THE BASE ENGINE FOR SOLAR STIRLING POWER

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ABSTRACT

A new concept in Stirling engine technology is embodied in the "Base Engine" now being developed at Stirling Thermal Motors, Inc. This is a versatile energy conversion unit suitable for many different applications and heat sources.

The Base Engine, rated 40 kW at 2800 RPM, is a four-cylinder, double-acting variable displacement Stirling engine with pressurized crankcase and rotating shaft seal. It incorporates remote-heating technology with a stacked-heat-exchanger configuration and a liquid metal heat pipe connected to a distinctly separate combustor or other heat source. It specifically emphasizes high efficiency over a wide range of operating conditions, long life, low manufacturing cost and low material cost.

This paper describes the Base Engine, its design philosophy and approach, its projected performance, and some of its more attractive applications.

BACKGROUND

In 1972, Ford Motor Company obtained a worldwide exclusive license from N.V. Philips of the Netherlands for the Stirling engine, covering virtually all applications, including automotive.

Under this license agreement the Research Lab of N.V. Philips was to design and build four 175 HP engines, two of which would be installed in Ford Torino automobiles [1]. See figures 1 and 2.

In 1976 the two Stirling powered Torinos and the older Philips Stirling bus, equipped with a 4-cylinder rhombic drive Stirling engine [2], were successfully demonstrated for three days in Dearborn, Michigan.

A few years later, in 1978, Ford terminated its Stirling engine activities to make manpower available for short-term technological problems, and a year later Philips stopped work on the Stirling engine.

Upon these events, Stirling Thermal Motors, Inc. (STM) was founded in the United States to continue the work done at Philips, so that the results of the years of research and development work at Philips, which had resulted in a technical breakthrough since its last license agreement in 1968, would not be lost.

STM's main purpose upon its foundation was to develop commercial Stirling engines. Philips Laboratories had only made laboratory models for research. The only engine made for a special purpose was the one for Ford. When this particular engine was made, Philips was confronted with the practical reality of designing and building a Stirling engine for the most complex application imaginable - an automotive engine. During this time it was discovered that some components of the engine might form obstacles for commercialization because of their complexity and vulnerability.

From 1974 on, a real breakthrough was made in avoiding these complexities. This made a more simple four-cylinder, double-acting Stirling engine possible.

Unfortunately, by this time it was too late to incorporate these improvements into the Ford engine. The intent was to use these new developments in a second-generation Ford engine. This, though, was not done before Ford dropped its Stirling engine program. The engines being built by earlier licensees of Philips were based on designs older than the Ford engine. Their configurations had been frozen for several years. It was therefore impossible to utilize the new improvements.

From the outset STM was convinced that the time was ripe for commercialization of the Stirling engine, because all the ingredients for a simple, inexpensive and reliable engine with a long service life were present.

GENERAL APPROACH, BASIC APPLICATIONS

STM's general approach is based on the conclusion that we should avoid competition with existing internal combustion engines, at least in the beginning. We should rather find markets where the IC engine can not be used and where the use of the Stirling engine would be very economical, making use of the unique properties of the Stirling engine. Of the many possible applications, we gave particular attention to the following two:

- Solar energy conversion
- Prime mover for heat-driven heat pump.

If the manufacturing cost of the engine could be sufficiently low, particularly in mass production, the market in these fields alone could be vast.

TECHNICAL APPROACH

The whole drive of STM is to commercialize the Stirling engine. This means that the engine must be simple, reliable, inexpensive, and it should have a long life. None of these requirements should have an adverse effect on the performance of the engine.

More than three years of designing, discussions with suppliers and vendors, component testing and price calculations, led to the Base Engine. Studies for NASA have shown that the Base Engine's configuration is suitable for a whole range of power sizes up to 500 hp.

Special emphasis was placed on the flexibility of the the engine to adapt readily to a wide range of specific applications, duty cycles and heat sources.

Consequently, remote-heating technology is an integral part of the development effort, making it possible to divide the engine into a thermal conversion unit and a distinctly separate external heating system. Different heat sources coupled to the same "thermal converter" will adapt the engine to different applications and enhance commercial introduction since most of the development complexity and cost is in the thermal conversion unit.

A liquid metal heat pipe [3] is used to transport the heat from the heat source to the expansion heat exchanger of the thermal converter.

So far, most of the development effort has concentrated on the thermal converter, which is designated STM4-120RH (4 cylinders, 120 cm^3 swept volume per piston, remote heated) and referred to as the Base Engine.

ADVANTAGES OF REMOTE HEATING

One of the obstacles for mass-production of the Ford-Philips engine was the heater head. This was built as an integrated unit for the four cylinders (Figure 3). The huge mass of heat resistant material was very expensive and made the brazing cycle much too long. The reason for this large amount of material is that the tubular-expansion heat exchanger common to direct-flame Stirling engines must accomodate the relatively difficult heat transfer from the flue gas to the walls of the heat exchanger tubes. It is, therefore, characterized by a complex cage geometry as well as volume and flow-path length which are much larger than those required for the relatively easy heat transfer from the tube walls to the working fluid of the engine.

By contrast, an expansion heat-exchanger heated by the condensing metal vapor with a large film coefficient in a heat pipe can be ideally sized to suit the requirements of the working fluid and can be shaped in the most convenient manner for ease of fabrication (Figure 4).

