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The Evolution of the Stirling Engine.

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THE
EVOLUTION
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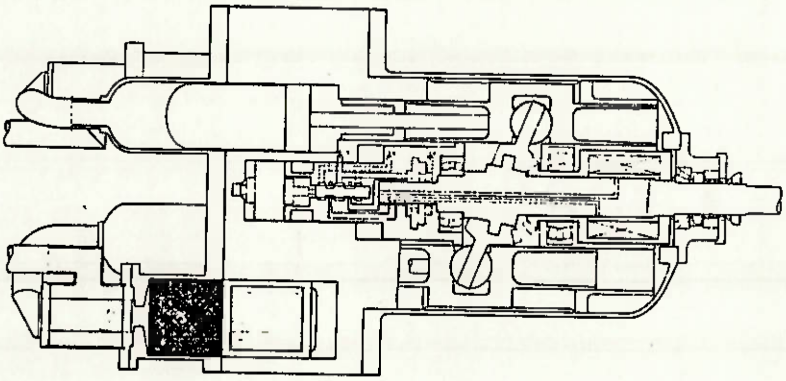
STIRLING ENGINE



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STIRLING THERMAL MOTORS, INC.

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THE EVOLUTION OF THE STIRLING ENGINE

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STM

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Introduction and Background

The Stirling engine, also known as the "hot-air" engine, has a long history for an engine that is not yet commercially available. It was invented by Scottish clergyman Robert Stirling in 1816 and for a time was used quite successfully as a small power source. Its only serious competition was the steam engine, and it was produced and sold in large quantities in the latter half of the 19th century.

According to the 1885 price list from a German factory, the largest hot-air engine they produced was a 2 hp machine weighing 4100 kg (with packing and masonry) with a volume of 21 cubic meters. It is not surprising that it was soon displaced by the more efficient and powerful internal combustion engine. It was only after the internal combustion engine had been more or less perfected, and its strengths and weaknesses known, that interest in the Stirling engine was revived.

Shortly before World War II, scientists at the Research Laboratories of N.V. Philips Gloeilampenfabrieken in Eindhoven, the Netherlands, recognized the need for a heat-driven power source for radios and communications devices in parts of the world where the fuel needed for such a device was easier to obtain than batteries. The hot air engine, which was not dependent upon petroleum fuels, was an obvious choice. This was the beginning of an intense research and development program at Philips which almost returned Stirling engines to the market place.

The 1948 introduction of transistors eliminated the need for a radio battery substitute. Philips had a small Stirling engine ready for mass production at this time, but it was suddenly obsolete, and the research team turned its attention to higher-powered automotive models. This program lasted for almost twenty years, and culminated in the successful demonstration of two Stirling powered Ford Torinos in 1976.

Philips was uniquely qualified for such a development program because of its unusual corporate structure. A highly integrated, multi-national operation with several hundred thousand employees, it operates not only in Western Europe, but world-wide as a major producer of electronic and electrical equipment and household appliances. In addition to research and development groups within its many product divisions, Philips has a separate research organization which is totally independent from the commercial aspects of the corporation and is responsible only to the Board of Management. This independence from product divisions frees researchers from interferences and allows them to analyze and solve sophisticated technical problems in depth. This set of conditions allowed the Stirling engine to be thoroughly investigated for many years.

Unfortunately, by the time the Stirling-powered Torinos were demonstrated, in 1976, the auto industry was in serious trouble. In 1978 Ford Motor Company terminated its world-wide, exclusive, Stirling engine license to concentrate on short-term technological problems. Faced with this major setback, Philips also stopped its Stirling work.

At this time, Dr. Roelf J. Meijer, who had headed the Stirling development at Philips since 1947, retired from Philips and founded Stirling Thermal Motors, Inc. (STM) to continue the development of the engine so that the results of all the years of research and development work at Philips would not be lost. STM, which is a licensee of Philips, has continued the research and development work begun at Philips and has overcome the final obstacles in the way of commercializing the Stirling engine.

Principle of the Stirling Engine

The modern hot-air engine, or Stirling engine, is based on a concept patented in 1817 by Robert Stirling, a Scottish clergyman. Stirling's engine was meant to be a safer and more efficient alternative to the steam engines then in wide use.

The Stirling engine is an externally heated engine, and is very versatile, with many favorable properties:

- Suitable for different energy sources, such as liquid and gaseous fuels, solar radiation, and even solid fuel such as coal
- High efficiency
- Low emissions when burning fossil fuel
- Low noise and vibration levels
- High potential reliability under all load conditions
- Low maintenance
- No lube oil consumption or lube oil changes required.

The Stirling engine is based on the same thermodynamic principle as internal combustion engines: if gas is compressed at low temperature and is then heated and allowed to expand, mechanical energy is produced. However, in the Stirling engine there is no combustion of fuel inside the cylinder. The heat comes from an external source and reaches the gas through a wall.

Since it is impossible to heat and cool a metal wall rapidly, one part of the engine is kept at a high temperature and another part at a low temperature. The working gas is shuttled from a space which is at a constant high temperature (red hot) into a space which is at constant low temperature (ambient temperature).

In order to obtain mechanical energy from this process, the working gas must be compressed when it is mainly in the cold space and allowed to expand when it is mainly in the hot space. In order not to lose heat during this shuttling process, a regenerator is placed between the hot and cold spaces.

Figure 1 is a diagram explaining the action of an "ideal" Stirling engine. Suppose we have a cylinder with two pistons, between which there is an amount of working gas. The right hand part of the cylinder is at low temperature, T_C (ambient temperature) and the left hand part is at high temperature, T_E (red hot). These two parts are separated by a regenerator, which is a space filled with porous material, such as layers of very fine metallic gauze, and which is exposed to the temperature gradient from T_E to T_C.

For the sake of clarity, we can stylize the process by assuming discontinuous movements of the pistons and by assuming expansion and contraction at constant temperatures. We can then discern four phases in between the stages shown in Figure 1:

Phase 1: As we progress from Stage I to Stage II, the gas is compressed at temperature T_C. The heat of compression is dissipated locally.

Phase 2: Between Stage II and Stage III, the gas is pushed at constant volume through the regenerator, R, and is thus brought to the higher temperature, T_E. [The regenerator is able to pass heat to the gas as it flows from cold (T_C) to hot (T_E), and vice versa, as the gas flows from hot (T_E) to cold (T_C) to take up the heat again.]

Phase 3: Between Stages III and IV, the gas is allowed to expand at the higher temperature T_E. The requisite heat is supplied through the wall.

Phase 4: Between Stage IV and Stage I, the gas is pushed at constant volume through the regenerator R, and is thus returned to the lower temperature, T_C.

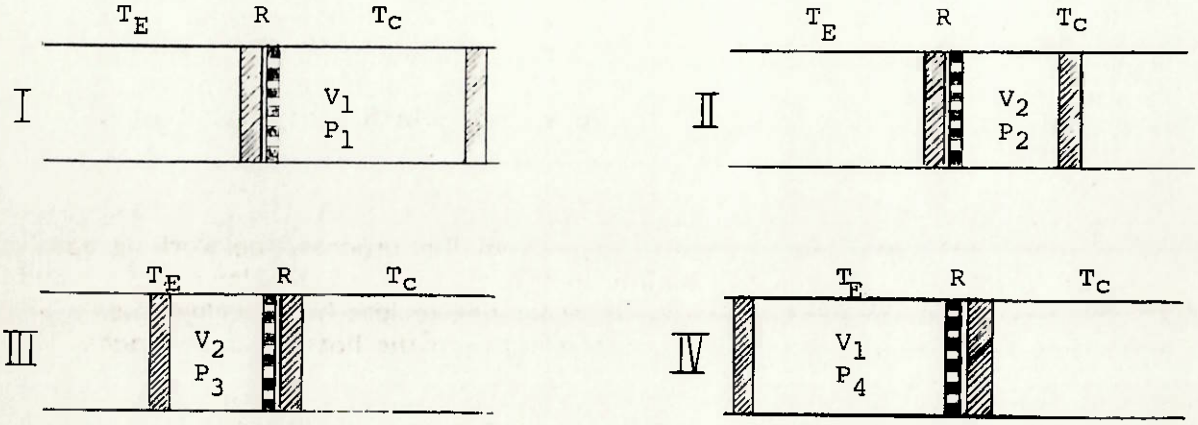


Figure 1

The Four Stages of the Stirling Engine Cycle

The ideal Stirling engine is a cylinder divided into a hot part at temperature T_E and a cold part at temperature T_C. These two parts are in open communication with each other through a regenerator, R. There is a piston in each part and a definite quantity of gas is contained in the area between the pistons. Four stages are indicated in the engine cycle. The transition between Stages I and II takes place at constant temperature T_C. Compression heat is rejected through the cylinder wall. The transition between II and III takes place at constant volume. The regenerator, R, yields heat stored from the previous cycle to the gas. Transition from III to IV takes place at constant temperature T_E. Heat is supplied through the wall to keep the gas at constant temperature. Transition IV to I takes place at constant volume. The regenerator, R, stores the heat from the gas.

In the p-V diagram presented in Figure 2 this stylized process is described by two curves of Phase 1 and Phase 3 (constant temperatures) and two curves of Phase 2 and Phase 4 (constant volume). The surface area of the p-V diagram is proportional to the work done by the engine. The work is also proportional with the pressure of the gas between the two pistons.

This stylized process, with compression and expansion at constant temperatures, ignoring all manner of losses caused by flow resistance, heat losses in the regenerator, etc., represents the highest efficiency which can be reached with a heat-driven prime mover between temperatures T_C and T_E. It is equal to $1 - T_C / T_E$, the Carnot efficiency.

In practice, discontinuous movement of the pistons is replaced with continuous movement generated by some sort of drive. Given the above assumptions, this will have no effect on efficiency, and the work per cycle is reduced only slightly.

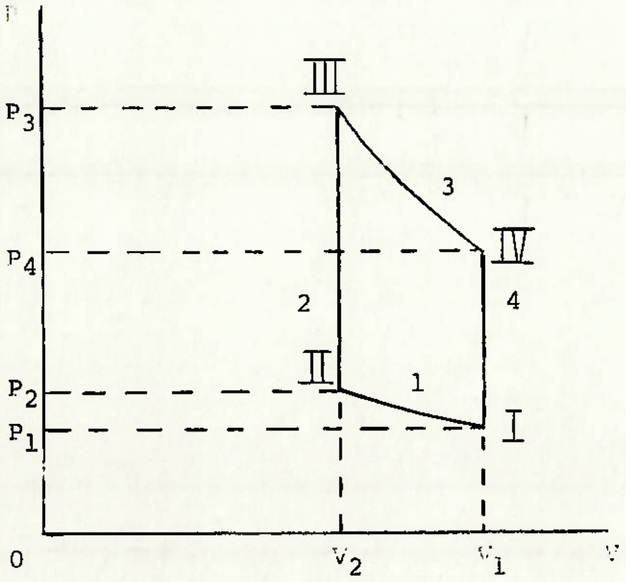


Figure 2

The p-V Diagram of the Cycle Through Which the Working Medium Passes

Because the pressure is higher during the hot expansion (III-IV) than during the cold compression (I-II) more work is produced during expansion than during compression. This produces a positive work surplus for the cycle as a whole. This surplus is represented by the area of the curvilinear quadrilateral I - II - III - IV.

As a rule, the walls of the cylinders will not be used as heat exchangers. Instead, separate heaters and coolers are incorporated, and this has an effect on efficiency and power output.

The resulting basic principle of the Stirling process is illustrated in Figure 3.

Five spaces can be distinguished in any Stirling engine process. A variable volume called the expansion space (V_E), a heater, a regenerator, a cooler, and a variable volume called the compression space (V_c). The movement of the drive should be such that changes in volume of the expansion precede those of the compression space.

Many drives, heat exchanger arrangements and configurations for Stirling engines have been designed and built according to the basic principles. Each has had its own pros and cons, many depending upon the state of the art at the time of their development. Two piston arrangements gained prominence during the evolution of the Stirling engine at Philips, and different drives were developed for both. These arrangements are the displacer type and the double-acting type. Each will be described in more detail below.

