Rebirth of the Stirling engine

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A type of engine first conceived in Scotland 150 years ago is now on the brink of widespread use. Smooth, quiet and versatile, it can be run on any source of heat and will present a severe challenge to existing piston engines

THE STIRLING ENGINE differs radically from the more familiar diesel and spark ignition engines. Although all these types depend for their power on a heat source which causes a working gas to expand and drive a piston, today's common engines burn their fuel internally and intermittently whereas the Stirling burns its fuel continuously and outside the engine itself. The Stirling has a number of striking advantages over its more firmly established competitors. Its exhaust is relatively clean. It is quiet and almost free of vibration. It has favourable torque characteristics. And it can be run on almost any fuel, or other heat sources of sufficiently high temperature.

In the course of the next decade these should enable the Stirling engine to take its place side by side with petrol and diesel engines in driving ships and land vehicles, and for many other purposes. The reverse process, in which mechanical energy is used to drive a Stirling cycle machine producing cold, has already been in successful commercial production for a number of years; it is a popular and cheap method of producing liquefied gases.

At Philips Research Laboratories we have for 30 years been investigating engines that work on the principle of heating and cooling a gas in the closed Stirling cycle. We have recently made great advances and, now that the fundamental problems can be assumed to have been solved, work can proceed on optimum engines for specific applications. It need hardly be said that this involves a great deal of engineering development. Our research was done on single-cylinder models of 7.5, 30, 65 and 370 kW. An efficiency of 40 per cent can already be obtained with these engines, coupled with a specific power of 82 kW per litre of swept volume. It will be possible to increase these values quite considerably.

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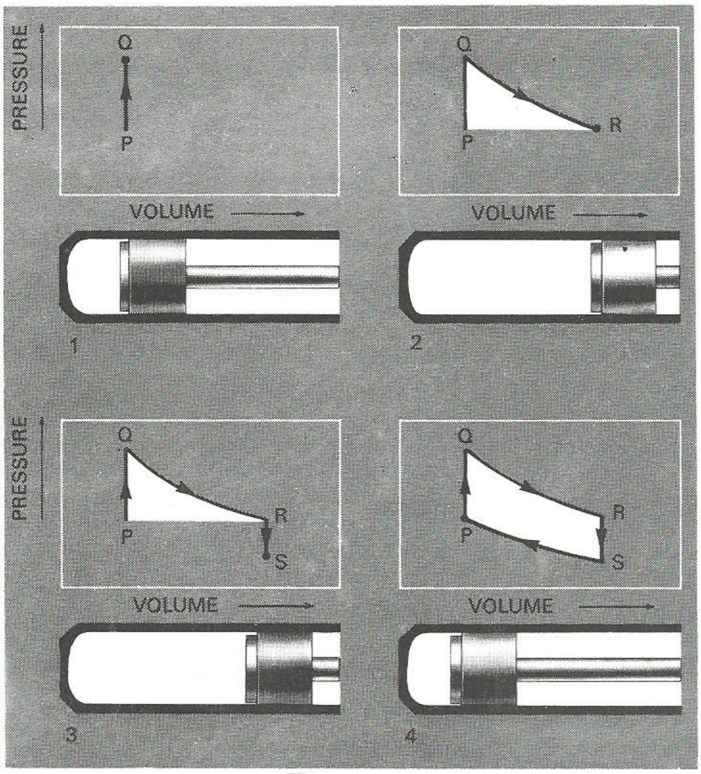
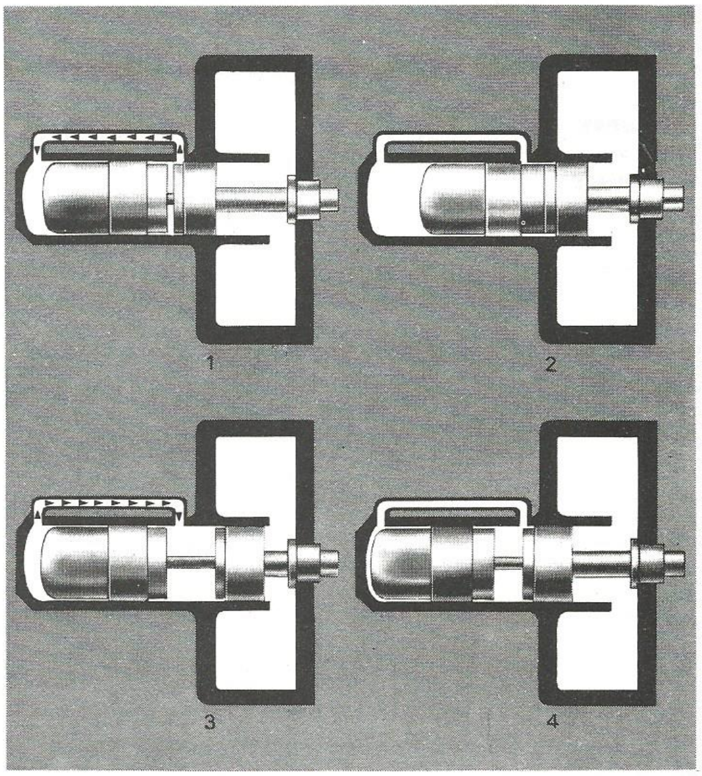
THE STIRLING ENGINE is based on an idea first proposed by Robert Stirling and described in a patent in 1817. This was long before the invention of the petrol and diesel engine, at the time when the steam engine was coming to the fore. The main motive that made the Scots inventor look for something other than an improvement to the steam engine was that the latter, with its cast iron boiler, had shown itself to be a dangerous piece of machinery. For many years more than half of all marine steam engines, together with many ship's hands, came to an untimely end as a result of boiler explosions. At the beginning of the 19th century this prompted many inventors to look around for a different working medium. The most obvious answer was air, and among various types of hot air engine was one by Stirling himself. All this happened at a time when there was no established theory of thermodynamics.