Of course, this itself does not solve the difficult external heat transfer problem, but rather shifts it to the evaporator section of the heat pipe where the size necessary for adequate heat transfer does not affect the thermodynamic section and is easily realized since the heat pipe does not have to support the high cycle pressure.

For solar applications a solar receiver will be the evaporator of the heat pipe system.

Remote heating thus offers a number of advantages in addition to the flexibility with which it endows the engine:

- It brings about major simplifications to the heat-exchanger design. The so-called heat-exchanger-stack configuration, designed to take advantage of the high film coefficient of the condensing metal vapor, is considerably less expensive and more suitable for mass production.

- It brings about considerable improvement of the engine performance by permitting the heater design to be ideally suited to the thermodynamic requirements.

- The uniform temperature throughout the confines of the heat pipe enclosure eliminates hot spots on the heater and thus enhance both the efficiency and the reliability of the engine.

NEW POWER CONTROL SYSTEM

Up to this time, the preferred method for changing power has been changing the pressure inside the engine, because the torque of the engine is approximately proportional to the mean pressure of the working gas [4].

The development of this type of power control at Philips was done with a single cylinder displacer engine, where this type of power control was acceptable. However, for a 4-cylinder, double acting engine it became quite cumbersome, particularly when very rapid changes are required, as in automotive applications. This type of system included many check valves, activator valves, and a storage bottle, along with a high pressure hydrogen compresser.

Figure 5 shows a diagram of the power control system of the Ford-Philips Stirling engine. Power increases when the working gas (in this case hydrogen) is dumped from the high pressure storage bottle into the engine. The reverse takes place when the gas is pumped out of the engine into the storage tank with the high pressure compressor. But because this is a slow process, during this time, a short-circuit power control - which is a loss-control - instantaneously cuts the power.

In 1974, during the work on the automotive engine, a relatively simple, heavy duty construction was found to vary the power [5], [6], [7]. In this case the mean pressure of the engine stays the same, but the stroke of the pistons changes. This method of power control has the further advantage of high part load efficiency. Such a construction could be used only with a swashplate drive since the stroke of the pistons is controlled by the angle of the swashplate. It was tested thoroughly in a test rig and applied in the Advenco engine, but the Advenco engine was never adequately tested. Philips eventually sold the Advenco engine to NASA, where further testing was done.

Figure 6 illustrates schematically the variable swashplate mechanism. The swashplate is mounted on a part of the shaft which is tilted an angle α from the main shaft axis. The swashplate is mounted in such fashion that its centerline makes an angle α with the tilted shaft axis and it can be rotated relative to and about the tilted shaft axis in order to change its angle, and, with this, the stroke of the pistons.

The swashplate angle variation affected by its rotation about and relative to the engine shaft, is accomplished with a rotary actuator. This is a hydraulic vane motor comprising two diametrically opposite vanes attached to the shaft and two attached to the housing as shown in the cross-section of the swashplate-power control of the Base Engine [8], [9],(Figure 7). Thus, two pairs, A and B, of diametrically opposite chambers are formed. Rotation of the stroke converter housing relative to the shaft is affected by pressurizing one pair and relieving the other. The rotation is transmitted to the swashplate via a bevel gear to which the actuator housing is attached. The supply and return lines to the actuator are concentric tunnels in the shaft connected to a solenoid actuated proportional valve mounted outside the crankcase. Figure 8 shows a practical model of a variable swashplate in two positions.

The torque applied by the actuator to the swashplate in order to maintain a certain angular position depends on whether it was rotated to such position in the positive or in the negative direction. Rotation in the negative direction requires less torque since the engine torque itself in this case acts to increase the swashplate angle.

Figure 9 shows the actuator torque as a function of the swashplate angular position relative to the shaft. The curves labeled $M_+(\psi)$ and $M_-(\psi)$ refer to that torque for the positive and negative direction of rotation respectively. The third curve, $\gamma(\psi)$ shows the corresponding swashplate angle. The curve $M_-(\psi)$ reverses its sign within its range of definition. The point of sign reversal is an unstable control point to be avoided by narrowing the range of definition to exclude it. In the case of the Base Engine, shown in Figure 10, the angle α is 12.5° yielding maximum theoretical swashplate angle of 2α = 25° corresponding to 180° rotation. The maximum swashplate angle of interest is only 22°, corresponding to a narrower range of definition (124°) within which the torque $M_-(\psi)$ does not change sign.

Loss of hydraulic power will result in the gas forces bringing the swashplate to a position perpendicular to the main shaft axis reducing the piston stroke to zero - an automatic safety feature.

SEALS

In a 4-cylinder, double-acting Stirling engine there are two types of dynamic seals:

- o Dynamic seals as piston rings to divide the four cycles from each other, and
- o Dynamic reciprocating seals on the piston rods, in order to contain the high pressure working gas in the engine. These seals should also prevent oil penetration into the cylinders from the lubricated drive.

For the dry-running piston rings, a good solution is found in using a reinforced PTFE material.

However, the different types of reciprocating seals for the piston rods are still not reliable. Philips developed the rolling diaphragm seal, but this was shown, in the Ford-Philips engine, to be vulnerable in non-laboratory environments.

STM was able to avoid the gas containment function of these reciprocating seals entirely.

The new power control, with its variable swashplate, made it possible to enclose the relatively small drive with a pressure hull and to use a commercially available rotating shaft seal. Preventing oil penetration into the cylinders is, in this case, much easier, and has already been thoroughly tested in other engines.