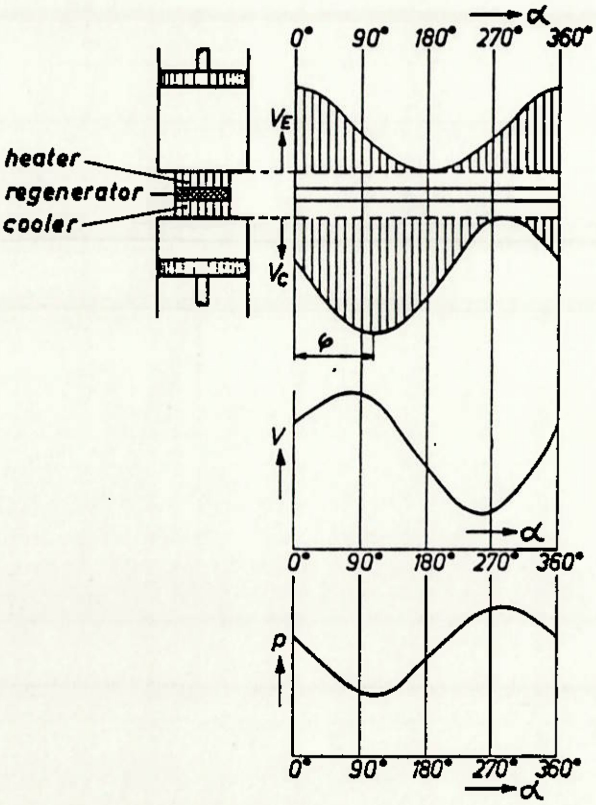


Figure 3

Sinusoidal Variations of the Volumes V_E and V_c as functions of the crank angle α.

The phase relationship can be clearly seen. This continuous variation of the compression and expansion space does not change the efficiency. The addition of a heater and a cooler effects the efficiency.

Piston arrangement for the displacer type Stirling engine

The piston arrangement for the displacer type engine is shown in Figure 4. Here we have two pistons in one cylinder. One piston is called the displacer piston. Its function is to push the gas from one space to the other. The displacer piston has no gas forces acting on it except those of flow resistance. It separates the (hot) expansion space from the (cold) compression space, and therefore has an isolating dome on top.

The other piston is the "working" piston, which feels the pressure forces and transmits those forces to the drive in order to provide useful work. The working piston is always at cold (ambient) temperature.

The variable expansion space is formed between the fixed wall of the cylinder and the (moving) top of the displacer. The variable compression space is formed by the (moving) top part of the piston. The compression space is connected to the expansion space via cooler, regenerator and heater.

Except for external heat exchangers, this is the original configuration described by Robert Stirling in 1817.

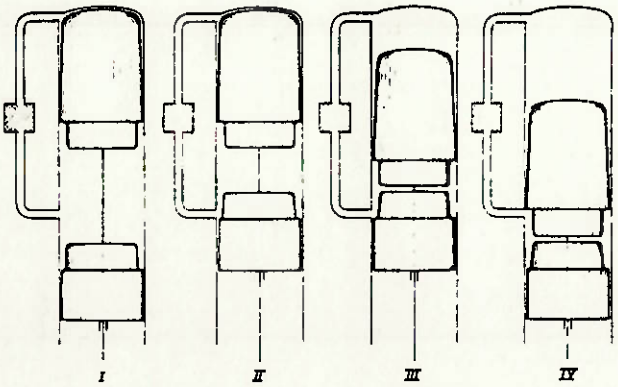


Figure 4

Piston Arrangement for the Displacer Type Stirling Engine

I - Piston in lowest position; displacer in highest position; all the gas is contained in the cold space.

II - The displacer has remained in the highest position; the piston has compressed the gas at low temperature.

III - The piston has remained in the highest position; the displacer has pushed the gas through the cooler, regenerator and heater, into the hot space.

IV - The hot gas has expanded, displacer and piston have, together, reached the lowest position. Thereafter, with the piston stationary, the displacer pushes the gas, through the heater, regenerator and cooler, into the cold space so that position I is reached again.

Piston arrangement of the double-acting type Stirling engine

The double-acting system was invented at Philips by Ir. F.L. van Weenen in 1942. The piston arrangement for this type of engine is shown in Figure 5. Each cylinder has only one piston. The variable expansion space is formed between the fixed top wall of the cylinder and the (moving) top of the piston. The variable compression space is formed by the fixed bottom wall of the adjacent cylinder and the (moving) bottom of the piston located in that cylinder. The compression space is connected via cooler, regenerator and heater to the expansion space. At least three cylinders are needed for a double-acting system and, from a theoretical point of view, the use of four, five or six cylinders is preferable.

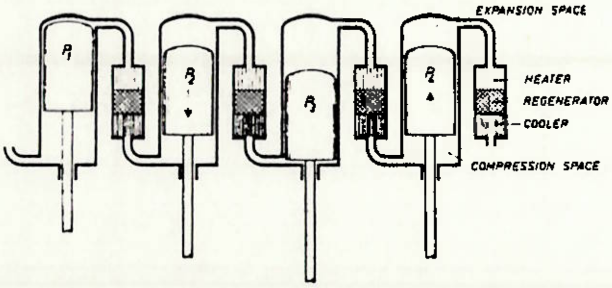


Figure 5

Piston Arrangement of the Double-Acting Type Stirling Engine

Each of the cylinders has a hot space/expansion space at the top and a cold space/compression space at the bottom. The cold space of a cylinder is connected to the hot space through a cooler, a regenerator and a heater. The pistons P_n of the cylinder move with suitable phase shift between them. In the case of four cylinders, as shown here, this shift is 90°.

Stirling Engine Development at Philips

N.V. Philips of Eindhoven, the Netherlands, was involved with Stirling engine research and development from 1938 to 1979. A summary of the areas of investigation studied appears in Figure 6.

Philips' interest in the Stirling engine began in 1938, with the search for a small power source for the generation of electricity. A heat-driven electric generator was needed for radio receivers and similar equipment used in parts of the world without public electricity supply, where the fuel for the generator would be easier to obtain than batteries.

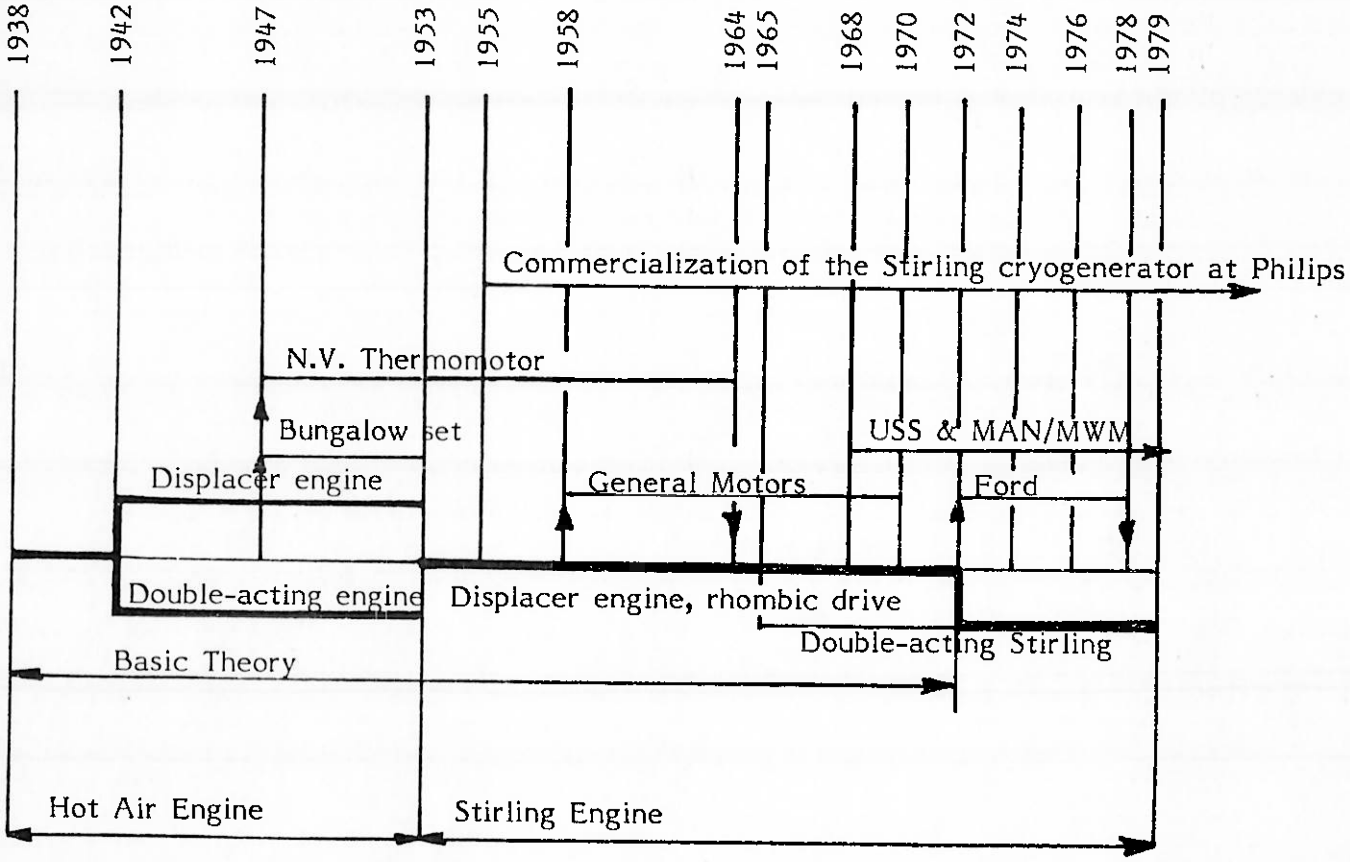


Figure 6

Areas of Investigation in the Philips Stirling Engine Program

Philips started its investigation of the hot air engine in 1938. After hydrogen and helium replaced hot air as the working medium the name was changed to Stirling engine.

Ir. H. Rinia selected the Stirling engine (then known as the hot air engine, since air was used as its working medium) for this application. The hot air engine operated quietly. It was adaptable for use with many different fuels because it employed an external heating system. Also, its closed gas system endowed it with a long and useful life with very low maintenance requirements [1]. In the period from 1938 until the end of World War II more than twenty different hot air engines were designed and several of them were built.

Figure 7 is a schematic representation of one of the first test model hot air engines built at Philips Research Laboratories. The air working medium was at atmospheric mean pressure, and the setup was suitable only for very low power ratings. The cooler-regenerator-heater arrangement was thermodynamically and aerodynamically sound, but the model's mechanical function, lubrication, and external heating system were fraught with problems [2].

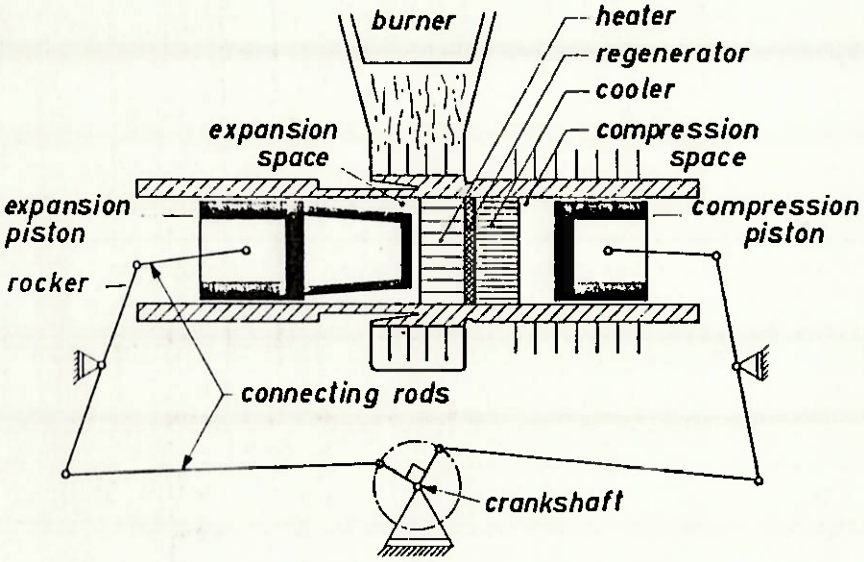


Figure 7

Early Philips Hot Air Engine Design

The pistons act on the crankshaft in such a way that the volume variations of the expansion space are about 90° in phase ahead of those in the compression space.

A working model of this engine is shown in Figure 8. The drive shaft is connected to a fan, which also serves as a flywheel.

The drive shown in Figure 9 is much simpler than the one in Figure 7. It also has the advantage of allowing a higher mean pressure in the working space when the crankcase is pressurized to compensate for the forces on the piston and to limit leakage along the piston. This model had problems with low efficiency and specific power. Another major problem was keeping the working space free of lubricating oil.