Although Stirling believed in a *perpetuum mobile* of the second kind, in that he assumed that all supplied heat could be converted into mechanical energy provided the regenerator—another of his inventions—had 100 per cent efficiency, nevertheless this cycle was interesting to Philips because theoretically it can reach the maximum conversion efficiency when it is allowed to work between a heat source and sink at different temperatures. This maximum conversion efficiency is identical with that obtained with the well known Carnot cycle. But Stirling's cycle has a great advantage over Carnot's in that much more work can be produced in each cycle; specific power can be high.

The Stirling cycle can best be described by comparing it with the process taking place in an internal combustion engine. The latter provides a surplus of work when a quantity of air is compressed inside it at a low temperature, either before or after the addition of the fuel, and the mixture then rapidly heated by combustion and the gases produced allowed to expand at a high temperature. The same principle of compression at low temperature and expansion at high temperature of a given quantity is the basis for the Stirling engine. Here, however, the heat is applied to the gas from outside, through a wall. Owing to the high heat capacity of the wall it is impossible to heat and cool the gas simply by rapidly





THERMODYNAMIC CYCLE of a simple hot air engine (left) begins with gas above the piston at atmospheric pressure. Heating the gas, keeping piston stationary, raises pressure from P to Q. Without further heating, the gas is allowed to expand, driving piston to right, back to atmospheric pressure at R. Expanded gas is cooled to point S, and returning piston then compresses it back to P. Work done by this cycle is proportional to area PQRS of the complete pressure/volume diagram. A more complex hot air engine (right) has not only a piston P but also a reciprocating displacer D. The resulting behaviour is seen in these four pressure/volume diagrams. The buffer space to the right of the piston enables the engine to work at higher pressure and so generate more work per cycle, and the displacer piston allows the gas to be pumped between hot and cold regions while keeping temperature at each place constant. This leads to Stirling's engine (facing page)

heating and cooling the wall. Nevertheless, I can best explain the Stirling cycle by first considering such an arrangement.

IMAGINE A CYLINDER in which some gas is enclosed by a piston. We let the gas pass through an imaginary cycle by alternately heating the cylinder and then cooling it, at the same time drawing the pressure/volume diagram. We begin with a given volume at atmospheric pressure. When heat is supplied to the cylinder, the pressure rises and the distance PQ in the first figure above is proportional to the force acting on the piston. When the gas expands, its pressure drops and the force becomes smaller; area PQR is proportional to the work done by the gas. During cooling, the pressure of the gas in the cylinder is lowered, and, when the piston is then returned to the left, the gas absorbs still more energy. The work performed in the cycle is proportional to the area PQRS. This cycle does convert heat into mechanical energy, but the work performed by such a cycle is small and the efficiency low.

The work per cycle can, of course, be increased by raising the pressure of the system. To avoid large unilateral forces on the piston, we must then increase the pressure on the right hand side of the piston as well. The pressure on this side can be kept reasonably constant by the introduction of a closed 'buffer space'.

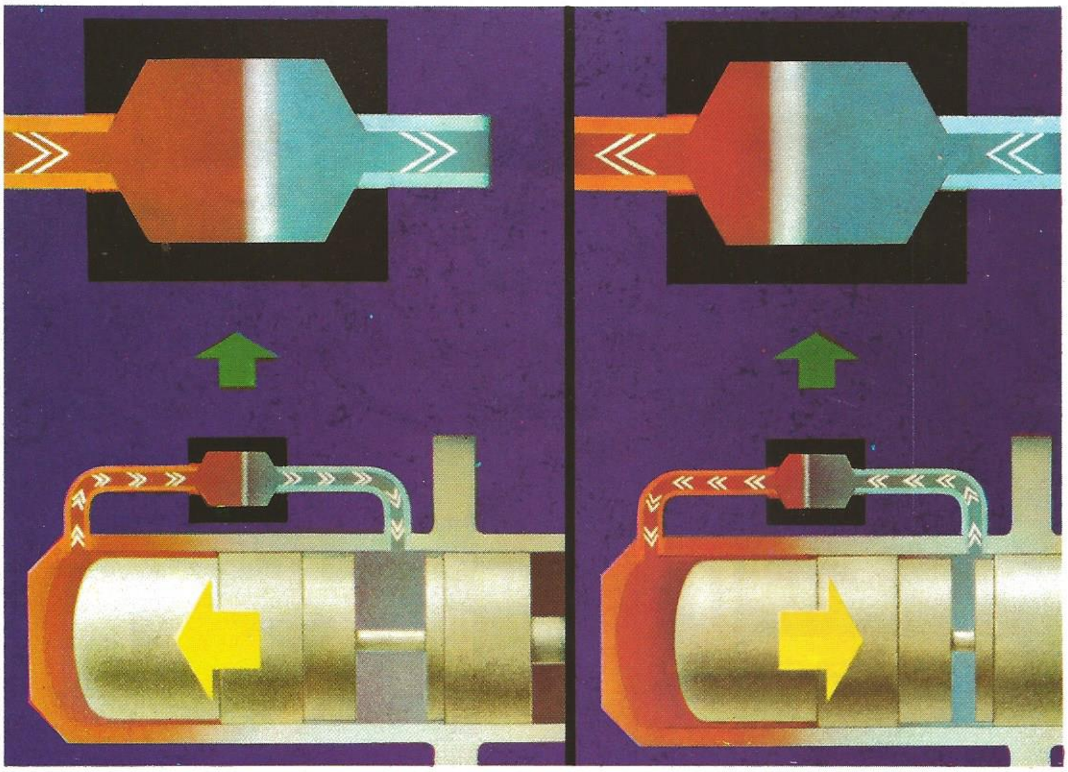
The efficiency can be increased by modifying the construction in such a way that the temperature of the cylinder wall does not change with the alternating gas temperature. Owing to the high heat capacity of the wall, the repeated heating and cooling causes considerable heat losses. Stirling solved this problem by introducing a 'displacer piston'. Nowadays this drives the gas from one end of the cylinder to the other through outside ducts, which requires scarcely any work as the pressures on both sides of the piston are practically equal. The cylinder head can now be kept at a constant high temperature and the other end at a constant low temperature, and the whole cycle can take place without heat being lost through the cylinder wall.