SPECIAL FEATURES

Amenability to dynamic balancing and the ease of starting the engine are two additional features of the variable swashplate drive and power control elaborated upon in this section.

DYNAMIC BALANCING is achieved by adjusting the swashplate moments of inertia to the reciprocating mass. This is done in a manner enforcing perfect dynamic balance at a certain swashplate angle within its range of variation. At different angles unbalanced moments will appear, but since perfect balance automatically occurs at zero angle, these will be very small.

STARTING of the engine can be accomplished by heating up the expansion heat exchanger and the regenerator and then suddenly using the control pressure to increase the swashplate angle. This will cause the pistons to move in their normal way causing the engine to immediately develop sufficient power to perpetuate the motion. An accumulator fed by the hydraulic pressure pump will be used for that purpose.

Obviously, such a simple procedure may be used only for such applications as solar conversion since no accessories are required for the combusiton. In other cases only a very small starter motor is required to power the accessories needed for combustion, such as the air blower. When the engine has reached its correct temperature the accumulator pressure may be used to quickly increase the angle, having the engine self-start as mentioned above.

DESCRIPTION OF THE ENGINE

A layout drawing of the Base Engine STM4-120RH is shown in Figure 10. This engine is distinguished by two major features:

- o Variable swashplate drive and power control contained in a pressurized "crankcase" with a commercially avail able rotating shaft seal containing the working fluid and making it possible to avoid the reciprocating rod sealing problem; and

- o Remote heating, featuring heat-exchanger-stack configuration and liquid metal heat pipe heat transport system.

The cross heads are long in order to reduce contact forces and to relieve their bridge section from having to sustain any appreciable bending moment.

The drive components are supported and located by two aluminum castings forming the major building blocks of the engine (see Figure 11).

The crankcase pressure containment is formed by a commercially available rotating shaft seal placed in a seal-housing which also supports the thrust bearing, and by a pressure hull placed over the entire crankcase and bolted to the aluminum casting. The pressure hull serves no structural function other than containing the crankcase pressure.

The front casting also incorporates the cold part of the thermodynamic section, namely, the cylinders, coolers, cold ducts and coolant passages. Four identical assemblies, one for each cycle, form the hot portion of the thermodynamic section, as described in the previous section. These are made of the iron-based alloy CRM-6D sized to endow the engine with creep failure life well in excess of 50,000 hours at full load.

Table 1 summarizes some of the important features and parameters of the Base Engine.

PERFORMANCE

A set of engine parameters governing the performance of the thermodynamic section was selected for the Base Engine through an extensive and painstaking effort to tailor the engine performance to the design approach described above.

This approach required a high level of efficiency to prevail over a wide range of operating conditions, making the engine suitable for any duty cycle. Hundreds of different combinations of engine parameters were simulated before the optimal set was selected and established the design base of the engine.

The result is shown in Figure 12 as two performance maps at mean cycle pressure levels of 11 MPa and 6.3 MPa respectively. Figure 12a shows that between the power levels of 8 kW and 40 kW the shaft efficiency is between 45% and 47% (excluding auxiliaries and collector efficiency). Over a wide power range the efficiency hardly hanges with the engine speed.

For applications requiring less power, a smaller charge of helium may be used with very little effect on the efficiency. This is shown in Figure 12b for an engine charged to 6.3 MPa to provide power output of no more than 25 kW. This will greatly enhance the life of the engine.

Major contributions to the high efficiency of the Base Engine are derived from the heat-exchanger-stack configuration, the variable stroke power control and the design of the drive mechanism.

The heat-exchanger-stack configuration adds more freedom to the set of parameters governing the thermodynamic performance. These can be exploited to facilitate tailoring of the performance characteristics of the engine.

The variable-stroke power control inherently inhibits degradation of the efficiency at part load since power reduction is accomplished partly through the addition of void volume or, equivalently, reduction of the pressure wave amplitude, which is beneficial to the indicated efficiency.

Figure 13 schematically illustrates the Base Engine with solar receiver, solid fuel combustion, and with a liquid or gaseous fuel combustor.

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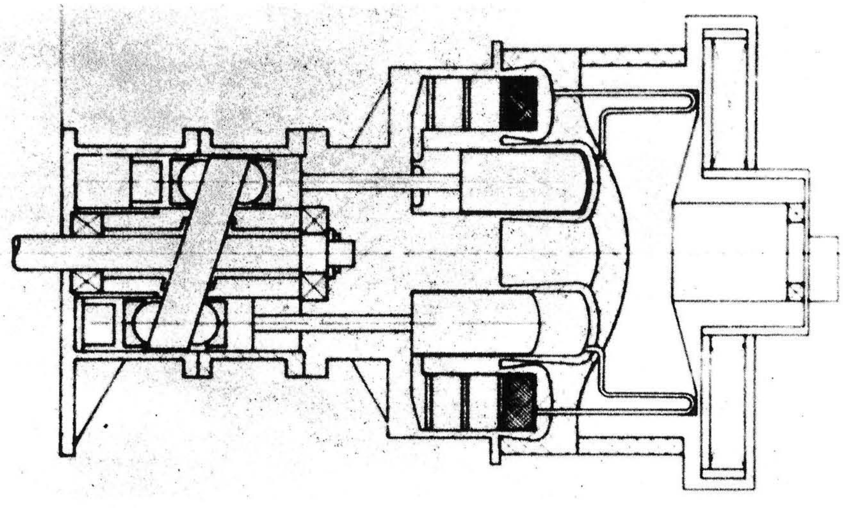

Figure 1
Schematic of the Ford-Philips Torino engine. This is a 4-cylinder double-acting Stirling engine with swashplate drive. Two of the four cylinders and two of the four cooler-regenerator units are shown in cross-sections. In these engines the movement of the pistons is transmitted to the main shaft by a swashplate.