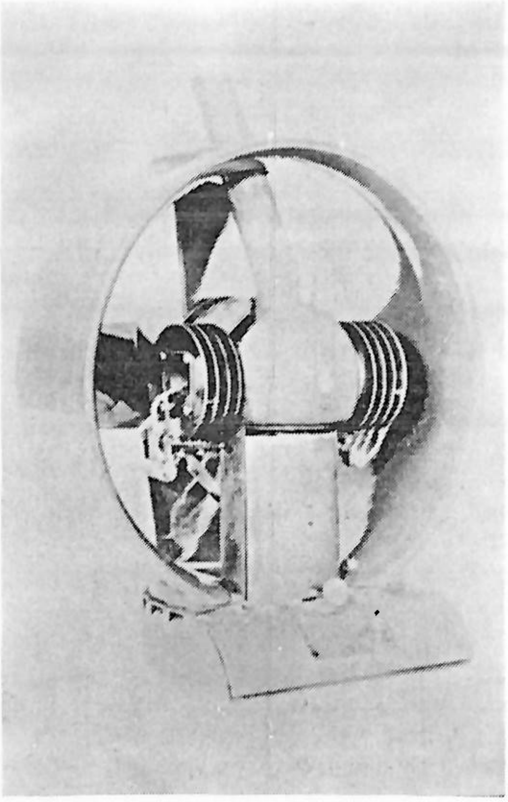


Figure 8

Fan Driven by a Hot Air Engine

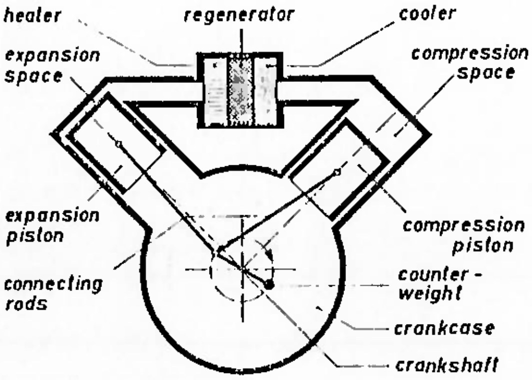


Figure 9

Schematic Representation of a V-type or L-type Hot Air Engine Configuration

A schematic representation of a working model built in 1948 is shown in Figure 10. The drive of this engine was used extensively to study control of the lubrication oil.

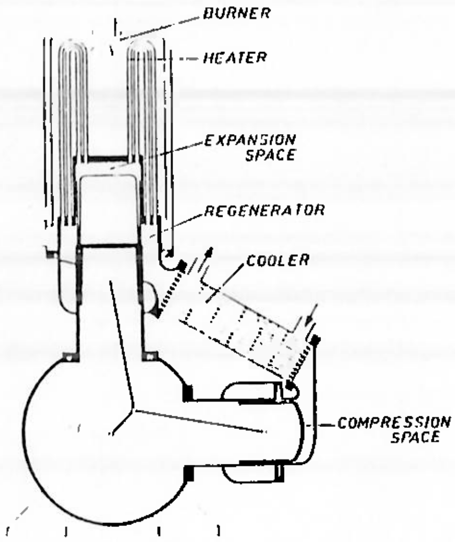


Figure 10

Schematic Representation of an L-type Model Built in 1948

Philips built its first displacer type hot air engine in 1942. This water-cooled engine had a crankcase that could be pressurized to 10 atmospheres. At this pressure and a speed of 1500 rpm, power output was 1 hp and the efficiency (without preheater) was about 5%. The schematic of this engine is shown in Figure 11, and a photograph of it appears in Figure 12.

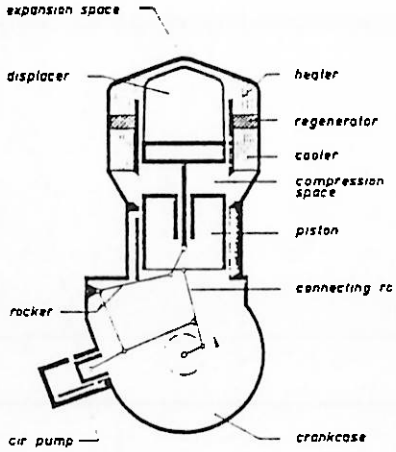


Figure 11

This diagram shows the typical drive mechanism used in hot air displacer-type engines. The forked connecting rod of the piston is connected to the crankshaft. The displacer connecting rod is activated by means of a rocker arm, which is driven from a point on the piston connecting rod. Also, a small air pump is connected to this displacer drive mechanism.

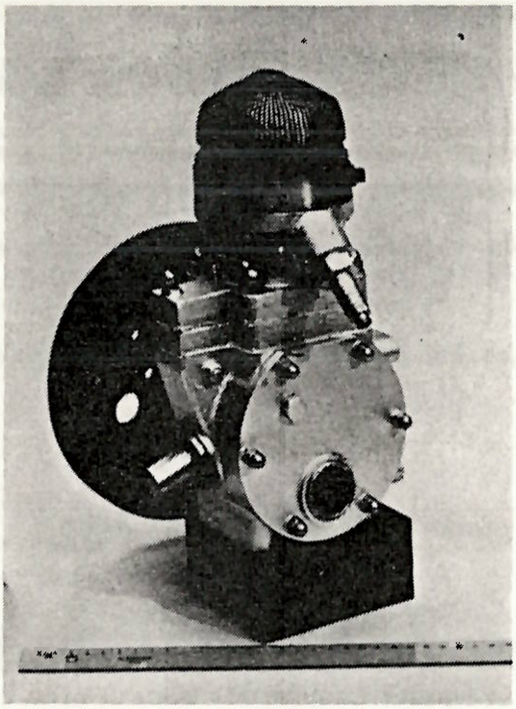


Figure 12

Water-Cooled 1 hp Engine Built in 1942, and Shown Schematically in Figure 11

During the war, when the Netherlands was occupied, working with hardware carried with it the risk of drawing the attention of the occupying forces. Because of this, the war years were a time for concentrating on theoretical work.

In 1942 Ir. F.L. van Weenen invented the double-acting engine. This new type made bigger, more powerful hot air engines a possibility, and after the war two lines of hardware can be distinguished.

At Johan de Witt, a Philips subsidiary in Dordrecht, work continued on displacer type engines, still with the goal of producing a small prime mover for a generator set. The ultimate result of this work was the "Bungalow Set," which was capable of producing 200 Watts electric power. It was driven by an air-cooled engine based on the drive shown in Figure 11. About 150 of these engines were built in the pre-production stage. Unfortunately, with the invention of the transistor in 1948, the Bungalow Set, shown in Figure 13, became obsolete as a source of power for radios. In 1953, the Bungalow Sets produced by Philips were donated to different universities all over the world.

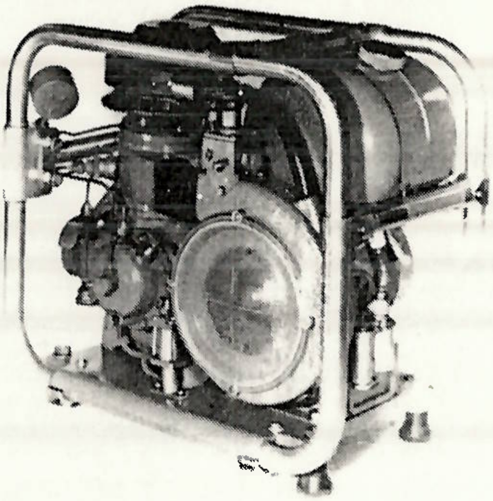


Figure 13

The Bungalow Set

Air-cooled displacer-type hot air engine driving a 200 Watt generator. About 150 of these were built in the pre-production phase.

The second hardware investigation program was directed towards larger, double-acting engines. The first double-acting hot air engine had a wobble-plate drive and was water cooled. A schematic of the drive is presented in Figure 14. With a mean working air pressure of 10 atmospheres, this engine developed 4.5 hp at 3000 rpm. Unfortunately, such high speed operation with air as the working medium resulted in very poor efficiency, and there were also serious lubrication problems. Sealing was not such a problem since the low pressure made it possible for leakage to be compensated for very easily with a small air compressor. Figure 15 is a photograph of the engine.

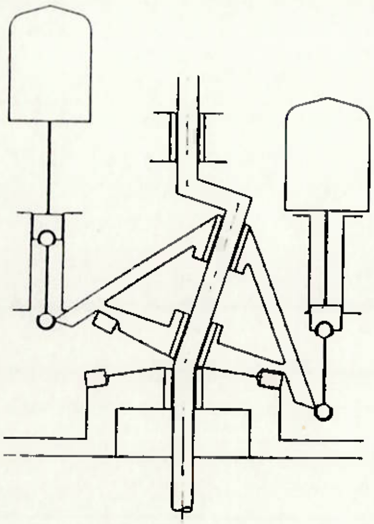


Figure 14

Schematic Representation of a Double-Acting Hot Air Engine with Wobble Plate Drive

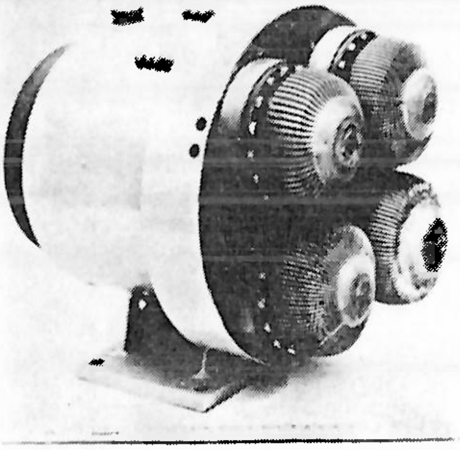


Figure 15

Double -Acting Hot Air Engine Built in 1944. Output was 4.5 hp at 3000 rpm and a Mean Air Pressure of 10 Atmospheres.

Several other models with higher power output were made, both with wobble plate drives and with crankshaft drives. Figure 16 shows a schematic representation of the crankshaft drive for a V-type four-cylinder double-acting hot air engine. This engine had one crankshaft and normal connecting rods and crossheads. The cylinders were arranged in a rhombus so that they could each have cold connecting ducts the same length. Each heater had its own burner and controls. A photograph of this engine appears in Figure 17.

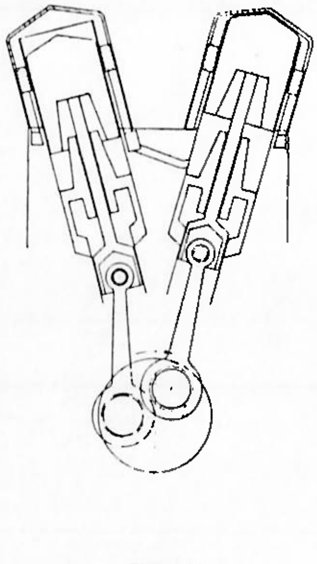


Figure 16

Four-Cylinder, V-Type, Double-Acting Engine

This engine has one crankshaft and normal connecting rods and crossheads. The heat exchangers (heater-regenerator-cooler units) are the same as in Figure 15. The cylinders are arranged as a rhombus so they can have cold connecting ducts of the same length.

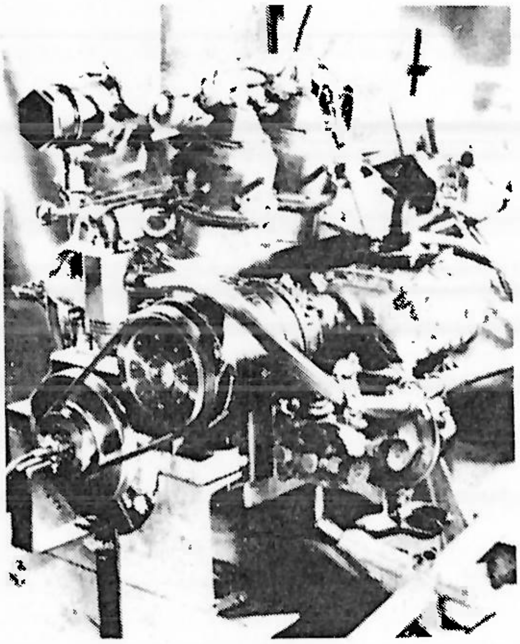


Figure 17

Four-Cylinder, V-Type, Double-Acting Hot Air Engine Built in 1948. Each heater had its own burner and controls.

After the war N.V. Philips and N.V. Werkspoor, a diesel engine manufacturer, formed N.V. Thermomotor for the purpose of doing extensive hardware work on larger engines. Gradually, though, it became clear that large hot air engines would not ultimately be successful. Their specific power and efficiency were too low to compete with existing engines. They also suffered from many lubrication and sealing problems, heater and preheater difficulties, and trouble with the power controls. This, coupled with the unexpected obsolescence of the Bungalow set, led Philips to reexamine its hot air engine program. In December of 1953, the Philips Board of Management decided to terminate all hot air engine activities outside the Research Labs.