In this modified construction the displacer moves first to the right, causing the gas to flow into the hot space. The hot gas expands, while displacer and working piston both move to the right. The displacer returns to the left, causing the gas to flow into the cold space. Finally the cold gas is compressed by the working piston moving to the left as well.

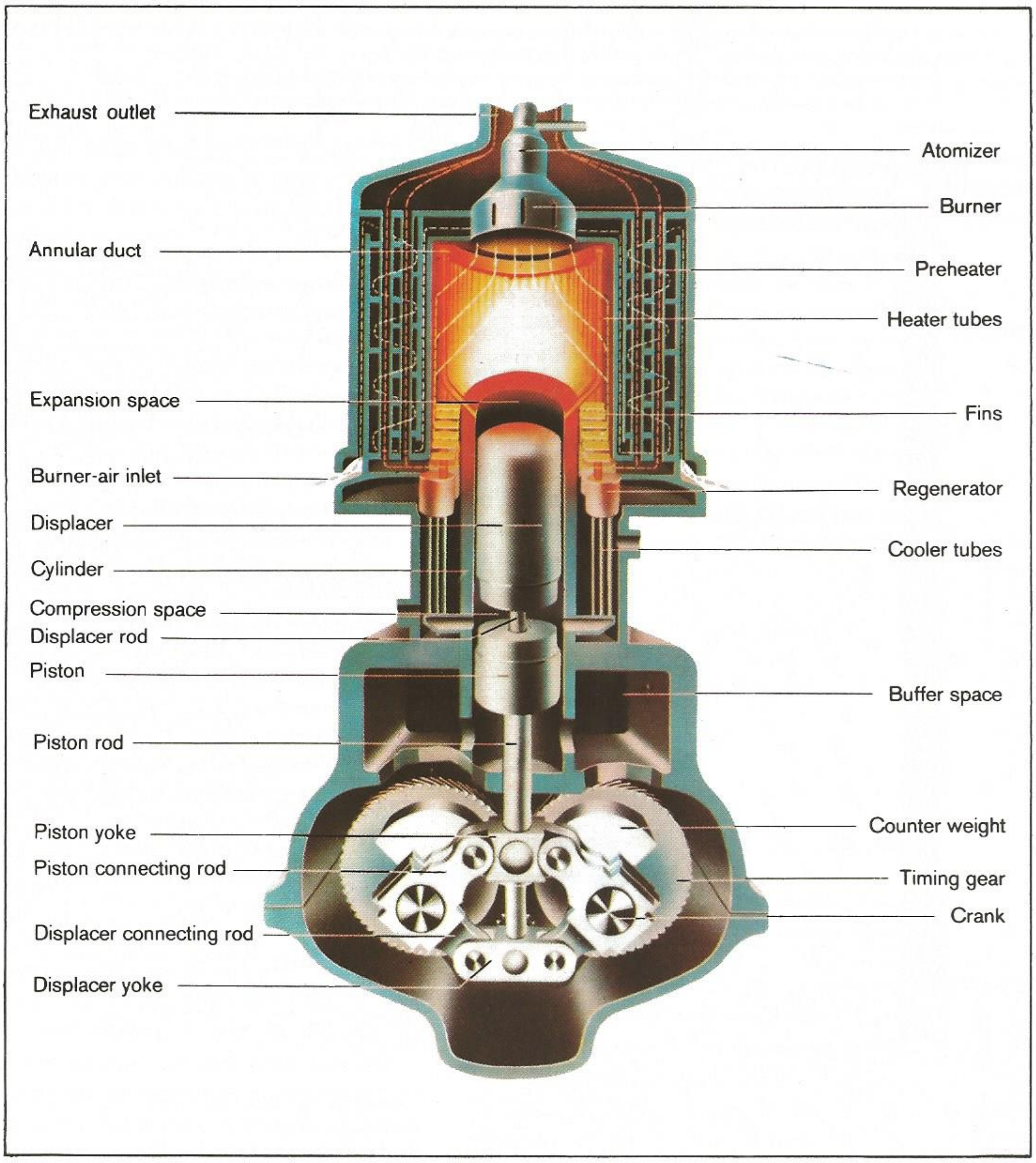
But there is still an unnecessary loss of heat when the gas flows from the hot space to the cold. The efficiency of the engine could be substantially increased if it were possible to store the heat from the hot gas somewhere in order to use it later when the gas is transferred from the cold space to the hot. This can be done by means of a 'regenerator', a chamber filled with a porous metal which acts like a heat store, situated between the hot and the cold parts of the communicating duct. During one half of a cycle the gas gives up heat to this chamber, and recovers it during the other half.