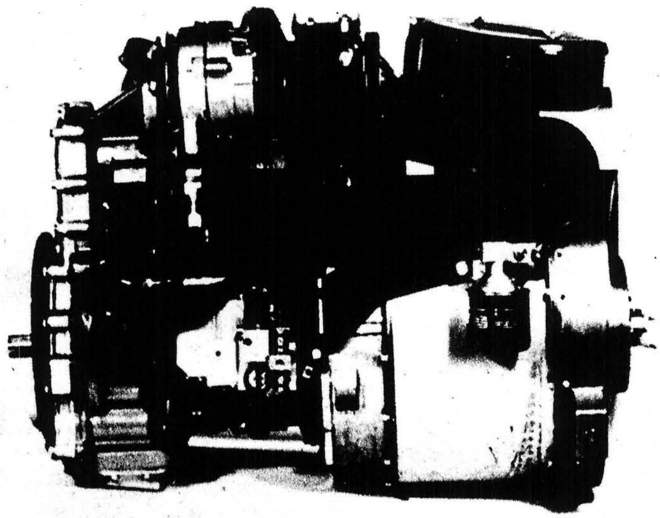

Figure 2
A 175 HP 4-cylinder double-acting type Stirling engine with swashplate drive to be mounted into a Ford Torino automobile (1975).

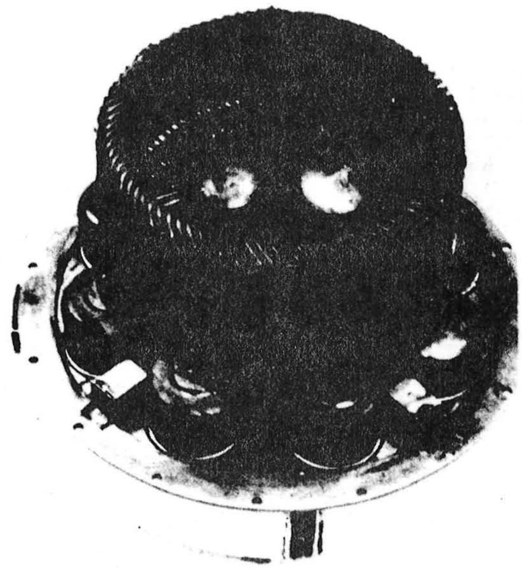

Figure 3
An example of the integrated direct-flame-heated heater head (from the Ford-Philips engine)

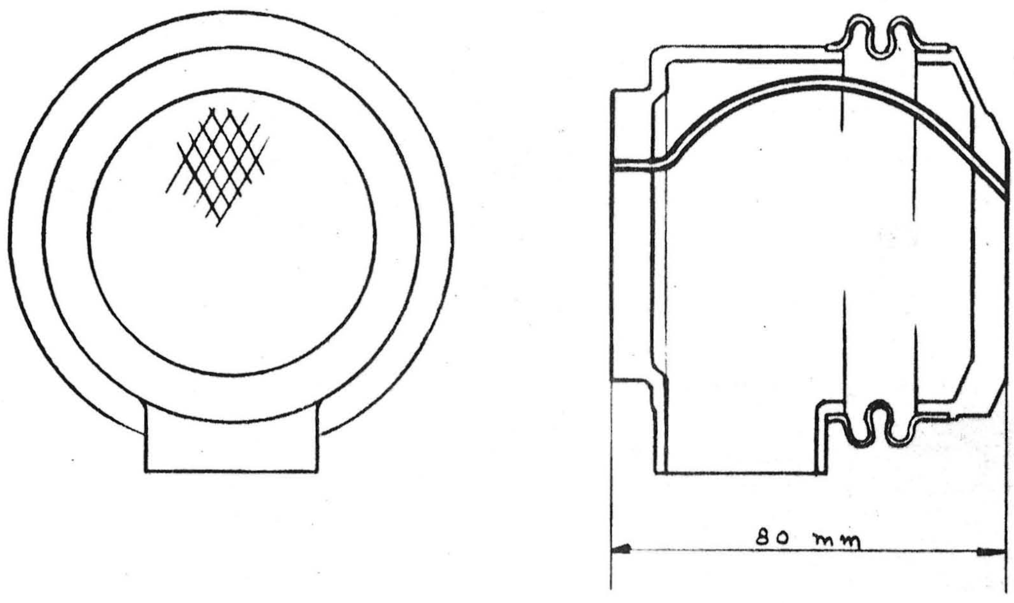

Figure 4
Expansion heat exchangers of the Base Engine. There is one per cylinder. These will later be electron-beam welded in the heat exchanger stack. The tubes are curved, enclosed in a flexible cannister, and brazed to two end plates.