One fortunate event kept hot air engine research alive in the Research Labs. A month earlier, Dr. R.J. Meijer had invented a promising new drive for displacer type engines. This drive, shown schematically in Figure 18, later came to be called the Rhombic drive. Dr. F.J. Philips, who was then Vice President of Philips, and who later became President and Chairman, saw the promise of this new drive. He influenced the directors of the Research Labs to allow the hot air engine program to continue [4].

Although the Rhombic drive provided a fresh start to the program, there were still important problems to be dealt with. The hot air engine offered many potential advantages, but before it could gain general acceptance, both the efficiency of the engine and its specific power had to meet or exceed those of conventional engines. In order to meet these goals, hot air was abandoned as a working medium in favor of helium or hydrogen, and much higher pressures were used. After this, Dr. Meijer renamed the engines. Instead of "hot air engines," they were now called "Stirling engines."

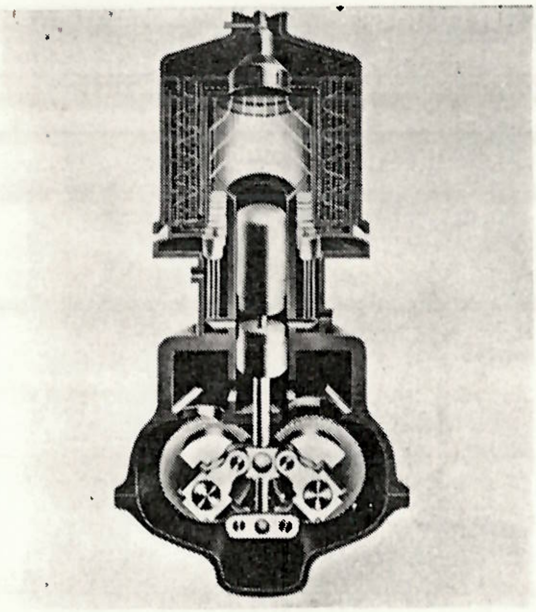


Figure 18

Section View of a Single-Cylinder Displacer-Type Stirling Engine with Rhombic Drive

In the center are the cylinder, piston and displacer. Below is the crankcase with the rhombic drive, which governs the movement of the piston and displacer with respect to each other. The movements of the masses of the drive, piston displacer and the counter-weights with this configuration allow a complete balancing of the engine. The part above the cylinder is the heater head, which is surrounded by a preheater. The air required by the burner enters the preheater at the bottom and passes through a channel heated by the exhaust gasses before reaching the flame. The exhaust gases escape at the top.

The first of these new engines was water-cooled and delivered 40 hp at a speed of 2500 rpm and a mean pressure of 110 atmospheres hydrogen. This engine almost entirely met the goals that had been set for efficiency and specific power. In 1956 this engine achieved an efficiency (defined as the ratio between shaft output and fuel input) of 38%, without auxiliaries. The specific power, related to the swept volume of the expansion space, was 110 hp per liter.

The invention of the Rhombic drive was a breakthrough for displacer engines with high power output per cylinder. It was now possible to design such engines without pressurized crankcases. Rhombic drive also made it possible to completely balance a single-cylinder engine. This was an important advantage, both for experiments performed on this type of drive and later, in practical applications. Between 1954 and 1965 the Philips Research Labs concentrated almost exclusively on this configuration, seeking solutions to remaining problems and improving the existing technology [5].

In the meantime, theoretical studies were providing deeper insights into the potential of larger engines. Electrically heated engines such as the one shown in Figure 19, were built especially for this line of study. Further insight was gained from work on Stirling-type cryogenerators.

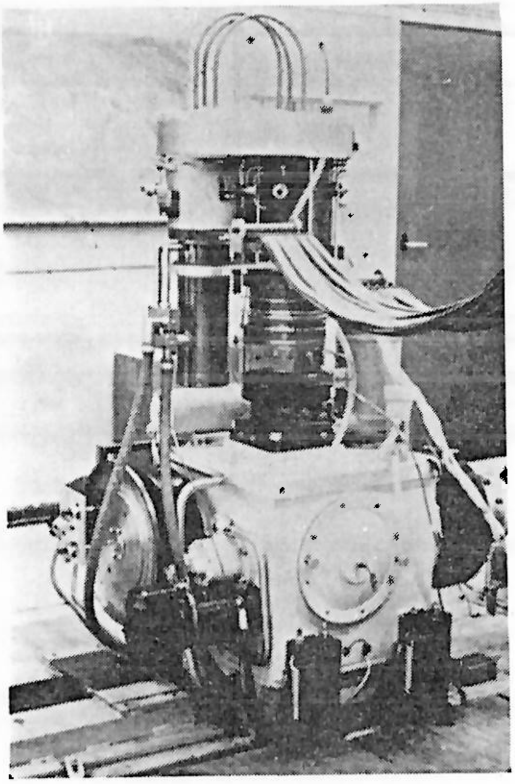


Figure 19

Electrically Heated Engine

This was one of the electrically heated engines built especially to study the thermodynamic and aerodynamic behavior of a 400 hp single cylinder engine

Most of the hardware investigations were carried out on single cylinder engines of different sizes and power ratings [6]. Figure 20 shows a 10 hp engine, a 40 hp engine and a 100 hp engine of the same basic configuration. The 100 hp engine was the predecessor of the four-cylinder, 400 hp engine shown in Figure 21.

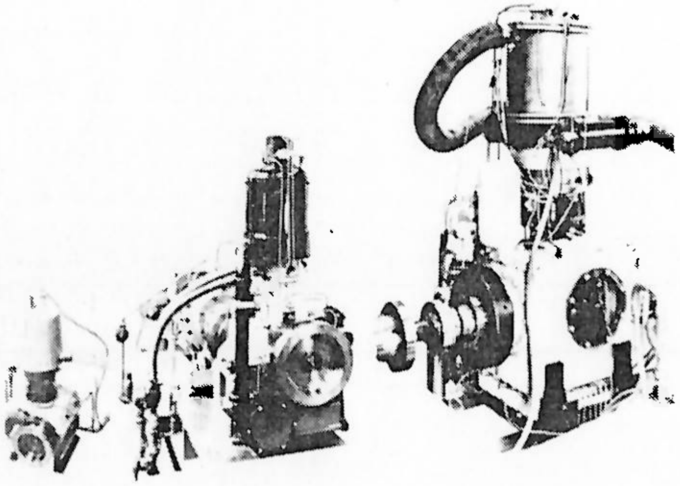


Figure 20

Single Cylinder Prototype Engines with Rhombic Drive

Left to right: 10 hp at 3000 rpm, 40 hp at 2500 rpm, 100 hp at 1500 rpm. All of these engines operated at a mean working pressure of 110 atmospheres.

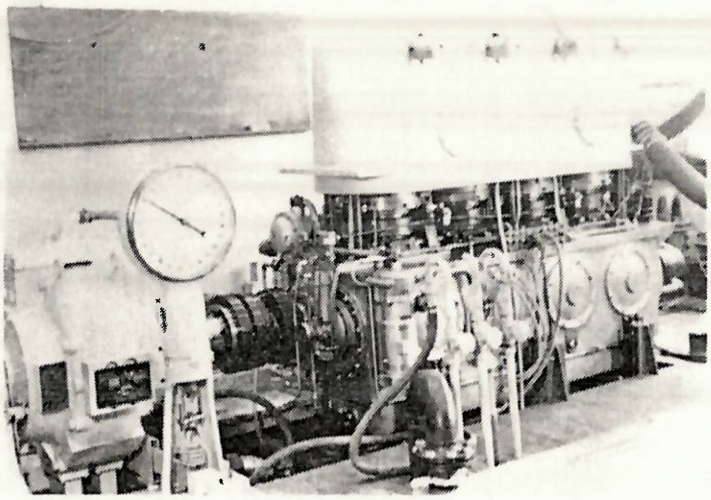


Figure 21

Experimental 400 hp 4-Cylinder Engine

This engine was developed from the single-cylinder 100 hp engine shown in Figure 20. Power output was 400 hp at 1500 rpm, heater temperature 700°C, cooling water temperature 20°C, and mean pressure 110 atmospheres. Several of these engines were built at Werkspoor. One was delivered to the U.S. Navy for metal and airborne noise testing in 1964.

Many of these single-cylinder engines were built not for any specific application, but rather, for a wide range of basic investigations. Some research models were used in particular applications without being optimized accordingly simply to get experience outside the research lab facilities [7].

A 40 hp, single-cylinder displacer type Stirling engine with Rhombic drive was installed in a 10 meter yacht in 1959. This yacht, shown in Figure 22, was used for demonstration purposes until 1977. A riding lawn mower powered by a 10 hp Stirling engine is shown in Figure 23.

Figure 22

The motor yacht "Johan de Witt" was equipped with a 40 hp, single-cylinder displacer-type Stirling engine with rhombic drive.

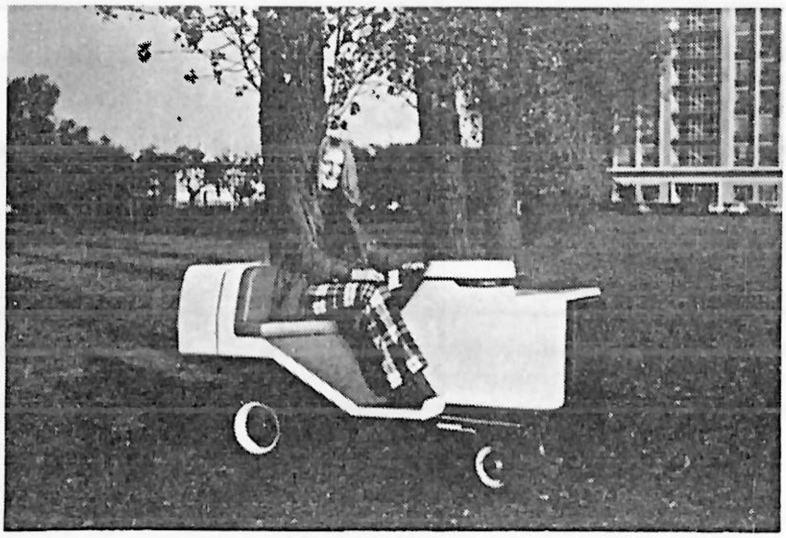


Figure 23

Garden Tractor Equipped with a 10 hp, Single-Cylinder Displacer-Type Stirling Engine with Rhombic Drive

A generator set with a 10 hp engine was built to show the Stirling engine's multi-fuel capabilities. This engine, which appears in Figure 24, was demonstrated all over the world.

The most ambitious of these projects was the installation of a 200 hp, four-cylinder Rhombic drive Stirling engine in a DAF bus. The engine is shown in Figure 25. The bus, which was used for demonstration purposes for several years in the Netherlands and other countries, appears in Figure 26.

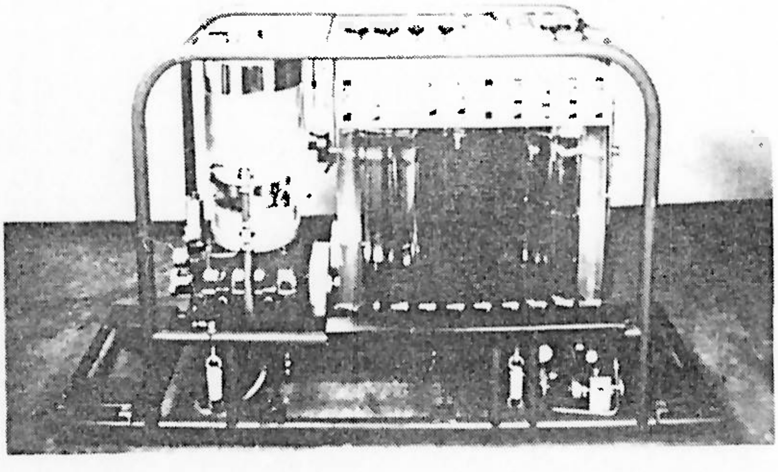


Figure 24

10 hp Stirling engine with generator set up to demonstrate multi-fuel capabilities. Fuels used were alcohol, gasoline, diesel, lubricating oil, olive oil, salad oil, crude ooils, propane, butane and natural gas.

