# THE EXPERIMENTAL V4X STIRLING ENGINE
# – A PIONEERING DEVELOPMENT

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## ABSTRACT

A Swedish double-acting 35 kW V4 Stirling engine was developed in a pioneering effort with a number of simplified and novel design features. The overall design was made with the intention to fit a passenger car. The engine used standard automotive journal bearing technology, a new robust crosshead design, and sliding seals. A balancing shaft was used to remove first-order imbalances. Cooler, regenerator and heater geometry were first inherited from the Philips 4-65 swash-plate engine. Later a sequence of experimental heaters were designed and tested.

Very little has until now been published on this engine, since its development was discontinued in favour of the double-crankshaft U4 engines 4-95 (P40), 4-275 (P75 Mk II and III) and 4-123 (MOD1). These designs were in turn later abandoned (with exception of the solar P40 engine) because of problems with for instance rattling gears. The V4 design concept was then revived in the automotive 60 kW MOD2 engine and the successful Kockums submarine 75 kW V4-275 engine.

This paper describes the innovative design features, heater performance results and applications used for the development of fast power control.

## INTRODUCTION

The development company United Stirling (Sweden) started in 1968 with the goal of developing a 200 hp engine suitable for city buses, off-road vehicles, and submarines using a license from N. V. Philips Gloeilampenfabrieken in Eindhoven in The Netherlands. During 1969-70, Philips developed a rhombic drive engine for city bus use, the 4-235 (4 cylinders of 235 $cm^3$ swept volume each), which at 220 bar mean pressure and 3000 rpm would yield the desired 200 hp, see reference 2. However, because it was not probable that the specified service life of 10 000 hours could be achieved at that pressure and speed, United Stirling developed its own engine, the 4-615. This engine was also designed to give 200 hp, but at the more modest conditions of 150 bar mean pressure and 1500 rpm. This combination was, according to the load-speed-life experience (although very limited) at the time, reasonable.

The 4-615A was designed in cooperation between United Stirling and Philips. It was manufactured in Linköping by Förenade Fabriksverken, the United Defence Works. The engine ran for the first time in 1971. A modified version, 4-615B, was also designed at United Stirling, mainly in order to reduce manufacturing cost.

At the same time the Marketing Division was far ahead of the Development Division. Their marketing “waves of attack” plans on the diesel and gasoline engine market were aggressive. 1971 a Production Sector was formed headed by Sten Henström, who had solid experience from industry. Production cost calculations were made for the 4-615 engine. These showed that the production cost in 10 000 engines/year series was about 2.5 times what the Marketing Division had assumed! - Not surprising when the engine had four combustors and four preheaters, and each cylinder had 2 pistons, 2 piston rods, each with a rolling diaphragm seal (“rollsock”), 3 yokes and 6 connecting rods working on two crankshafts geared together.

It was very soon understood that the 4-615 cost could not be reduced 2.5 times. As a submarine engine it could have been developed but only a few engines per year could then possibly be sold.

So, other ways had to be sought for the engine design with a minimum of engine parts that would give the lowest cost.

At the same time, Philips’ Research Laboratories had an interesting engine solution in their laboratories: The double-acting swash-plate engine in Figure 1 below, see also reference 2 by C. M. Hargreaves for a detailed description.