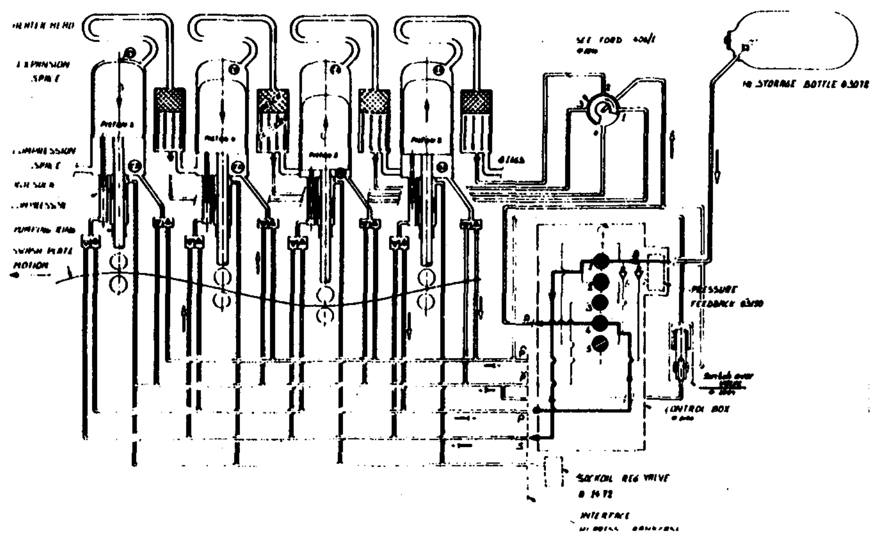

Figure 5

Power control system for the Ford-Philips Stirling engine. The torque of the engine is controlled by the pressure of the working gas. For more power, the woking gas from the storage bottle is supplied to the engine. For less power, small hydrogen compressors (connected to the bottoms of the pistons) are pumping the gas out of the engine and back into the storage bottle.

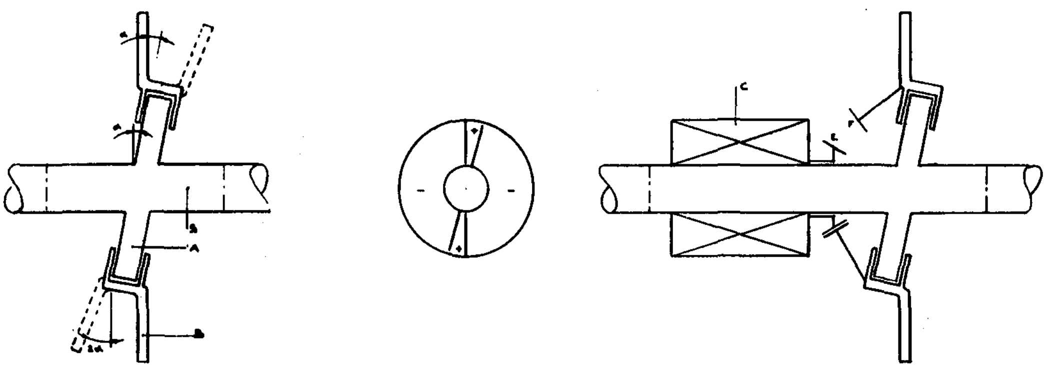

Figure 6

Schematic of the variable swashplate mechanism, showing the principle of changing the angle of the swashplate, which it makes with the shaft from 0 to 2α. The small plate A is fixed on the shaft S with an angle α. The engine swashplate (drawn here as a solid line) is perpendicular on the shaft S. This situation, $\alpha - \alpha = 0$, means that the strokes of the pistons are zero. When the engine swashplate B is turned 180° relative to the small plate A, the angle then becomes represented by the dotted lines. In this case the strokes of the pistons are maximal. By turning B relative to A between 0° and 180° any angle of the swashplate between 0 and 2α can be obtained, so the strokes of the pistons can be changed from zero to maximum. C is a hydraulic vane mechanism, the housing of which can turn in one or the other direction depending on which chambers are pressurized and which are not. The oil is fed via two channels in the shaft S. The turning of the housing is transmitted to the engine via the bevel gears E and F.

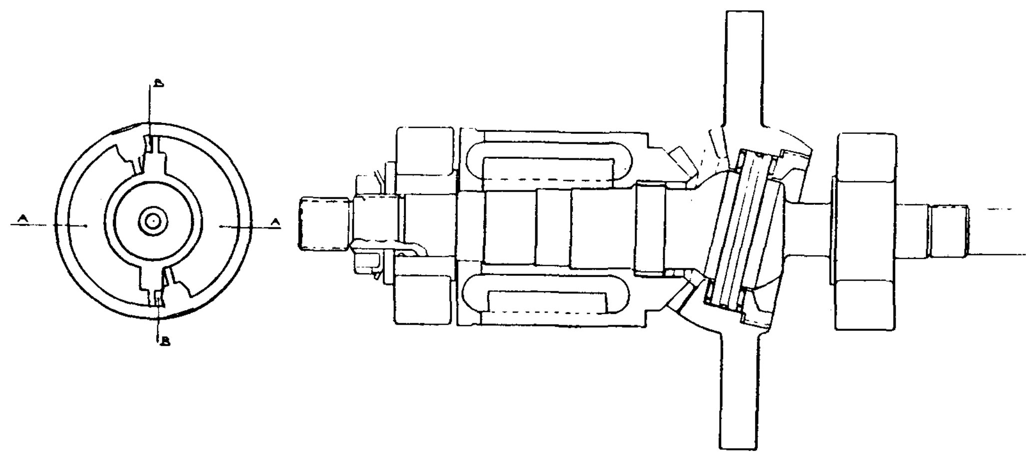

Figure 7

Cross-section of the rotary actuator of the Base Engine. The torque caused by the hydraulic vane-motor will turn the swashplate relative to the shaft via pinion and bevel gears.