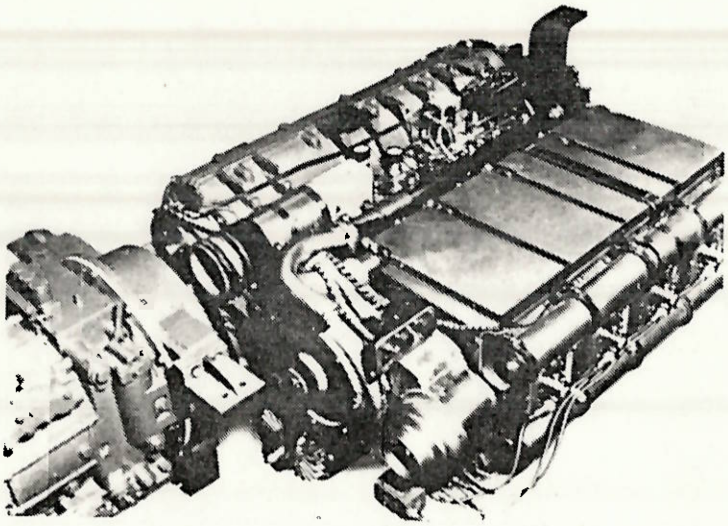


Figure 25

This 200 hp, 4-Cylinder, Horizontal Engine was Installed in the DAF Bus Shown in Figure 26

Figure 26

This Bus, Equipped with the Engine Shown in Figure 25, was Demonstrated Many Times in Different Countries Around the World

This work was not only to provide experience outside laboratory environments. It was also calculated to interest possible licensees in the potential of the Stirling engine. Attracting licensees for Stirling engine work had been a high priority since the invention of the Rhombic drive. Unlike some electronics companies in the Unites States and Germany, N.V. Philips was never directly involved in the production of heavy machinery. Philips management knew from the beginning that the Stirling engines they developed would, in the end, be produced by licensees rather than at Philips.

In 1958 General Motors, in an action initiated by Mr. Arthur Underwood, manager of the GM Research Laboratories, became Philips' first Stirling engine licensee, though they later terminated the contract to work on the unsuccessful Wankel engine. In 1968 two German companies, M.A.N. and M.W.M., and the Swedish consortium United Stirling Sweden, also became licensees.

Up to this time, the size and weight of the Philips Stirling engines had been more comparable to that of diesel engines than to light-weight gasoline engines. Then, in the mid-1960's, it became apparent that a solution to the emissions problems in automotive engines might not be attainable with existing internal combustion engines. Philips redirected its research and accelerated programs to develop compact, light-weight engines suitable for use in automobiles [8].

This research program led back to the double-acting type Stirling engine. 1965 marked a new beginning for the double-acting engine. All of the knowledge and experience gained in the years of intensive work on rhombic drive engines was incorporated into the new program. Difficulties with double-acting engines which had once seemed insurmountable had been whittled down to the point that they no longer posed serious problems.

The use of rollsocks took care of sealing the piston rods against the crankcase. The problem of sealing the piston in the cylinder was solved with the use of new, dry-running materials which had been used in the displacer type engines. A much improved understanding of aerodynamics led to the belief that the asymmetrical construction of the heat exchangers could be overcome.

Philips decided to develop a swashplate drive for these new engines, making use of General Motors' experience with their swashplate driven freon compressors for automobile air conditioners. The piston arrangement as a kind of integrated system was very much simplified by the use of a swashplate, but there was still one complication. In order for this four-cylinder engine to require only one burner and one air-fuel control system instead of four (one for each cylinder), the heaters had to be integrated into one heater cage. Technically this was not difficult, but severe limitations were imposed on the number of heater tubes per cycle. This threatened the outstanding efficiency that would otherwise have been attainable. The problem could conceivably have been overcome with the use of heat pipes, but the technology had not advanced that far in 1965. However, even the compromised efficiency possible with an integrated heater head was considered sufficient for car engines.

Figure 27 is an artist's view of the first double-acting Stirling engine with swashplate drive. Figure 28 is a photograph of the same engine, which delivered 30 hp at 3000 rpm with a mean pressure of 110 atmospheres hydrogen.

Late in 1970 Philips began contacting U.S. government agencies and industrial concerns about Stirling engine development for vehicular applications in the United States. Among those contacted were the Environmental Protection Agency (EPA), the National Academy of Science (NAS), the Office of Science and Technology (OST), and the Advanced

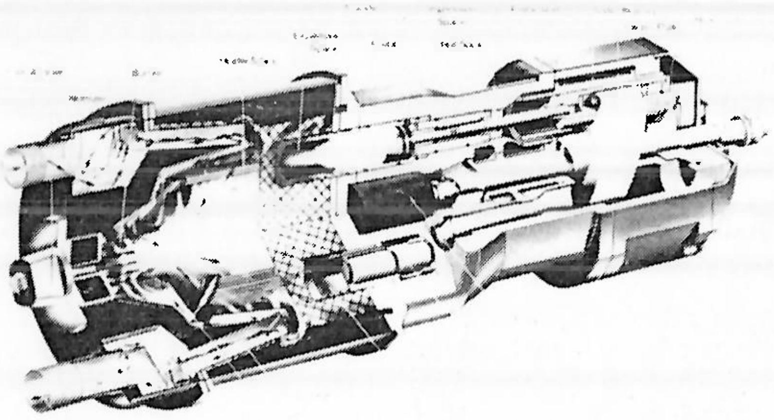


Figure 27

Artist's View of the First Double-Acting Stirling Engine with Swashplate Drive

A single burner, supplying heat to the heater tubes, is located at the front of the engine. The heater tubes belonging to each of the four cycles are arranged in such a way that the tubes from all four cycles form the shape of the heater cage, but are still kept separate. A preheater of the recuperator type surrounds the heater cage. The swashplate is a disk mounted onto the main shaft at a certain angle. The reciprocating piston units act on this swashplate via sliders, transferring the reciprocating movements to rotation.

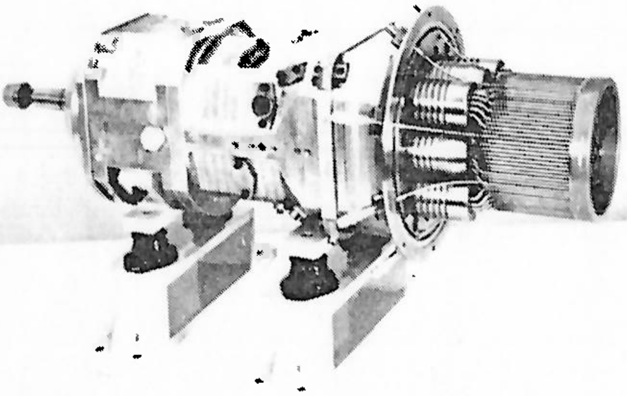


Figure 28

The four-cylinder double-acting swashplate engine shown in the artist's rendition in Figure 27. Shown without the burner and preheater, it illustrates more clearly the arrangement of the heater tubes.

Automotive Power Systems Office (AAPS). Though the EPA expressed interest in the development of the Stirling engine, they were unable to offer financial support due to lack of funds. The Department of Transportation also became interested in several applications for the Stirling engine.

About this time Ford Motor Company initiated an internal program in cooperation with Philips to investigate the potential of a second-generation Stirling engine for an alternative automotive power plant. As a result of this study, Ford became a Philips licensee in 1972.

One of the most important requirements of the feasibility study for Ford was the demonstration of the emissions control potential of a full-scale Stirling engine combustor. Philips designed and built a full-scale test rig and tested the engine against the CVS test cycle specified in federal regulations. This rig is shown in Figure 29. Results of this testing, shown in Figure 30, were very good [9] [10]. Based on the results, Ford obtained a worldwide exclusive license from Philips for the Stirling engine, including automotive.

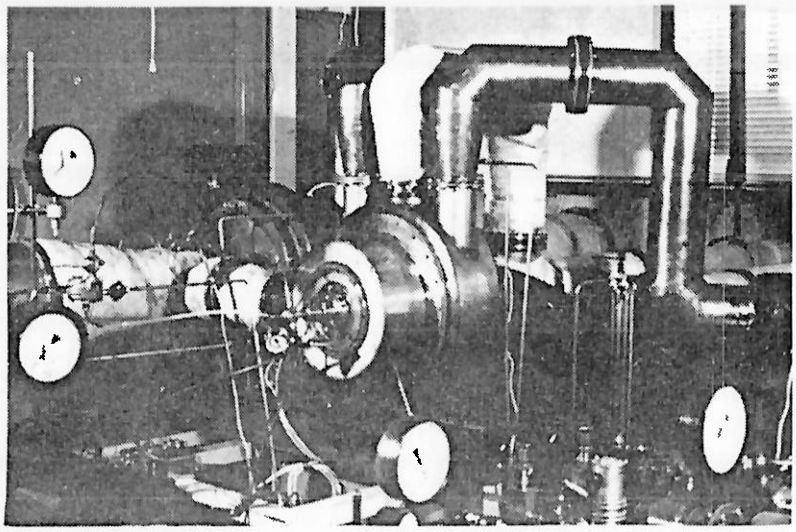


Figure 29

Test Rig for Measuring the Emissions of a Burner-Heater Assembly Suitable for the 170 hp Ford/Philips Engine

A combination of a laminar airflow and a turbulent exhaust flow for exhaust gas recirculation (EGR) automatically gives an increase in EGR as the load decreases. This phenomenon reduced the NOx emissions over the whole load range and gave good mixing of air and fuel at low load, preventing CO_2 and soot emissions.

RESULTS OF CVS TEST SIMULATION *

(GRAMS PER MILE)

CONSTITUENT	STIRLING ENGINE	1976 STANDARD
UNBURNED HYDROCARBONS	0.20	0.41
CARBON MONOXIDE	1.20	3.40
OXIDES OF NITROGEN	0.14	0.40

* ENGINE AT ZERO MILES

Figure 30

Results of the Emission Test Simulation Shown in Figure 29

Philips Research Labs designed and built four 170 hp engines for the Ford Torino car. Two of these engines were actually installed in the automobiles. Figure 31 presents a schematic representation of this engine, which is shown photographically in Figure 32.

In 1976 the two Stirling-powered Torinos and the older Stirling bus from Philips were successfully demonstrated in Dearborn, Michigan, for three days. Unfortunately, by this time the entire auto industry was in trouble. Ford terminated its Stirling engine activities in 1978 to make manpower available for short-term technological problems. A year later, Philips, discouraged by the loss of such a major licensee, stopped all work on the Stirling engine.

At this time, Dr. R.J. Meijer, who had headed the Stirling development program at Philips since 1947, retired from Philips and formed his own company. Stirling Thermal Motors, Inc. (STM) was founded so that the results of the years of research and development work done at Philips since its last license agreement would not be lost.

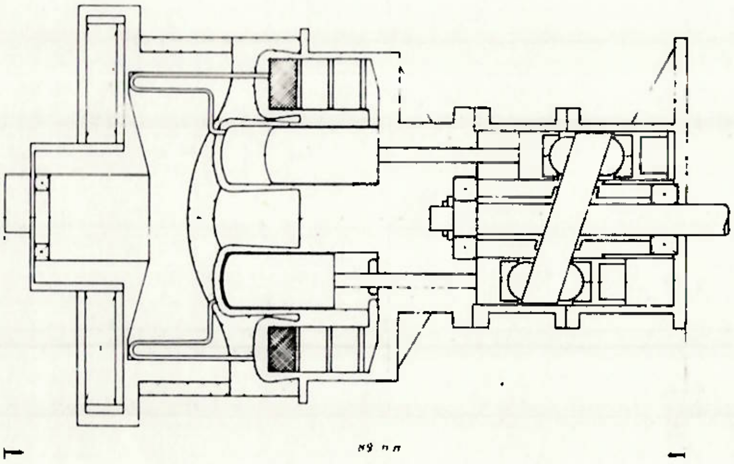


Figure 31

Schematic of the Ford/Philips Engine

The configuration is the same as for the engine shown in Figure 27 except that its preheater is of the rotating regenerator type.

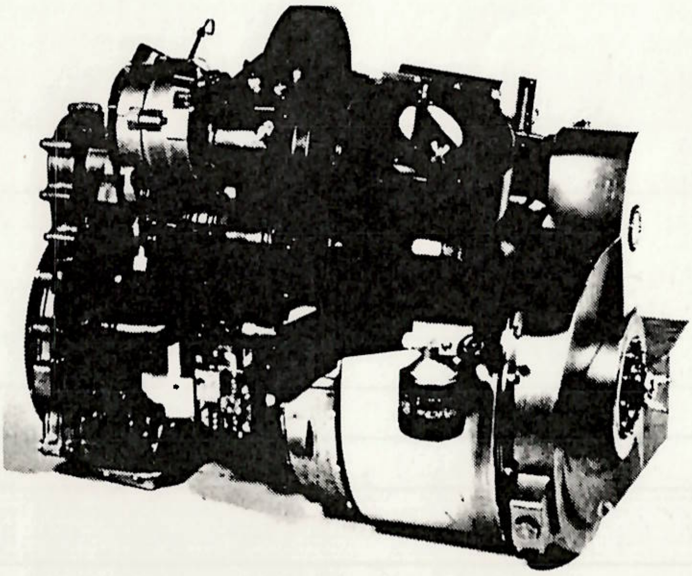


Figure 32

The Ford/Philips Stirling Engine

This 170 hp, four-cylinder, double-acting engine was mounted into a Ford Torino automobile in 1975.