A REGENERATOR has been developed which stores and gives up 99 per cent of the heat otherwise lost, without offering unacceptable flow resistance to the gas passing through it. With this configuration using a regenerator the only essential reason for supplying heat to the cylinder head is to compensate for the tendency of the gas to cool down upon expansion. And the only reason for removing heat from the other end is to compensate for the tendency of the gas to heat up upon compression. In this way the quantity of heat to be supplied or removed can be reduced to the minimum.

We have seen that the work performed per cycle can be increased by raising the pressure. By means of the above configuration, using a displacer and a con-

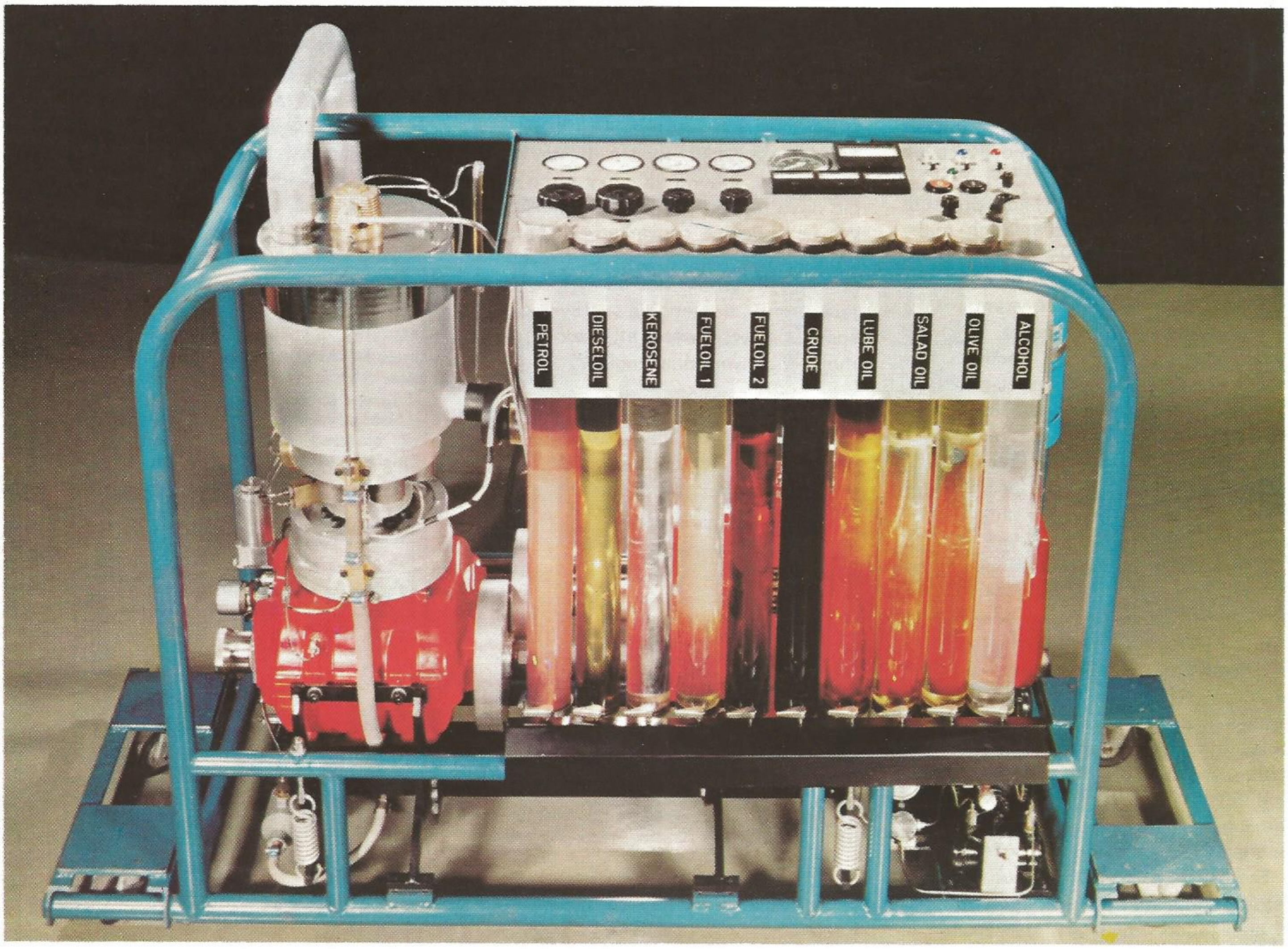


STIRLING CYCLE operation is presented in its simplest form in the series of four diagrams at left. It overcomes a drawback to the hypothetical engine on the right of the facing page in that it does not suffer severe heat loss through the external pumping duct. This is because a regenerator has been added in the duct to separate the hot and cold regions, absorbing heat from the hot gas and giving the heat up again to the cold gas when the latter flows back again