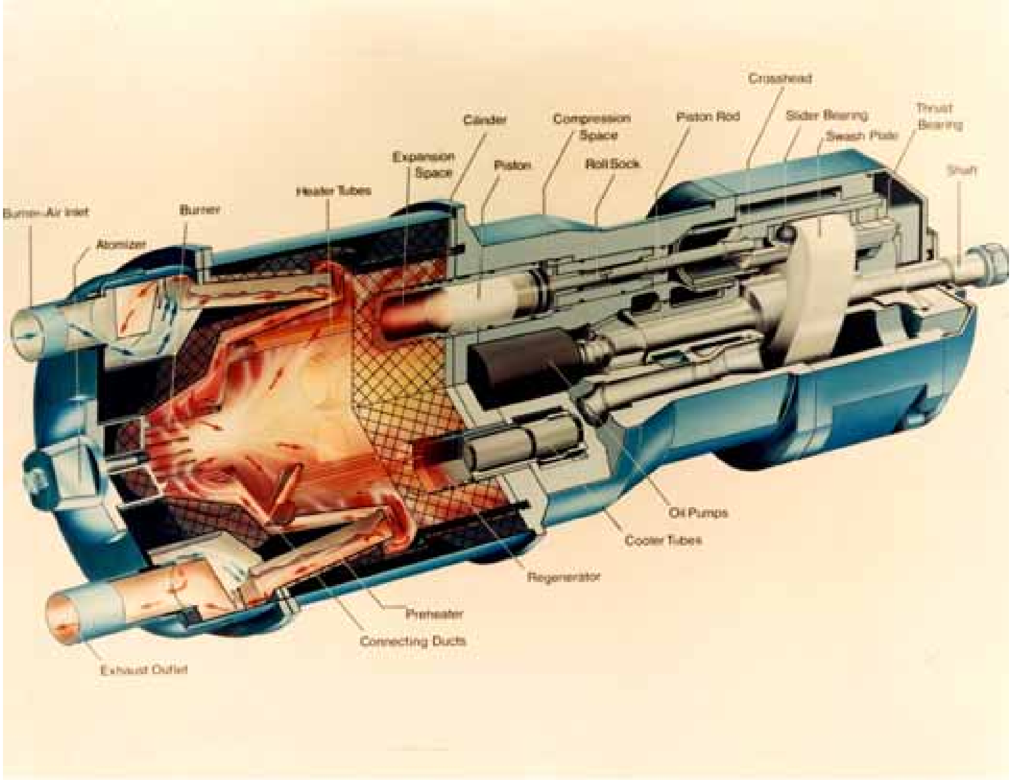


**Fig. 1. The Philips 4-65 swash-plate engine.**

This double-acting engine had one common burner and preheater, and each cylinder had one piston, one piston rod, one rod seal and one crosshead sliding on a common swash-plate. Quite a difference to the rhombic drive engine!

## THE V4X1

Already in 1970 it was realized at United Stirling that the company had to change to another concept. An experimental engine team was formed with Sven Håkansson as project leader, Per Grahn as design manager, and Tom Asp and Lars Lönnberg as designers. Lennart Strömberg assembled the engines for testing. Sven Håkansson had earlier solid experience with car and motorcycle design, building and racing.

His idea with the V4X1 was to use existing automotive technology as much as possible, rather than creating something completely new. He also had the ambition to make the engine as simple as possible. These two guidelines by Sven Håkansson, to use *proven technology and simple designs*, were considered to give the best chances for success.

The team designed a V4 engine, called the V4X1 (X for experimental) using a number of parts from the Ford-Köln developed SAAB V4 gasoline engine: Journal and connecting rod bearings, flywheel, gears to the balancing shaft, oil pump and oil filter. The engine used the 4-65 swash-plate engine bore (43 mm), stroke (45 mm), cooler, regenerator, heater design and design mean pressure of 110 bar because they was proven. As few uncertainties as possible were introduced. One difference to the swash-plate engine was that the heater was built with two heater tube rows contrary to the swash-plate engine which had one. The second row was provided with cast fins to ensure heat transfer enough to keep it at the same temperature as the first row. Another difference was the piston rod seals. It was a strong desire not to use rollsocks with their unpredictable life. The V4X1 was the first United Stirling engine to use the “Leningrad seal”, a sliding seal developed by the author and described in reference 1. The combustor was neatly placed inside the V, similar to the V4X2 in Figure 4.

**Fig 2. The V4X1 engine and its project leader Sven Håkansson.**

The engine ran for the first time in December 15, 1972. It ran on gasoline like all of the V4X engines. It ran well, and the max power, about 22 kW at 3000 rpm, was – not surprising – similar to the swash-plate engine. The figure in fig. 3 shows the complete engine in the engine laboratory. Tom Asp, one of the designers, is standing on the side.

