvious dangers as acid spillages, there is the ever present risk of explosion, fire and atmosphere contamination since hydrogen gas is produced during recharging. There are many other dangers associated with the operation of batteries and it has been suggested that 70–80% of the factors taken into account when designing underwater batteries are primarily concerned with safety[25].

Recharging batteries underwater further compounds the safety problems and indeed it is not operationally desirable to charge the batteries fully when submerged. Nevertheless, the use of non-liquid electrolytes such as thixatropic gels can significantly reduce the hydrogen problem[25] and microprocessor battery energy management systems currently under development should help to make the best use out of existing systems[26]. It has been suggested that submerged endurances may be increased by over 10% using such systems. In ROVs and similar vehicles where underwater recharging is not an operational necessity, the lead–acid electric motor combination is still an attractive powerplant but for military submarines newer, safer batteries are required with higher volumetric energy densities.

A review of battery developments has shown that improvements in such densities can be expected in the future but only if the customer is prepared to invest large sums of development money and pay more for batteries than at present[27,28]. Furthermore, a number of the new battery materials such as sodium and sulphur are potentially more hazardous than the lead–acid combination and have to operate at operationally undesirable temperatures. In the future it is likely that the lead–acid battery will be replaced by one of the new 'super-batteries' such as sodium–sulphur, silver–zinc, nickel–cadmium, etc., but for the time being the battery is not the answer to the problem of increasing significantly the submerged endurance of a military submarine of any reasonable size.

Another device worthy of consideration for the underwater generation of electric power is the fuel cell. This device is an electrochemical energy converter which changes chemical energy directly into electrical energy. The power is produced quietly and the cell's maximum efficiency is potentially greater than that of other fuel-burning devices such as heat engines because the performance of a fuel cell is independent of the Carnot thermodynamic limitations. The device was invented some 150 years ago and came to public attention during the U.S.A. Gemini and Apollo space projects. They were also used in the U.S. Navy's Deep Submergence Rescue Vehicle (DSRV) and Deep Quest Vehicle[29].

However, following the lunar missions interest in fuel cells generally decreased until the late 1970s. In recent years there have been many exciting developments in fuel cell technology, and powerplants using them have increased in size from the few kilowatts of the Gemini space packs to 4.8 MW generating stations[30]. The development work going on is mainly aimed at the electrical and gas utilities market, especially in Japan and the U.S.A. In West Germany, a consortium of Howaldtswerke-Deutsche Werft AG, Ferrostaal and IKL have developed a hydrogen–oxygen fuel cell for submarine use[31]. The development started in 1980, and following successful land trials in the period 1984–86, the decision was made by the German Ministry of Defence to install a fuel cell plant in a 205 class FG navy submarine for sea trials in late 1987/early 1988. However, apart from this and a similar French project, almost no attention has been given to the potential marine applications of the fuel cells.

Fuel cells offer possible advantages for some marine uses especially when silent operations are required but because the marine market itself is not large enough either to drive or to fund fuel cell development it is unlikely that there will be any market penetration or significant military use until they have become firmly established in the utilities industry[32].

At present the best method of increasing the submerged endurance of a non-nuclear submarine underway appears to be a closed-cycle heat-driven battery charger. The Stirling engine and the Argo-cycle diesel[33] are the frontrunners at present. The Italian navy already has a form of closed-cycle diesel submarine at sea and the Swedish navy are to conduct sea trials on a Stirling system in the near future. For most applications there is little to choose between the diesel and the Stirling but the latter is favoured in the military environment because it is inherently quieter and requires less scrubbing of the exhaust gases.

Whatever form of heat engine is used in the add-on battery charger role in a military submarine the fuel used will be naval grade diesel. This is because the diesel engines will still be used for surface transits and in those instances when it is acceptable