PHILIPS STIRLING ENGINE is shown in cross section in illustration prepared by the company. Piston and displacer drive concentric rods coupled to the rhombic drive turning twin timing gears. Cooler, regenerator and heater are annular units surrounding the cylinder. In the preheater the 800°C gas from the heater is cooled to 150-200°C while heating the combustion air to a temperature of about 650° C

STIRLING ENGINES have an extraordinary ability to run on a wide range of fuels. The small research unit built by Philips in 1949, seen at right driving a 200W generator supplying a battery of fluorescent lamps, runs on air heated by a coal fire seen burning in the open brazier. The later unit below is mounted on a portable frame together with ten fuel containers, any of which can be switched in while the engine is running. The output of 7.5 kW at 3000 r.p.m. is maintained on supplies as diverse as diesel fuel, crude oil, alcohol or salad oil



stant wall temperature, we can also increase the frequency of a cycle and run the engine faster. The result is a large amount of work per unit time: in other words a high power output.

Both the efficiency and the power can be further raised in two main ways. The first is to increase the temperature difference between the hot and the cold part. Secondly, in order to get better heat transfer and less fluid friction, we can use hydrogen or helium as the working medium instead of air, and this can be done in a closed system.

The movements of piston and displacer, assumed so far to be discontinuous, will in practice be continuous movements imparted by a suitable drive mechanism. There will then be some overlapping of the four phases in the pressure /volume diagram, but this in no way alters the principle of the cycle nor detracts from the efficiency.

THE CLOSED SYSTEM of the Stirling gives this engine many advantages and also some shortcomings. The continuous external heating of the closed system makes it possible, when fossil fuels are used, to cause the combustion to take place in such a way as to minimize the air pollution due to carbon monoxide, oxides of nitrogen and unburnt hydrocarbons. Through the intermediary of a suitable heat transport system any heat source at sufficiently high temperature can be used for this engine—radioisotopes, a nuclear reactor, heat storage, solar heat or even burning coal or wood.

The almost sinusoidal cylinder pressure variation and continuous heating make the Stirling engine very quiet in operation. An engine having four or more cylinders gives a virtually constant torque over a very wide speed range, which is particularly valuable for traction purposes. The present design also makes complete balancing possible, thus eliminating vibrations. There is no oil consumption and virtually no contamination because a new type of seal for the reciprocating rods shuts off the cycle hermetically from the drive mechanism.

Where direct or indirect air cooling is required the closed cycle has the drawback that more heat has to be removed from the cooler than in comparable engines with open systems, where a greater quantity of heat inevitably escapes through the exhaust. If it is envisaged as taking the place of existing engines, the Stirling will be ideal as a propulsion engine in yachts, passenger and cargo ships and tug-boats, and also for land vehicles wherever a larger radiator is acceptable.

The system of continuous external heating can also, however, open up fields of application which are inaccessible to internal combustion engines.

RESEARCH on the Stirling engine was begun at Philips in 1938. At that time the company was looking for a heat driven generator of electricity for radio receivers and similar equipment in parts of the world without a public supply, and where the fuel would be easier to obtain than batteries. In the early years Philips subjected the Stirling system to intensive theoretical investigation, and built small hot air engines.

When it appeared that the Stirling system was of more general interest, both for larger engines and for gas refrigerating machines, the research was continued on a broader front. The type of design for the smaller engines, in which the crankcase was used as buffer space, proved to be unsuitable for models with a higher output per cylinder because it would have resulted in excessively heavy construction. After many configurations had been tested a breakthrough came with the rhombic drive, which offers several advantages.

Our recent work has been entirely based on engines fitted with this type of drive. It makes it possible to use a separate buffer space, so that the crankcase can remain at atmospheric pressure. But it does require the hermetic seal round the reciprocating rods between the high pressure section and the crankcase. A further great advantage of the rhombic drive is that it enables the dimensions and weights of the reciprocating parts to be chosen to achieve complete balancing, even with a single cylinder engine.