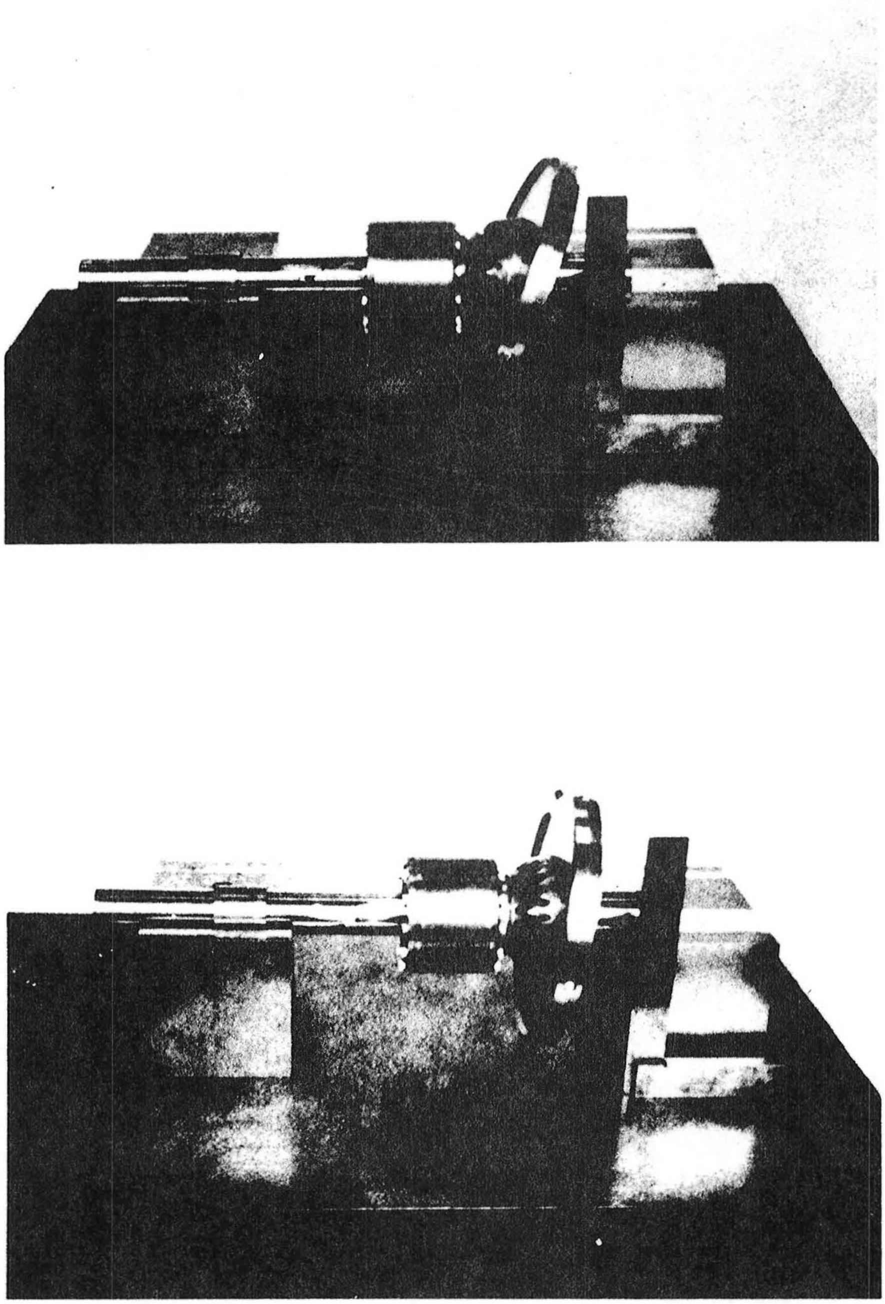

Figure 8
Practical model of a variable swashplate, shown in two positions.

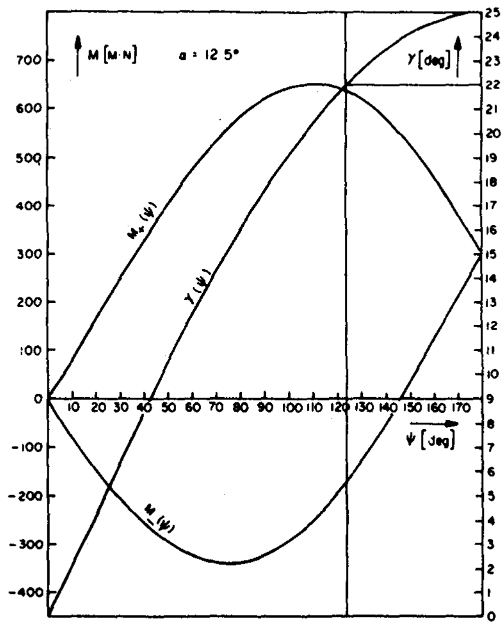

Figure 9

Rotary actuator torque requirements M_+ means relative rotation for larger stroke in the same direction as the rotation of the engine. M_- means relative rotation for larger stroke in the opposite direction from the rotation of the engine.