STIRLING THERMAL MOTORS

Stirling Thermal Motors, Inc. (STM), located in Ann Arbor, Michigan, was organized as a Delaware corporation on June 19, 1979. Dr. R.J. Meijer, who had headed the Stirling engine research at Philips since 1947, founded the company for the specific purpose of developing commercial Stirling engines.

STM became a licensee of N.V. Philips in November of 1979. This gave the company access to all Philips' Stirling engine know-how, patents, and simulation computer codes. Through the decades of research and development at Philips, Stirling engine configurations progressively evolved towards lighter, simpler and more efficient engines. This was especially true during the last decade of Stirling research at Philips, when important breakthroughs were made which, for one reason or another, could not be incorporated into the engines of any of the earlier Philips licensees. With the application of this information, new ideas, and new configurations of proven technology, a new generation of Stirling engines has been born.

The STM4-120 engine being developed at STM is a double-acting Stirling engine. Its configuration differs from any previous Stirling engine in its simplicity, compactness and versatility. Two major new technologies distinguish the STM4-120 from former designs:

- STM is pioneering the practical use of the variable swashplate drive and power control in the STM4-120. This device solves the problem of sealing the high pressure in the engine, while at the same time providing a simple, reliable and rapid power control, and enhancing the efficiency of the engine, particularly at part load. The sealing problem solved by the variable swashplate has always been a major obstacle to commercialization of the Stirling engine.

- Heat to power the engine is brought from its source by means of a high temperature sodium heat pipe. This allows the engine to be completely separated from its heat source, endowing the engine with unprecedented versatility. It is possible to keep the STM4-120 engine the same when using it with different heat sources. Thus the same engine could be used for either solar heating or coal simply by adapting the heat receiver. This permits a standardization which significantly lowers the cost of production. The heat pipe also allows the use of a simple, tube-bundle heat exchanger, which avoids complex geometry and costly manufacturing difficulties which plagued earlier heat exchanger designs and inhibited mass production. This simplicity and relative ease of manufacture dramatically lowers production costs.

Another advantage of the STM4-120's configuration is its adaptability to different engine sizes and power ratings. The same basic configuration can be used for virtually any engine size, and has been thoroughly studied for engines from 6 kW to 375 kW (8 hp to 500 hp). The STM4-120 has a peak output of 40 kW (53.5 hp) and an efficiency of more than 40% over a wide range of power. In addition, it weighs only 85 kg. A layout drawing of the STM4-120 appears in Figure 33, and a photograph in Figure 34.

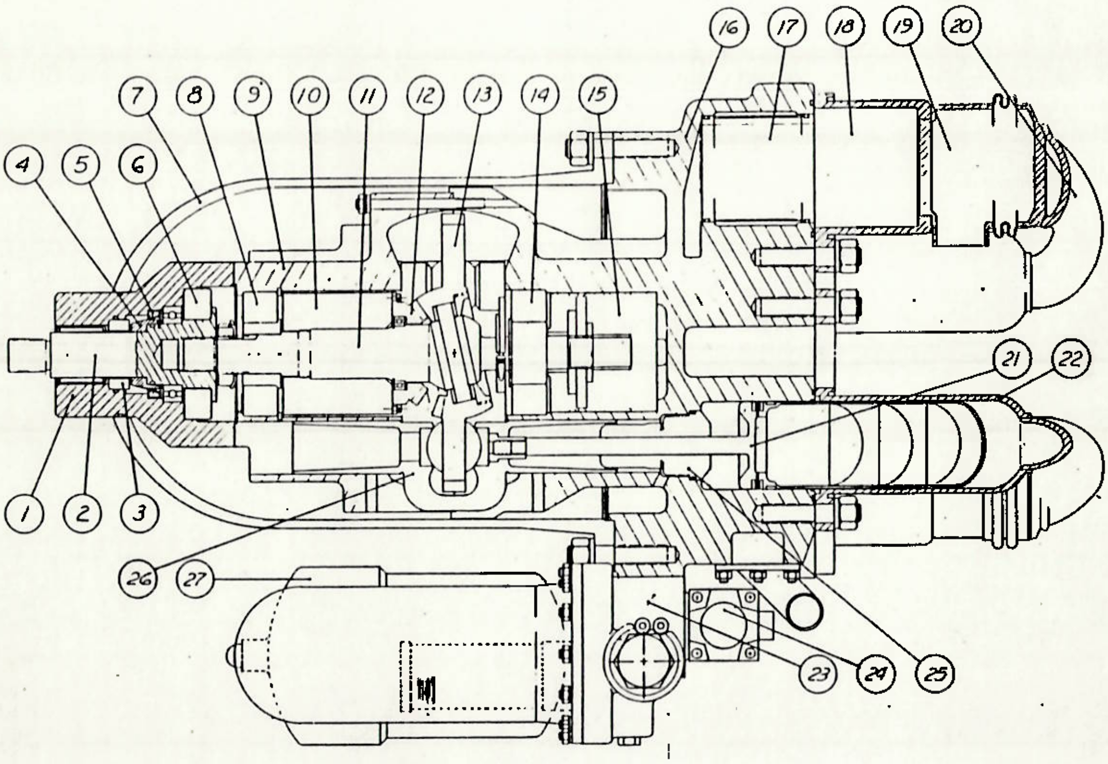


Figure 33

Layout Drawing of the STM4-120 Stirling Engine

(1) Rotating shaft seal assembly, (2) Drive shaft, (3) Mechanical face seal, (4) Mating ring, (5) Radial lip seal, (6) Thrust bearing, (7) Pressure hull, (8) Rear main bearing, (9) Rear crankcase, (10) Rotary actuator, (11) Main shaft, (12) Bevel gear, (13) Swashplate, (14) Front main bearing, (15) Oil pump module, (16) Front crankcase, (17) Cooler, (18) Regenerator, (19) Heater, (20) Hot connecting duct, (21) Piston assembly, (22) Cylinder/regenerator housing, (23) Hydraulic service assembly, (24) Power control valve, (25) Oil scraper/cap seal assembly, (26) Crosshead, (27) Accumulator.

The design of the STM4-120 is the result of a 45-year effort at Philips and STM, and has the following features:

1) Completely closed system with a rotating lube oil shaft seal.
2) Simple power control by means of changing the stroke of the pistons, contributing to high efficiency at part load.
3) Stacked heat exchanger arrangement. The heater has the same configuration as the cooler. This allows the highest possible thermodynamic efficiency in a Stirling engine, and also makes the engine suitable for mass production.
4) Remote heating via a heat pipe system. This allows the use of many different heat sources without changing the engine.

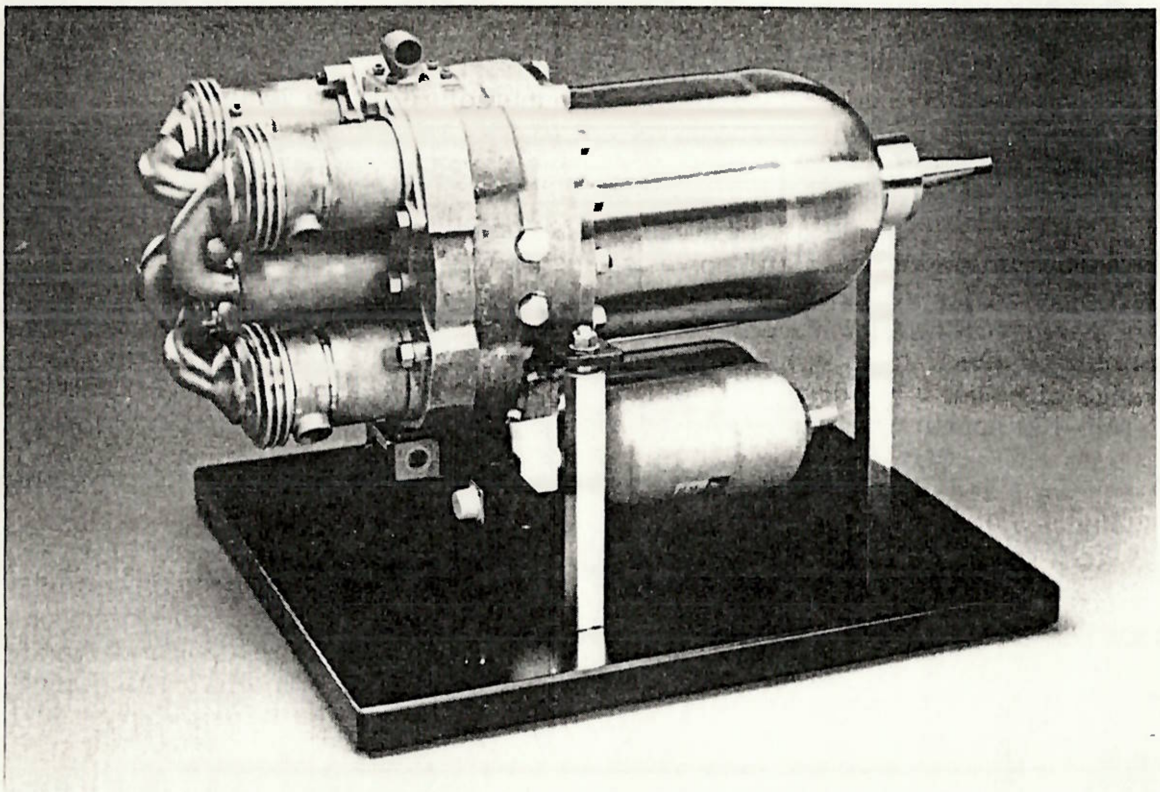


Figure 34

The STM4-120 Stirling Engine

The STM4-120 offers an advantage over gasoline and diesel engines in practically any of their current applications. In spite of this, STM will initially exploit only markets where the prime mover embodying these new concepts is unique - that is, in interesting applications where no other engine can be used.

Some such applications are:

- The STM4-120 using solar energy concentrated with a parabolic dish. The external heating system makes this possible and the high efficiency makes it very attractive because the investment per unit of installed power will decrease dramatically.
- Gas or oil fired STM4-120 engine driving a heat pump for heating and cooling offers tremendous energy savings compared with direct oil or gas heating and electric cooling. For heating, a fuel savings of 20-50% is possible, depending on the climate. In addition, the silent operation of the STM4-120 makes it attractive for residential use.

- Residential total energy systems (co-generation), generating the required on-site electric power and using the waste heat for space heating. The IC engine is not suitable for the application because its fixed ratio of power to rejected heat is generally incompatible with the required balance of electric power and heat demand of the site, which vary during the day and change with the change of seasons. In addition, the noise of the IC engine does not permit its operation on residential sites. The nearly silent Stirling engine has the unique feature that its efficiency can be controlled separately from the power so it can always match the electrical and heat requirements of the site.or oil fired STM4-120 driving a heat pump and an AC generator. When heat is required, the electricity obtained will cost only 20% more than the gas or oil price per unit of energy.

- Utilization of coal combusted in a fluidized bed. Work done at Philips Research Labs showed that it is possible to design and construct a small fluidized bed for coal burning that is suitable even for 10 hp with excellent temperature control. With a fully automatic coal-burning fluidized bed the Stirling engine in combination with a heat pipe is unique. This splendid combination of Stirling engine and heat source is important in applications, such as irrigation pumps, where the cost of the fuel and its availability are critical. In many places powdered coal is five times cheaper than diesel fuel. It is an abundant resource that cannot be used to power internal combustion engines.

- Energy for developing countries. Availability and distribution of refined fuel is a serious problem in many underdeveloped areas of the world. But Stirling engines can use such diverse heat sources as burning corn husks and cobs, rice hulls, sawdust, wood chips, trash, industrial waste, or unrefined oil. Using these easily available fuels, they can fill the pressing energy needs of people in such areas.

- Underwater power generation. A metal combustion process was developed at Philips and further investigated by STM. It involves the exothermic chemical reaction of lithium with sulfur hexafluoride to provide heat to the Stirling engine. The engine can, then, operate under water to provide power since it does not require air for combustion and does not generate gaseous exhaust. The STM4-120 fueled by metal combustion can be used as underwater generator sets for off-shore oil production and for propulsion of small civilian and/or military submarine boats.

- Bottoming plant utilizing the exhaust heat of diesel engines as its heat source. In this application the Stirling engine can convert the exhaust heat of diesel engines to useful mechanical energy, reducing the total fuel consumption and increasing the diesel engine efficiency by about 10%. The energy content of the diesel engine's exhaust is considerable (exhaust temperature in long-haul trucks is typically 600°C-750°C), and it is wasted. Fuel consumption of diesel engines can be decreased by 10%-14% with a Stirling engine bottoming plant.