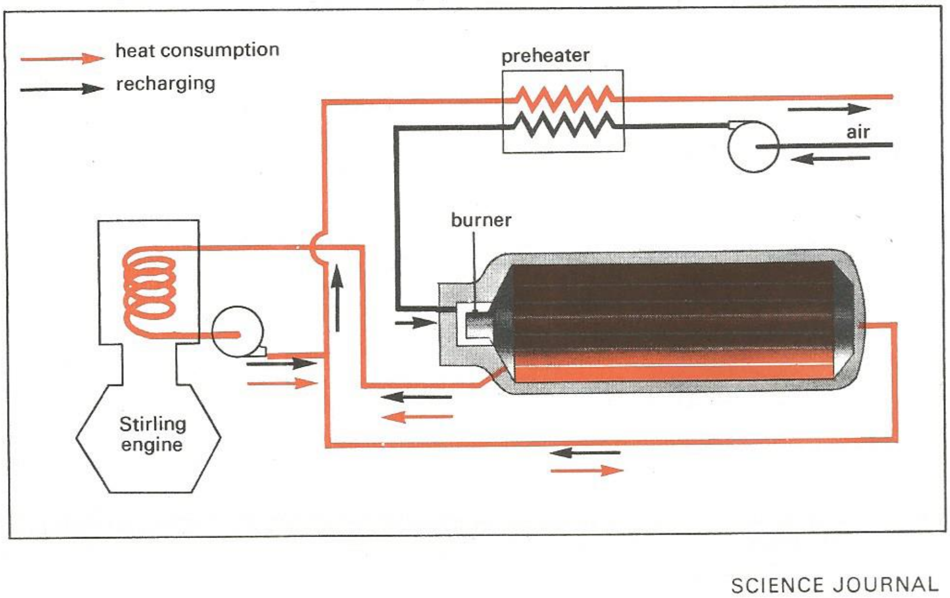
In a way, the introduction of the rhombic drive represented for us a fresh start. We had become convinced that, in spite of the many advantages of the hot air principle, it would not be of general interest until the engine's efficiency and specific power were at least equal to those of conventional engines.

These requirements prompted us to use hydrogen or helium instead of air as our working medium, and to employ much higher pressures. The first engine built on this principle, in 1955, almost immediately met our requirements: the maximum measured efficiency was 38 per cent and the specific power 82 kW per litre of swept volume.

Nevertheless, to obtain a general purpose engine there were still many problems to be solved, particularly those created by the introduction of hydrogen or helium under high pressure. We faced problems related to thermal stresses in the material; heat transfer from the burner gases to the heater tubes; and the design of the preheater, burner and heater assembly, and long life dry running piston rings for the seal on the working piston and displacer. I will take two further examples to demonstrate the modern techniques necessary in developing a new engine.

Any closed system under pressure supplying mechanical energy for use outside poses a sealing problem. Our drive mechanism is connected by means of two rods to the working and displacer pistons. These pistons are situated in the working space where a high gas pressure prevails, while the drive mechanism is situated in a crankcase under atmospheric pressure. Both rods must therefore be provided with a hermetic seal suitable for any size of engine, which has a long life at any working pressure, causes minimum friction and requires no maintenance. A few years ago we found what we believe to be the right answer to this problem in the form of an oil supported rolling diaphragm which we call the 'rollsock seal'.

FUTURE STIRLING engines are likely to include various types operated in conjunction with a reservoir able to store heat. The diagram shows a proposal for a unit using a heat storage tank filled with a suitable type of sintered aluminium oxide (alumina). This would oscillate between 700°-1500°C



This flexible diaphragm separates the working gas from the lubricating oil in the crankcase and is enabled to bear the great differences in pressure by the support of the almost incompressible lubricating oil in the space beneath it. To safeguard against wear and fatigue it is necessary to ensure that the length of the rollsock remains constant throughout its rolling cycle, while for practical reasons the quantity of oil under it must also remain constant. These conditions are fulfilled by making the swept volume of the step in the rod equal to the swept volume of the bottom of the rollsock. The high pressure oil seal is provided by an 'oil pumping ring', a metal ring surrounding the rod and pressed against it at the high pressure end by an annular spring. The ring behaves as a wedge on the upward movement of the oil coated rod and as a non-return valve on the downstroke, forming a very simple high pressure pump which continuously injects small quantities of oil into the space under the sock.

Rollsocks are made of a special type of polyurethane or Viton rubber. One of the conditions for achieving a long life is to pre-stress the rubber before it is subjected to any bending load. The degree of pre-stress can be adjusted by a regulating valve which maintains a constant pressure difference over the sock and causes the oil injected by the pumping ring to flow back to the crankcase. The oil renewal under the rollsock is necessary in order to remove the small quantity of gas that diffuses into the oil through the rollsock. We are now achieving reproducible sock lifetimes of more than 10,000 hours, and a life test on Viton examples at 100°C has already been running for more than 30,000 hours.

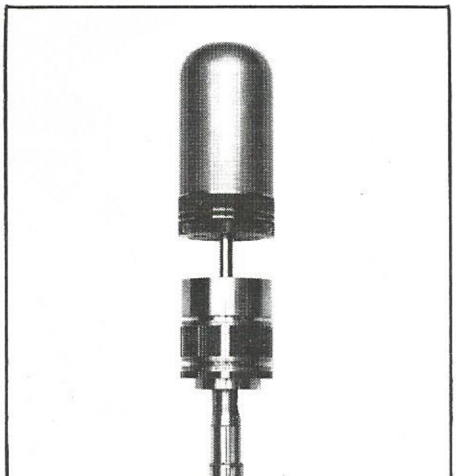
COMPUTERS are my second example. Only with their help have we been able to optimize the Stirling engine design by varying parameters that depend in a very complex way on many other quantities.