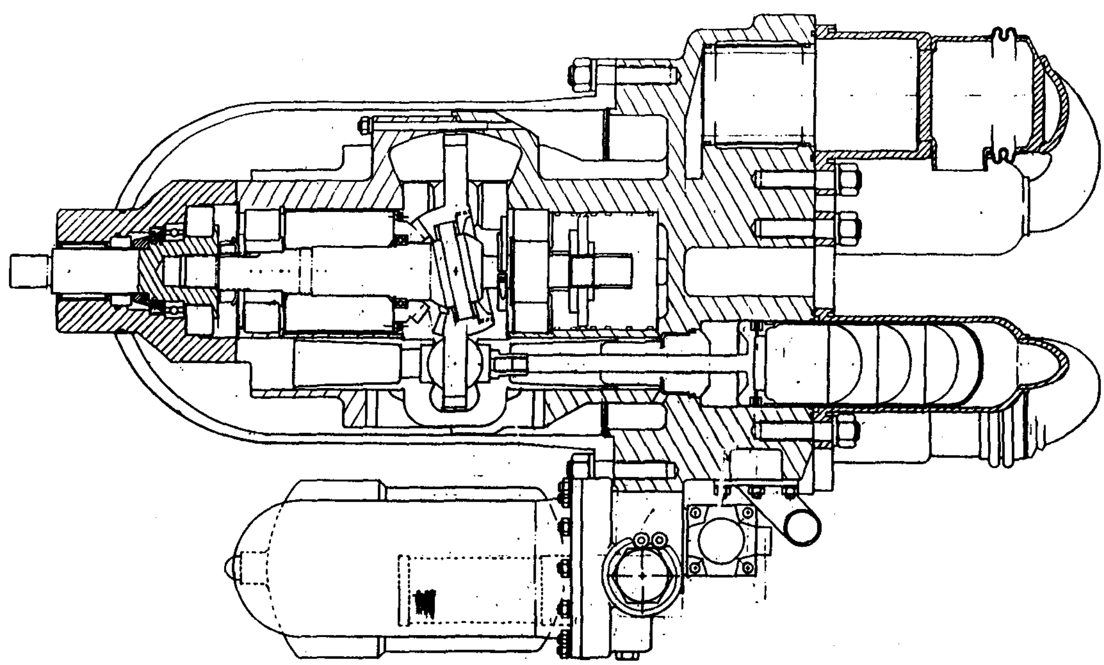

Figure 10

Layout of the Base Engine (STM4-120RH)

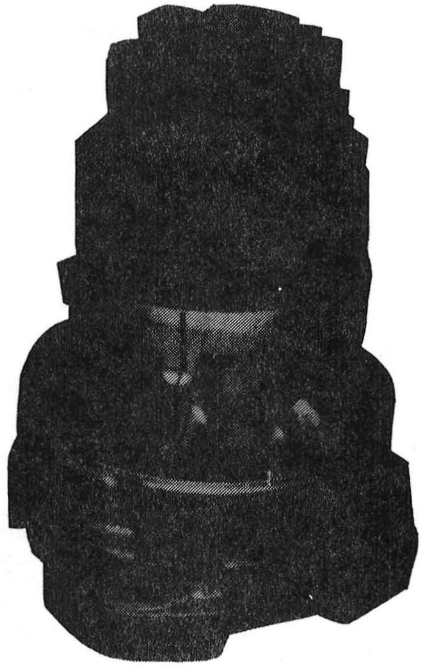

Figure 11
The aluminum castings for the front (bottom) and rear (top) parts of the crankcase. The front part incorporates the cold part of the thermodynamic section, mainly the cylinders, coolers, cold ducts and coolant passages.