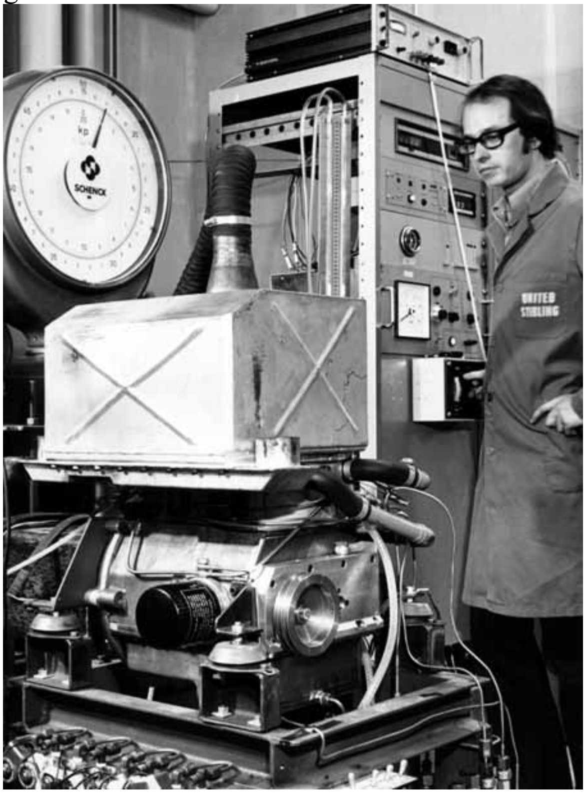


**Fig. 3. The V4X1 engine in dynamometer test.**

## THE V4X2

Encouraged by the successful testing of the V4X1, another engine was decided to be built, the V4X2. It had the same cold parts as the V4X1. The intent of the design manager, Per Grahn, was now to design a radically cheaper heater head, suitable for mass production. This was in contrast to the V4X1, which had individually bent heater tubes, all different.

The V4X2 heater had one welded-on tower manifold on each cylinder and on each regenerator housing. The horizontal heater tubes were arranged in two rows in contact with each other. So there were only a few tube sorts. The engine was assembled and run in dynamometer testing.

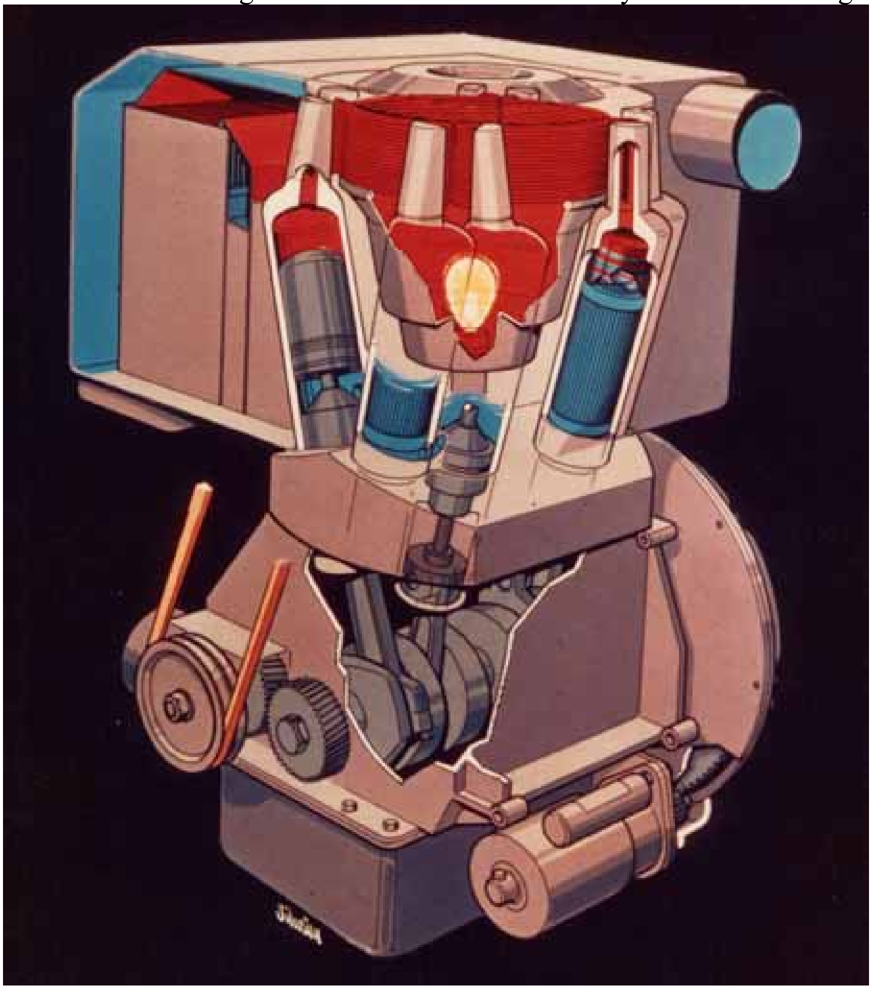


**Fig. 4. The V4X2 engine.**

However, the performance was a big disappointment. Power at low speed and low mean pressure was like the V4X1, but the power did not increase linearly with mean pressure as it should. It did not either increase as it should with engine speed. What was wrong? *The syndrome of "power drop" was now discovered*. The heater head was the only component that differed from the V4X1, so the problem must be with it.

It should here be said that Philips had not had any "power drop" in their engines, probably due to their longer engine development experience – Philips had worked with high-performance Stirling engines since the 1950'ies.