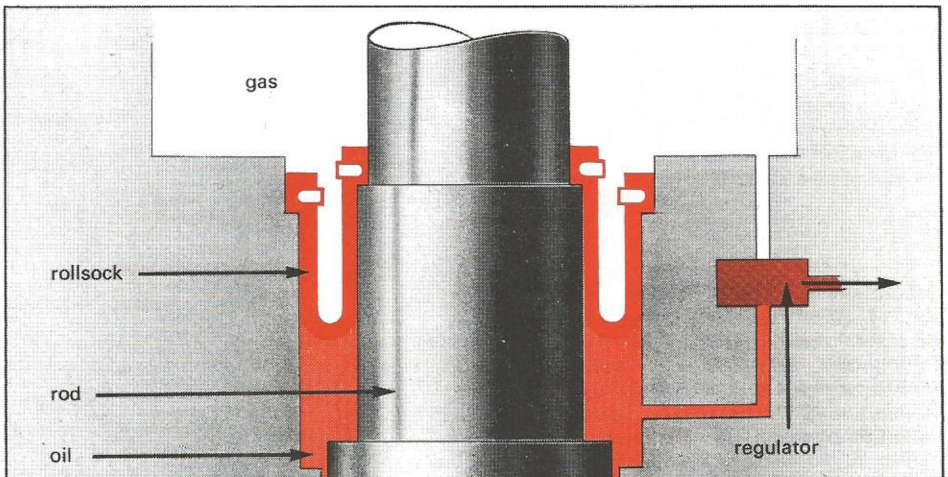
In the engine built in 1955 the design was 'done by hand' and optimized more or less by intuition. But, as there are some 20 independent variables in a Stirling engine (including the speed) which affect the power and the efficiency, the performance can be properly optimized only by using a computer. Of course it is simple to optimize any single parameter of interest, but in the design of a real engine it is of paramount importance to optimize the efficiency as a function of specific power. This is roughly inversely proportional to the size and weight of the engine and these in turn, if large numbers are to be built, dictate the selling price. Moreover, different classes of users will have to decide whether they want, for example, a somewhat larger and heavier engine with a higher efficiency which, though more expensive to buy, will 'pay for itself' because of its lower fuel consumption—or, alternatively, a lighter and cheaper model that consumes more fuel.

Optimizations of this kind have been done for an engine required to produce a shaft output of 170 kW per cylinder in order to learn the influence of working fluids as air, helium and hydrogen. The chosen configuration is one that will enable the engine to be built to the dimensions and design data indicated by the computer. Of course, the optimum efficiency for any given specific power is not an absolute maximum but depends upon the chosen configuration and design. For example, if extra cost is acceptable better heat and creep resistant materials can be used to allow the engine to run at higher mean pressures and temperatures.

OUR PRESENT ENGINES contain many novel features. One of these is an omnivorous burner for fossil fuels in either liquid or gaseous form. A Stirling engine fitted with this burner can run on almost any fluid fuel; it can be switched over from one fuel to another without any change in power, the temperature of the heater being maintained by a thermostat.

A promising application, comparable with an electric accumulator, is the combination of the engine with a heat storage tank. The heat required is drawn from preheated refractory material or salt with which the tank is filled. It is possible to use the 'sensible' heat between 1500 and 700°C from sintered aluminium oxide, or both the sensible and latent heats of a salt such as lithium fluoride. The first system has been tried out with success at the laboratories of General Motors, a licensee for Philips Stirling engines. The charging rate of such a system can be much faster than that of an electric storage battery, while the power density of the heat storage, related to weight or volume, can be eight to ten times that of the lead/acid battery.





Exhaust gases from Stirling engines with a standard burner are already relatively clean. Comparison with gas turbines, which are considered to have a far lower emission than internal combustion engines, shows that the Stirling engine is even more favourable in this respect. The virtual absence of carbon monoxide and unburned hydrocarbons is due to the fact that combustion takes place continuously in a hot walled chamber supplied with an excess of preheated air.

From further experiments we have learned that the already small amount of oxides of nitrogen can be reduced by a factor of about four if the combustion air is not preheated. But this is at the expense of engine efficiency, since it means that the heat in the exhaust gases is no longer used. The content of these oxides can also be reduced by recirculating part of the exhaust and adding it to the fresh combustion air. In this way the normal figure can be reduced by a factor of about three, without affecting efficiency.

As already mentioned, the quiet operation is due to the absence of sharp pressure fluctuations, to continuous combustion and to full dynamic balancing. At present the noise level is dictated largely by auxiliaries such as the blower and lubricating oil pump. In general it can be said that the structure-borne noise generated by the Stirling engine is 20 to 40 dB and the airborne noise at least 25 dB lower over the whole frequency range than that generated by a diesel engine of comparable power.

For various applications, including traction, it is important to know how the mean torque of the engine varies with speed, and also the speed range over which a torque can be maintained. The speed range of a single cylinder Stirling may be as great as 1:10. It is also important to know the torque variation on each revolution; a four cylinder engine has a practically constant torque and so requires no flywheel and causes practically no vibration.

I have already mentioned the one important drawback of the Stirling engine: because of the closed system relatively more heat must be dissipated from the cooling radiator than in internal combustion engines, and this must preferably be done at the lowest possible temperature. This applies particularly where the heat has to be dissipated directly or indirectly to the ambient air. Essentially this means a big radiator, but the drawback becomes the less significant the higher the efficiency of the engine.