Many other potential applications are also attractive, and most are suitable for the engine size which Stirling Thermal Motors has chosen to develop first in its STM4-120.

Since its beginnings in 1979, STM has brought the STM4-120 from idea through design to hardware. The first prototype was assembled in 1986, and cold motor testing began immediately.

Oil management of the entire engine was investigated first. A Plexiglas pressure hull facilitated visualization. The prototype, equipped with this pressure hull is shown in Figure 35. After cold motor tests, the heater heads were added to form a complete engine, heated with a gas-fired heat pipe. The STM4-120 ran for the first time in October, 1986, and the results were very encouraging. The testing and debugging effort now underway is expected to last about a year.

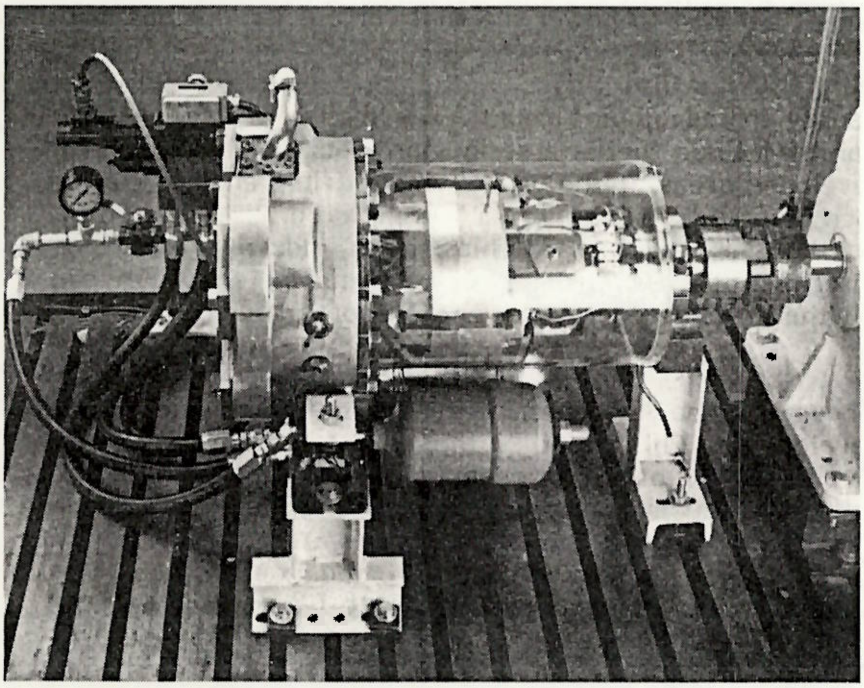


Figure 35

The STM4-120 Stirling Engine with Plexiglas Pressure Hull

APPENDIX I

Power Controls

Traditionally, the preferred method for changing power in a Stirling engine has been changing the pressure inside the engine, because the torque is approximately proportional to the mean pressure of the working gas. The development of this type of power control at Philips was done with a single cylinder displacer engine, where it was acceptable. However, for a four-cylinder, double-acting engine, it became quite cumbersome, particularly when very rapid changes were required. This type of system included many check valves, actuator valves, and a storage bottle, along with a high pressure hydrogen compressor.

In 1974 a relatively simple, heavy duty construction was found to vary the power [11]. In this case, the mean pressure of the engine stayed the same, but the stroke of the pistons changed. Such a construction could only be used with a swashplate drive since the stroke of the pistons is controlled by the angle of the swashplate. The new method of power control had the advantage of maintaining high efficiency at part load.

This type of power control mechanism was investigated at Philips, and was applied in an engine they named the "Advenco" engine. Philips never really tested this engine, and later sold it to NASA Lewis Research Center.

The variable swashplate drive from the Advenco engine was later incorporated into Stirling Thermal Motors' STM4-120 engine. A schematic drawing of this power control mechanism is shown in Figure 36. Figure 37 shows a practical model in two positions.

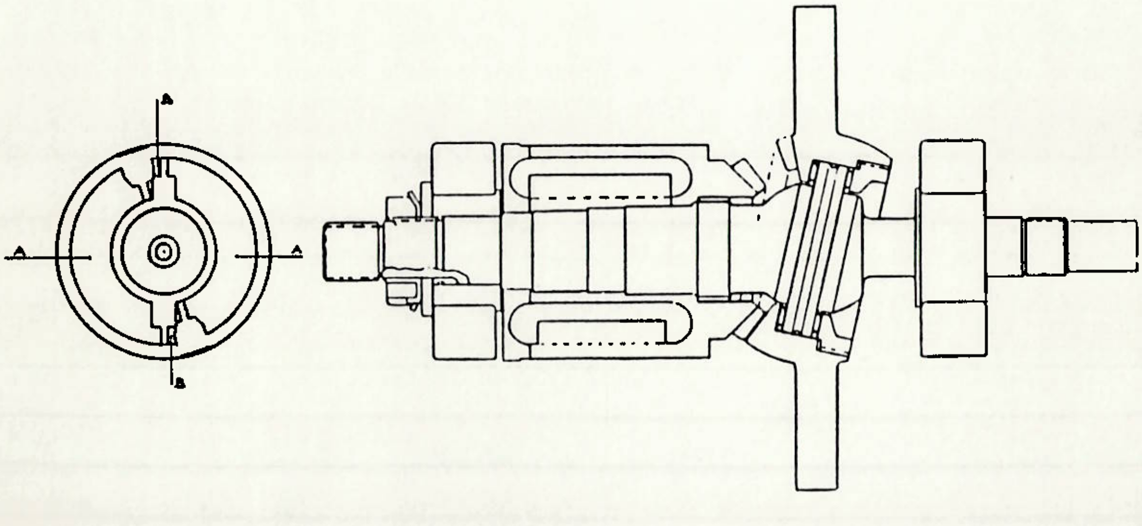


Figure 36

Cross Section of the STM4-120 Rotary Actuator

The torque caused by the hydraulic vane motor will turn the swashplate relative to the shaft via piston and bevel gears

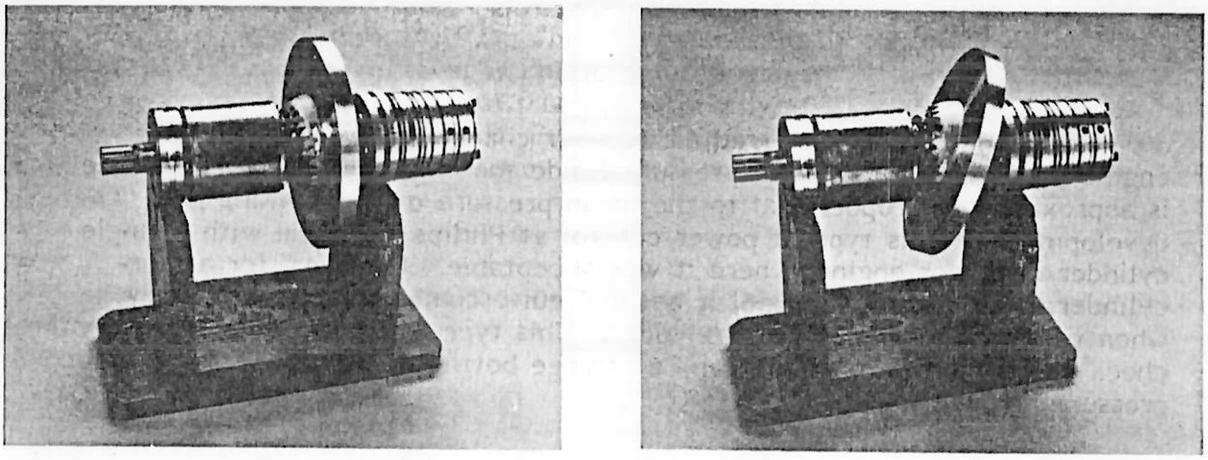


Figure 37

Variable Swashplate from the STM4-120, shown in two positions

APPENDIX II

Heat Pipes and Heat Sources

The Stirling engine can be heated by any heat source of sufficient temperature. This means it is not necessary to use liquid or gaseous fuels. The only problem in using non-conventional fuels is the transportation of the heat from the heat source to the engine. Philips recognized early the importance of the sodium-filled heat pipe as a very suitable heat transport device for the Stirling engine and, further, as a means of improving the efficiency of the engine [8][12].

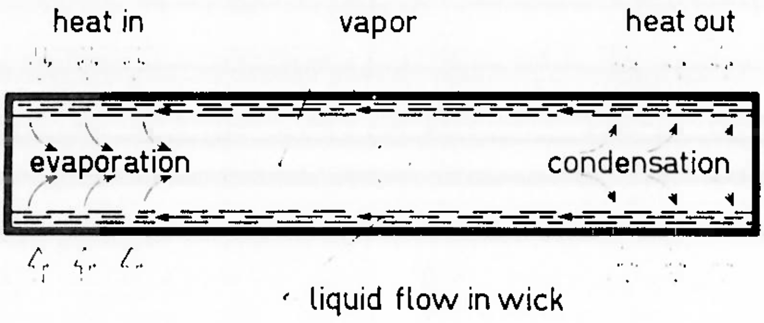
A heat pipe is, in itself, a very simple device, consisting of a closed space (for example, a closed steel tube with the walls inside covered with a porous structure, such as a few layers of fine wire gauze). In the case of a sodium heat pipe, this porous structure is filled with sodium. This means that a very small amount of sodium is needed. Figure 38 shows the schematic of a heat pipe.

Besides the gauze and the sodium, there is only sodium vapor inside the tube. If one side of the tube is heated (the evaporator) and the other side rejects heat (the condenser), then the sodium in the porous structure will evaporate. The resulting sodium vapor flows to the condenser side by means of a small vapor pressure difference, which is due to a very small temperature difference. The vapor will then condense on the porous structure of the condenser. The liquid sodium will flow back to the evaporator by means of capillary action. The heat pipe needs no mechanical moving parts, and it can transport a great deal of heat with only a small temperature difference.

Hot spots are not possible so long as the heat pipe is working properly. This is one tremendous advantage of the heat pipe-heated Stirling engine has over an engine heated by "direct flame." One of the biggest problems with direct flame heaters is maintaining a homogeneous temperature distribution over the heater tubes.

Figure 39 shows a practical demonstration of a heat pipe transporting heat from a coal fire in a brazier to Stirling engine "Bungalow Set" which is supplying electricity to five fluorescent lamps.

In addition to more familiar heat sources, heat pipe heat transport can also be used with less common sources such as fluidized beds and metal combustion.



HEAT PIPE

Figure 38

A heat pipe is nothing more than a hollow, vacuum-tight metal tube closed at both ends. Inside, on the wall, is a capillary structure composed of layers of very fine wire gauze, which contains sodium. When one end of the tube is heated the sodium evaporates. The vapor flows to the cool end and condenses there. During this process, heat is given up. Capillary forces send the condensed sodium flowing back through the gauze to the hot end, and the process repeats.

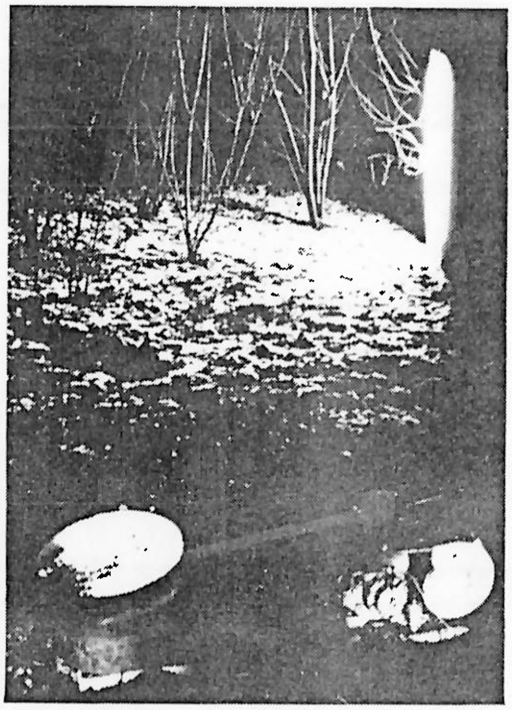


Figure 39

This photograph shows the practical application of a heat pipe being used to drive a small Stirling engine powered generator (The Bungalow Set) with the heat from coal burning in a brazier.

A fluidized bed is an extremely suitable method for burning pulverized solid fuel (such as granular coal) in a controlled way. The heat so developed can be transported by means of the heat pipe to a Stirling engine [13].