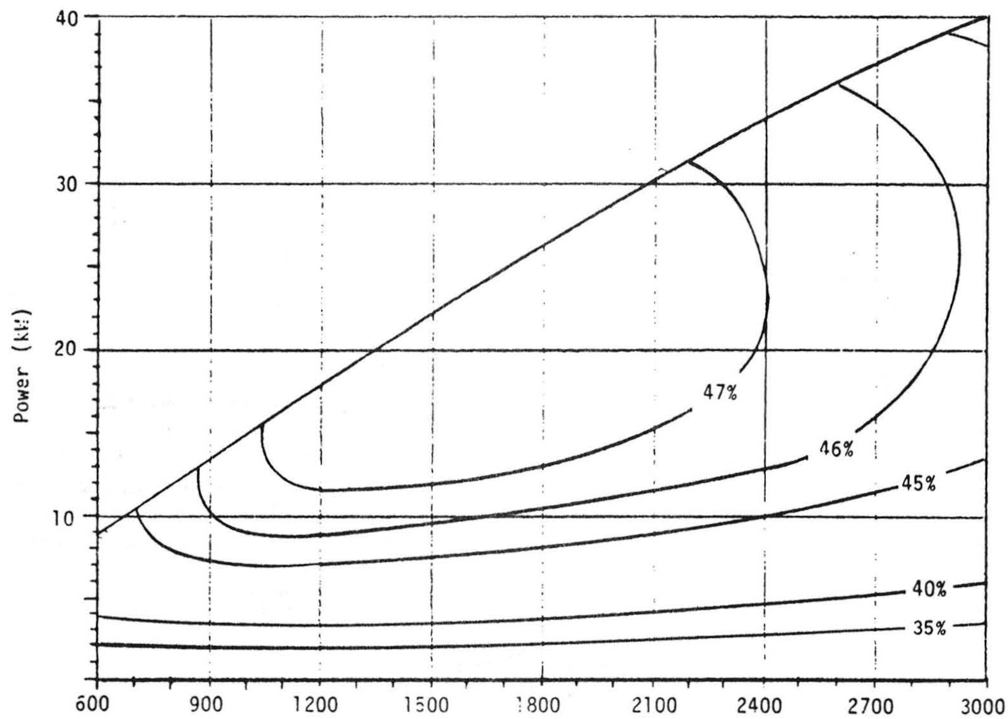

Figure 12a

Performance map of the STM4-120RH with mean pressure of 11 MPa showing lines of constant efficiency.

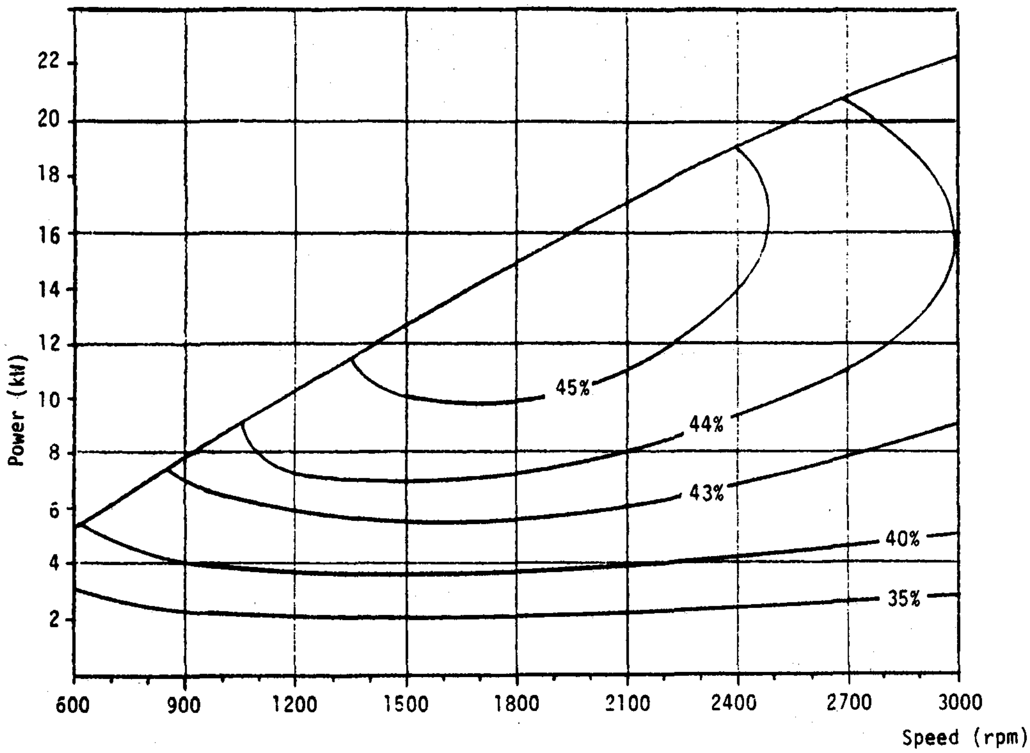

Figure 12b
Performance map of the STM4-120RH with reduced mean pressure (6.3 MPa) showing lines of constant efficiency.

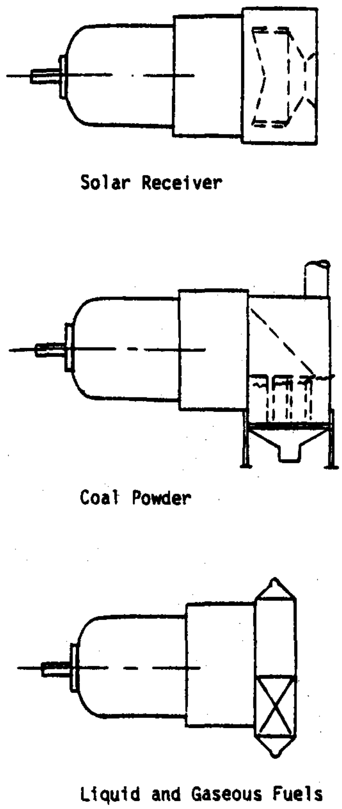

Figure 13
The Base Engine with Different Heat Sources

Arrangement:	Four double-acting cylinders symmetrically arranged about a common axis. One heat exchanger assembly per cylinder.
Bore:	56 mm
Maximum stroke:	48 mm
Overall length:	635 mm
Cross sectional dimensions:	Largest cross-section is 300 mm in diameter
Total estimated weight:	75 kg
Working fluid:	Helium
Mean cycle pressure:	11 MPa
Heater temperature:	800°C
Power control:	Piston stroke variation by means of a variable swashplate with a maximum angle of 22°
Heat transport:	Sodium heat pipe
Gas containment:	Crankcase pressurized to mean cycle pressure and sealed with a rotating shaft seal
Oil containment:	Reciprocating rod oil scraper
Materials:	Iron-base CRM-6D, CG-27 heater tube material

Table 1 - Important Features and Parameters of the Base Engine