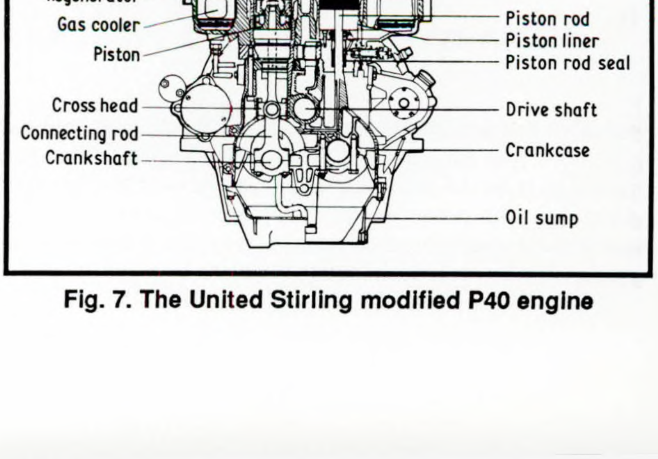

Fig. 7. The United Stirling modified P40 engine

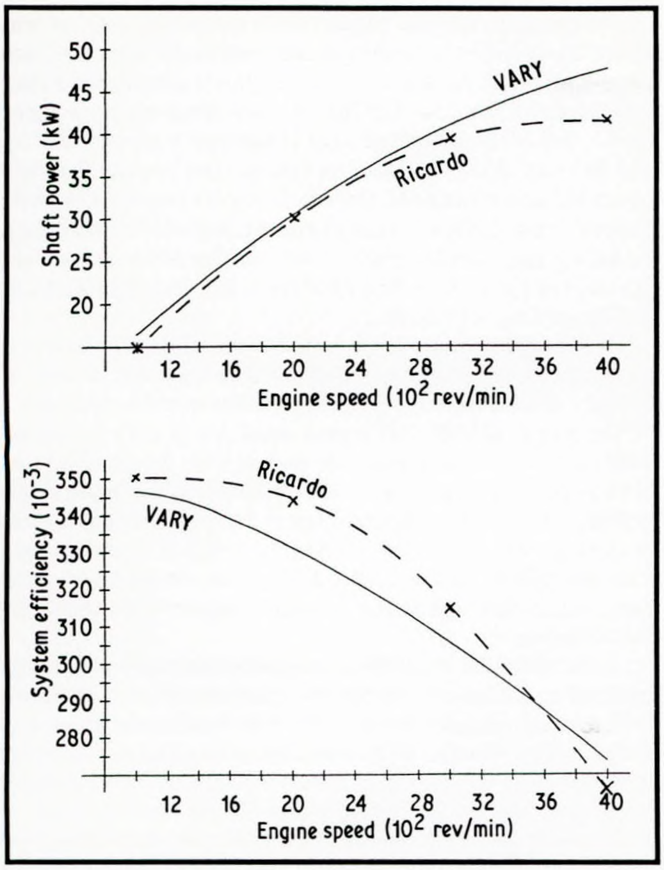

Fig. 8. Comparison of P40's theoretical performance (VARY) with actual performance (Ricardo)

to charge the batteries on the surface or when snorting. Logistically it is highly convenient to use a single fuel type. If a hydrocarbon fuel is to be used then an oxidant will be required. Since air will not be available under water the submarine will have to carry its own supply of oxidant. The amount of oxidant, i.e. oxygen, the submarine can carry will dictate the submerged endurance of the vessel. The Stirling and diesel systems in present use store the combustion oxygen in liquid form.

As previously stated, it has been claimed that the West Germans are or have investigated the underwater Stirling engine[1], but the open literature only contains information on the underwater application from two sources: the Swedish company United Stirling AB of Malmö[34–36] and RNEC. The latter have had a significant Stirling engine programme over 10 years and have developed both hardware and software in support of this programme. The underwater project has been centred around a United Stirling 40 kW P40 engine and a computer simulation developed at the College. The next section of the paper describes and discusses RNEC's work.

ROYAL NAVAL ENGINEERING COLLEGE PROJECT

Research work on the Stirling engine began at the College in the early 1970s and continues up to the present time. Several different programmes are being run on particular aspects of Stirling cycle technology, all with the general aim of assessing the Stirling engine for use in a naval environment[6]. The underwater programme was originally concerned with the design of a liquid metal combustion Stirling engine combination for use in a small underwater vehicle such as a torpedo[23]. Later the main emphasis changed to the consideration of the Stirling generator as an add-on plant to a non-nuclear submarine. The concepts of the total replacement of the existing submarine powerplant, the replacement of the open-cycle diesel and recharging of batteries underwater using Stirlings have all been investigated. The latter option appeared to be the most feasible and most acceptable for the near future. A United Stirling P40 engine was acquired and fully tested.

The P40 (see Fig. 7) is a 4-cylinder double-acting engine. The cylinders are set out in a square formation so that a single combustor can be used. Double-acting means that the top end of one cylinder is coupled to the bottom end of the adjacent cylinder to form a separate Stirling cycle. In this way a single piston acts as the expansion piston for one cycle and the compression piston for another cycle. Each cylinder is interconnected to the two adjacent cylinders and each piston is correctly phased to enable maximum power to be obtained from each of the four cycles. A fuller description of the working cycle can be found in refs. 1, 2 and 9.

Over the duration of the Stirling engine research programme at RNEC a full suite of computer codes has been developed for the design and simulation of a Stirling prime mover. The most advanced and developed computer simulation was used to model the operation of the P40 engine. An experimentally validated programme was considered to be essential for subsequent studies of the Stirling battery charger concept. In addition a 25 kW generator set based on the P40 has been built and fully instrumented to enable steady state and transient response of the system to be investigated under operational conditions. These investigations are currently in progress. The computer code developed for this work 'Vary' was found to provide very good correlation with the experimental data obtained by Ricardo from the P40 test programme, as can be seen from Fig. 8.