In principle the fluidized bed is a kind of furnace with a porous bottom plate that is covered with sand. When enough air is blown through the porous plate, the sand above the plate becomes fluidized, which means that the sand grains are floating in the air and the whole is acting like a fluid. If pulverized coal is fed into such a fluidized bed, this coal can be ignited and the whole system is heated up. The evaporator of the heat pipe is placed in the fluidized sand.

A schematic of a fluidized bed is shown in Figure 40. Figure 41 is a photograph of a small fluidized bed from which heat is delivered via a heat pipe to a 10 hp rhombic drive Stirling engine.

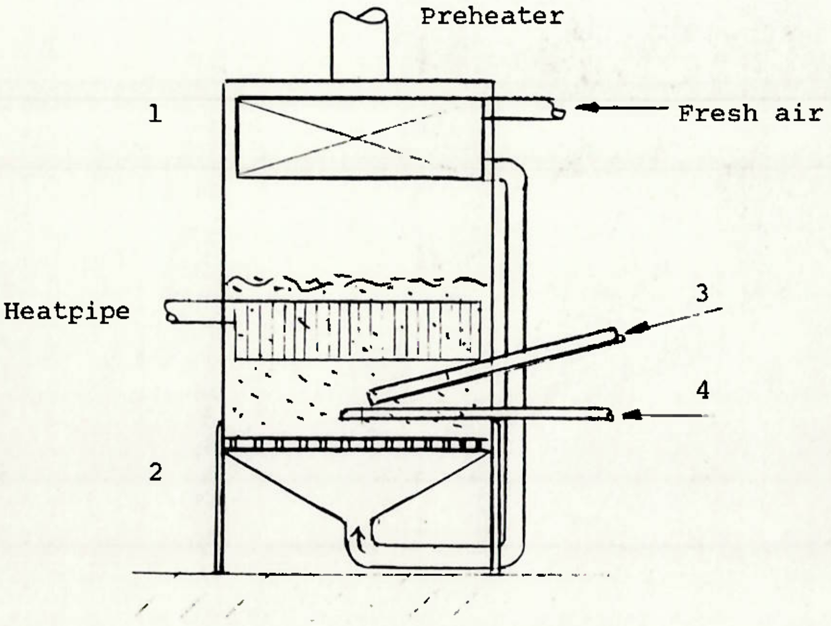


Figure 40

Schematic of a Fluidized Bed Solid Fuel Combustor

Fresh air enters the preheater (which is placed at the top of the device for greater efficiency) and is then supplied at the bottom of the furnace (1), and is equally distributed through the porous plate (2). The sand above this plate will float in the air when the air has sufficient velocity. Pulverized solid fuel, such as coal, can be fed into the floating sand, and will start to burn when the bed has reached a temperature of about 55°C. In order to start the combustor, gas is supplied to the bed via a tube (4). A heat pipe in the floating sand transports heat to the Stirling engine. A fluidized bed combustor can burn coal at a relatively low temperature (900°C), which means that the NOx emissions will be low. Moreover, if the sand is mixed with limestone (dolomite), a chemical reaction takes place to bind most of the sulfur from the coal so that it is carried off with the ash.

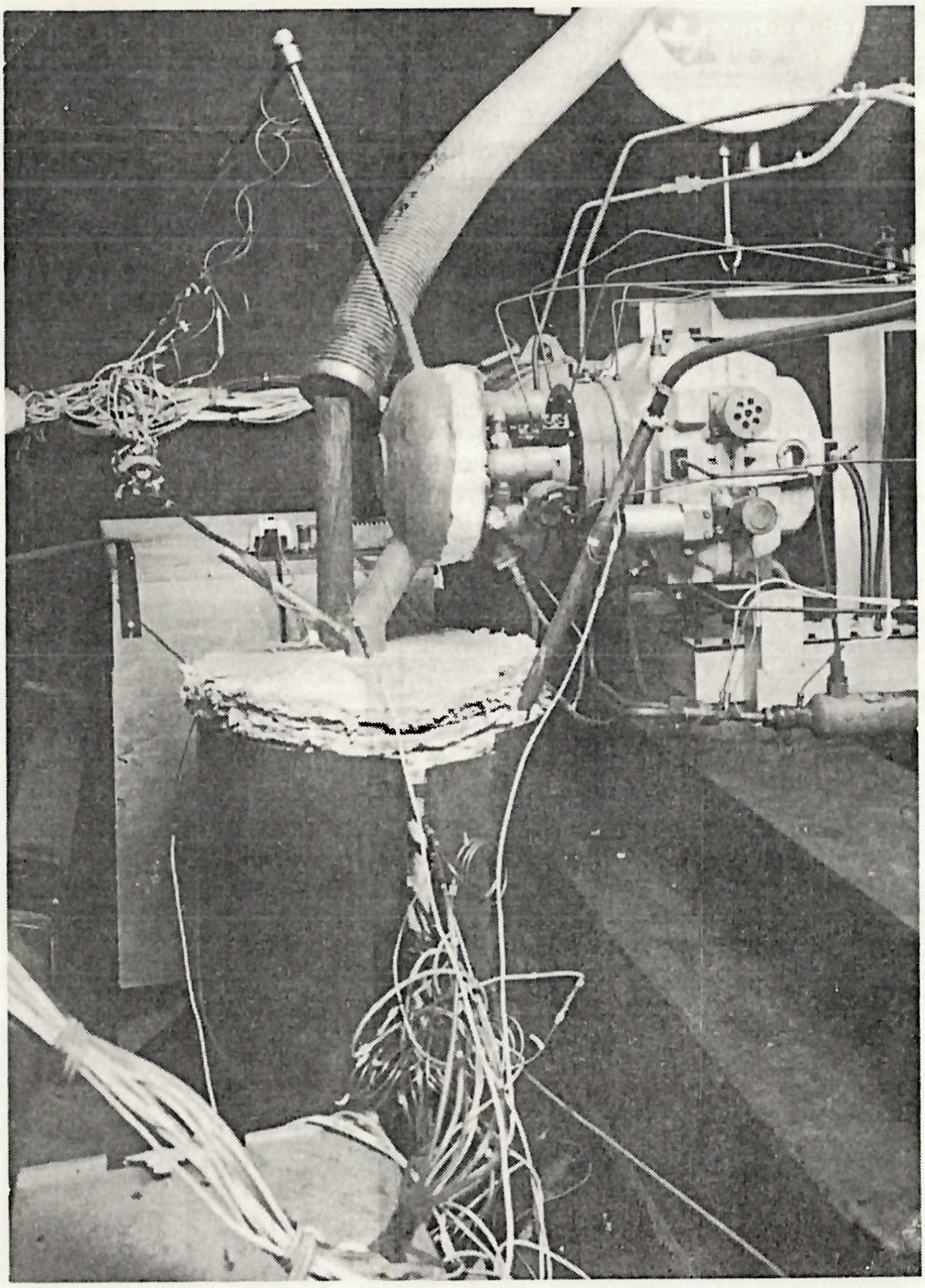


Figure 41

A Small Fluidized Bed Coal Combustor

Heat from the combustor is transported via heat pipe to the horizontally placed 10 hp Stirling engine.

A non-fossil heat source was investigated as part of a major effort undertaken by Philips Research Labs and M.A.N. to study and build a heat source with no exhaust gasses for underwater applications.

The chemical reaction between the metal Li and SF6 (sulfur hexafluoride) was shown to be very suitable. The product of the reaction is mainly LiF, a salt. Figure 42 shows the chemical reactor vessel with a part of the heat pipe and a throttle valve, which was necessary to keep the reactor at a higher temperature than the rest of the heat pipe, which is connected to a Stirling engine.

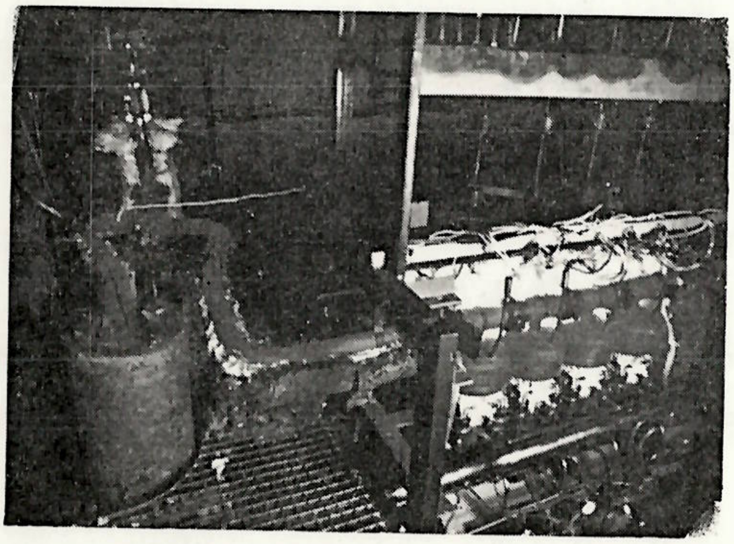


Figure 42

Chemical Reactor, Heat Pipe at Two Temperatures, and Stirling Engine

In a chemical reactor vessel the metal lithium (Li) reacts with sulfur hexafluoride (SF_6), producing a great deal of heat. The reaction product is mostly LiF, which stays in liquid form above 848°C. The reactor vessel shown here is surrounded by part of the heat pipe system. Sodium vapor pressure is controlled by a throttle valve to reduce the vapor pressure and, thus, the temperature, to about 750°C, which is suitable for the Stirling engine.

In some applications, it is desirable to store heat energy for later use. Philips did a considerable amount of work in this field, along with developing treatments to block corrosion at the Philips Lab in Aachen, Germany. The heat energy should be stored at a temperature suitable for heating the Stirling engine. Fluor salts were found to be the most promising for this purpose - the latent heat yielded by solidification is considerable higher than that of other materials. The right temperature can also be obtained from eutectic mixtures.

Figure 43 shows the properties of several mixtures for comparison with the properties of LiF, which is the most expensive salt [14] studied for use in this manner. A practical model of a heat buffer, heat pipe system and Stirling engine is shown in Figure 44.

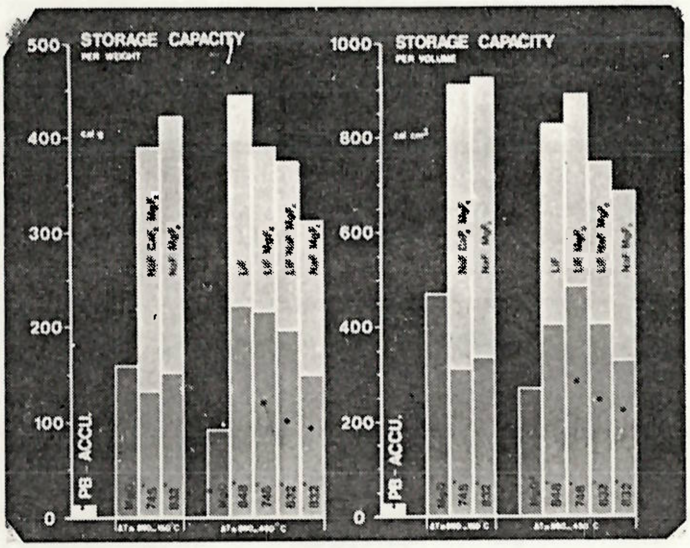


Figure 43

Comparison Between Different Heat Energy Storage Materials

Eutectic mixtures of some metal fluorides are very suitable for heat energy storage at higher temperatures.

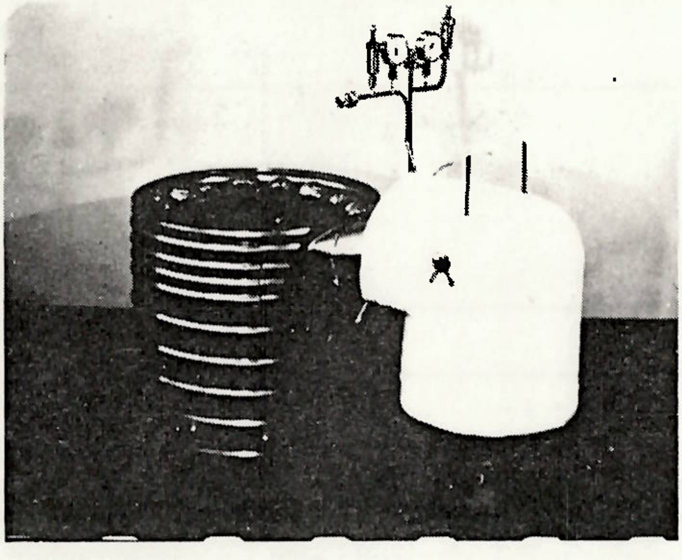


Figure 44

Practical Model of Heat Buffer, Heat Pipe System and Stirling Engine

The heat buffer contains several small containers which are filled only partially with LiF so that there is room for expansion when the LiF melts.

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