TO SUM UP, the Stirling engine has the following outstanding features: multi-fuel capability, adaptability to any heat source of sufficiently high temperature, high efficiency even at part load, clean exhaust gases, no lubricating oil consumption, quiet operation with no vibration and good torque characteristics. Additional benefits include: powerful braking on the engine, brief overloading permitted, reliable cold starting and insensitivity to dust. A relatively large amount of heat must be rejected by the cooling system, and the efficiency depends on the temperature difference between the heater and cooler. The specific weight is roughly the same as that of a diesel engine. But, as the engine is still in the laboratory stage, nothing can yet be said about the price.

Our future research will be directed mainly towards making the engine lighter, and considerable improvements are possible if the heater is made of superior materials. And if use is made of indirect heating with the aid of heat pipes, a further modification of the heater can allow an increase in engine speed and enable a multi-cylinder engine to be heated by a single burner or other heat source.

We have done the groundwork; now we face a considerable programme of development leading to saleable engines. The pace can be expected to accelerate now that various firms in Europe (MAN/MWM in Germany and United Stirling in Sweden) are working on the Stirling engine as well as GM in the United States. The big debut of the 150 year-old concept is fast approaching.

FURTHER READING

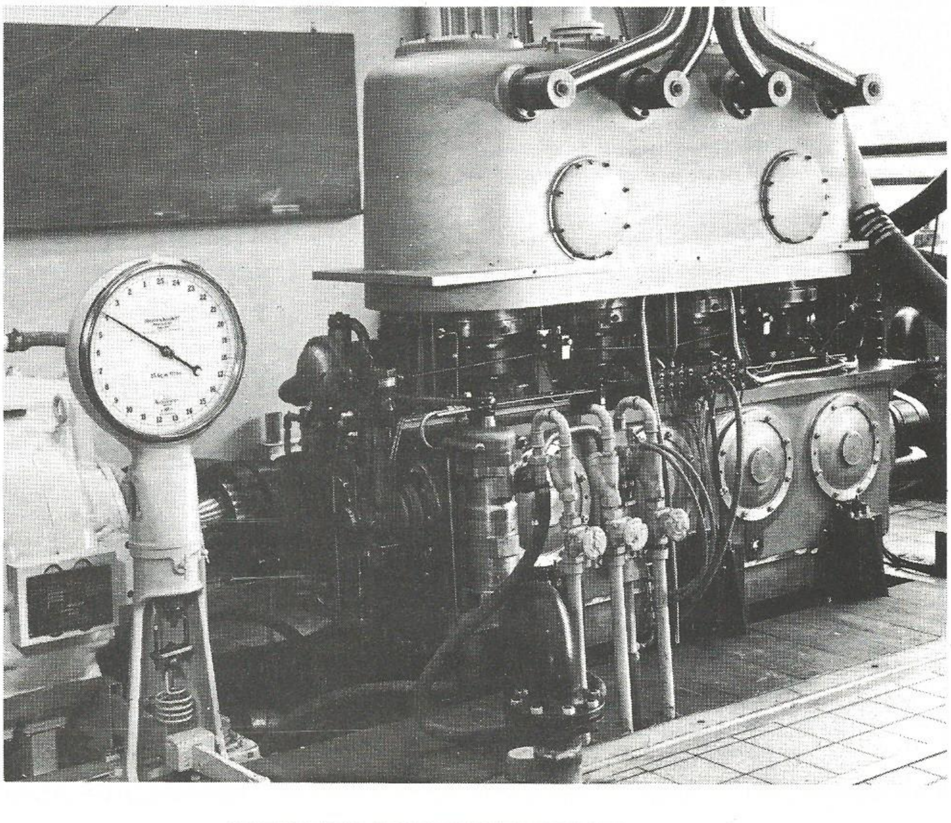
HIGHLIGHTS FROM 6500 HOURS OF STIRLING ENGINE OPERATION by F. E. Heffner *(Paper 949E presented at the US Society of Automotive Engineers conference, Detroit, January 11-15, 1965)*

A ROLLING DIAPHRAGM SEAL FOR HIGH PRESSURES AND HIGH SPEEDS by H. C. J. van Beukering and H. H. M. van der Aa *(Paper G4 presented at the 3rd International Conference on Fluid Sealing, Cambridge, England, April 1967)*

DER PHILIPS-STIRLING MOTOR by R. J. Meijer (in *Motortechnische Zeitschrift 29 (1968), 7, 284-298)*

RHOMBIC DRIVE, here shown (far left) without crankshafts or gearwheels and with piston and displacer separated, is so arranged that the centre of gravity of the whole system remains stationary during one revolution of the crankshaft. This gives perfect balance which, due to the system's symmetry, also extends to higher harmonics

ROLLSOCK SEAL (left) separates the working space from the crankcase and also eliminates consumption of oil. The oil is continuously changed by a very small quantity pumped on each stroke by the oil pumping ring, the regulating valve simultaneously bleeding off the same quantity to the crankcase to maintain the pressure difference over the rollsock at a steady level



LARGEST STATIONARY Stirling engine known to be in operation is shown right. This experimental unit from the Philips Laboratories has four cylinders with rhombic drives and stems directly from an earlier unit with a single cylinder of the same rating. Power is 270 kW (360 hp) at 1500 r.p.m. with a heater temperature of some 700°C

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