Armed with a validated computer programme the next stage in the investigation was to specify a submarine so that the concept of using a Stirling could be investigated. It was decided to consider the retrofitting of a Stirling to a typical modern conventional submarine and thus a restriction put on the system design was that the hull length could be increased by no more than 10% of its original length in order to house the Stirling generator unit(s). Using data from the open literature[24] the following major parameters were used in the study:

Length overall	70 m
Hull diameter	7.5 m
Submerged displacement	2400 t
Maximum speed	≈20 knots
Diving depth	<200 m
Main motor size	4 MW
Submerged endurance	≈240 h

A full system design was completed based on an uprated version of the USAB P40 engine. To meet the above requirements, including the normal hotel load of such a vessel, it was found that the Stirling set would have to provide 126 kW of power at 3000 rev./min using a synchronous 2-pole a.c. generator. The uprated engine was designed and optimized to use hydrogen working fluid at a mean pressure of 150 bar and a cylinder head temperature of 750 °C. The designed engine retained the 4-cylinder double-acting configuration of the P40 but the cylinder displacements were increased to 275 cm^3.

The Stirling system was designed to burn normal submarine diesel fuel and oxygen. The oxygen would be stored in liquid form (LOX) in a pressurized container. Exhaust gas disposal was an important consideration. At deep diving depths, if dumped overboard the exhaust would encounter back pressures of over 25 bar. To overcome this problem the over-pressure combustion concept developed by United Stirling was chosen for the study. Thus the fuel and oxidant would be supplied to the combustion chamber at a pressure of 20–30 bar and the exhaust gases merely released overboard in a carefully controlled manner. Fuel would be brought to the combustor pressure using a small pump and the LOX would be bunkered at an appropriate temperature.

Within the space limitations it was found that storage for approx. 47 t of LOX could be accommodated in the 7 m add-on section. With this amount of LOX and the uprated engine design it was calculated that for a typical mission profile the submerged endurance of the specified vessel would be 214 h. Although this time did not meet the target set, nevertheless it represents an order of magnitude increase on that normally possible. It was estimated that the total cost of the add-on unit including the retrofitting would be approx. 5% of the cost of the initial shipbuild.

OTHER MARINE USES OF STIRLING ENGINES

In the preceding part of this paper the naval submarine application was focused on in some detail. Of course, a similar type of system could be used in commercial submersibles but this particular application is not discussed here as it is covered in some detail by United Stirling in this part of the Transactions. To conclude this somewhat brief overview of the Stirling in a marine environment a few general observations will be made as to their potential use.

1. Applications in which quiet operation is essential: (a) naval submarine propulsion main/auxiliary and (b) remote underwater vehicles (military).
2. Applications in which quiet operation is desirable: (a) oceanographic/hydrographic research vessel propulsion and auxiliary power, (b) anti-submarine warfare vessel propulsion and auxiliary power, and (c) geological/seismic vessel propulsion and auxiliary power.
3. Commercial ship propulsion/auxiliary power: (a) tankers, (b) bulk carriers, and (c) offshore supply vessels.
4. Other applications: (a) power for remote sites (navigation, radar, data acquisition systems, etc.), (b) offshore platform auxiliary power, and (c) cryogenic plant for air conditioning/superconducting machinery/sensors.

The lists of course could be endless but the above give some idea of the areas which could be exploited. However, in most of the above cases there has been very little research and development effort.

CONCLUDING REMARKS

The Stirling engine represents existing technology. Its claimed multi-fuel capability, low noise and exhaust emissions, quietness and good efficiency, especially at part-load, are now all experimentally proven properties. In combination with closed sources of energy the engine is an attractive powerplant for underwater applications. In the refrigeration mode the Stirling is a commercial success and the eventual advent of superconducting materials may provide a further outlet for this particular branch of Stirling technology.

In terms of marine engineering, the naval and civilian sector have different requirements, although these are not always mutually exclusive. Cost is not necessarily the major concern in building naval ships and if Stirling engines prove to be the best technology for a particular application then they will be used. So far no naval or commercial organization has identified any application for which the Stirling is considered uniquely suited. Most certainly a return to a mixed-fuel policy including coal would improve the prospects for the use of Stirlings in the surface fleets but there are few indications of this happening at present.

In the intermediate future the use of the Stirling underwater seems the most likely application. The case for its use in military submarines is very strong. However, unless the navies of the world identify an urgent need for greatly increased submerged endurance then the strength of the case for the Stirling is largely irrelevant. To a large extent, the future of the Stirling in this area depends upon the performance of the Stirling-powered Swedish submarine which is to undergo sea trials in 1988/89. Even in this application the Stirling has its competitors although at the moment it may have a technological advantage.

In the next century, if the developments in superconducting materials, machinery and micro-electronic devices maintain their present pace the Stirling may find itself in common use. However the promise of the Stirling thermodynamic cycle has not been fully realized in practical systems and it may never be. Improvements are being made all the time and just as importantly the engineering community is now becoming more familiar with the technology. Nevertheless, as previously stated, the Stirling is an engine waiting for an application. It has yet to find acceptance, and the extended endurance submarine may prove to be its benchmark.

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