It took long time before this disastrous "power drop" phenomenon was fully understood. The design manager had been misguided by too optimistic calculations by the Heat Transfer group: *The cause was insufficient heat transfer capacity on the outside of the heater*. This means that at increasing loads, the outside cannot deliver as much heat as the inside requires. Later measurements showed that the hot gas temperature falls at high pressure and high speed, thus reducing the power and efficiency.

Many years' work was spent on understanding and curing this "power drop". The next prototype V4X engine, the V4X31, was critical because of its planned use in a Ford Pinto car.

## THE FORD PINTO CAR WITH UNITED STIRLING ENGINE V4X31 – THE FIRST DIRECT-POWERED STIRLING CAR IN THE WORLD

In July 1972 Ford Motor Company had signed an agreement with Philips in Eindhoven to develop a 170 hp swash-plate engine for the 1975 Ford Torino passenger car, see ref. 2 by C M Hargreaves which gives the full history and description the Stirling development at Philips. It was demonstrated in April 1976. But Ford wanted an early preview and feeling of how a Stirling engine behaves in a car, and ordered also an installation of the V4X31 in a Ford Pinto car with automatic transmission, all to be done by United Stirling.

The swept volume was increased to 4-90 (bore 50 mm, stroke 46 mm) and the design pressure to 150 bar to get more power. The heater was more like the 4-65 swash-plate with a single row with wire-wound tube surface enlargement. Tubes were horizontal.

Now, the biggest concern was the power control system! The mean pressure control system used by Philips on the 4-235 bus had two disadvantages: Power reduction was very slow. It took 30 seconds to pump down the mean pressure and the engine had to be short-circuited to get the power down. The other disadvantage was that it took too long time (seconds) to fill the engine to high power. Too rapid filling resulted in an unpleasant torque drop when demanding full power. The bus could live with a filling time of five seconds (which gave no torque drop), but a passenger car is judged slow by a customer if full throttle is achieved in more than 0.5 seconds.

So, the innovative Sven Håkansson designed a digital dead volume control system with 17 steps, see figure 5 below. It was fast, both up and down in power. Mean pressure was 110 bar at step 1 to 16. The last 17th step emptied the dead volumes to minimum pressure, thereby increasing the engine mean pressure to 150 bar. Design principle is shown in Figs. 5 and 6.

Sven Håkansson now left United Stirling. His belief in the Stirling engine for passenger car propulsion had faded. The author took over as project leader with special responsibility to find auxiliaries for the car installation. Lennart Lundström also joined the group with a responsibility to install the complete engine in the car, and make it work!

**Fig. 5. Dead volume control steps.**

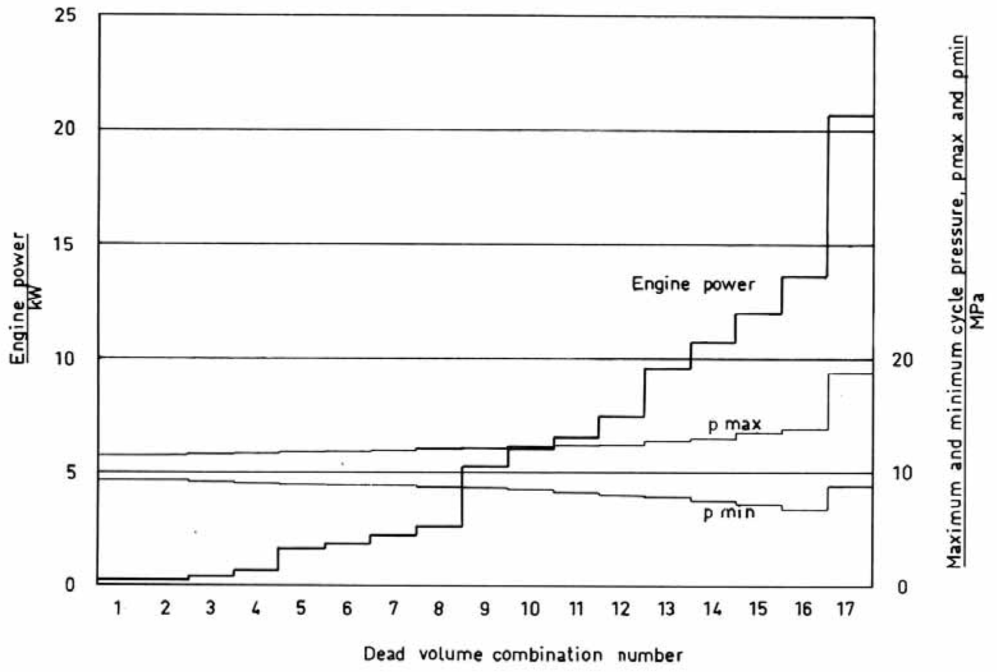
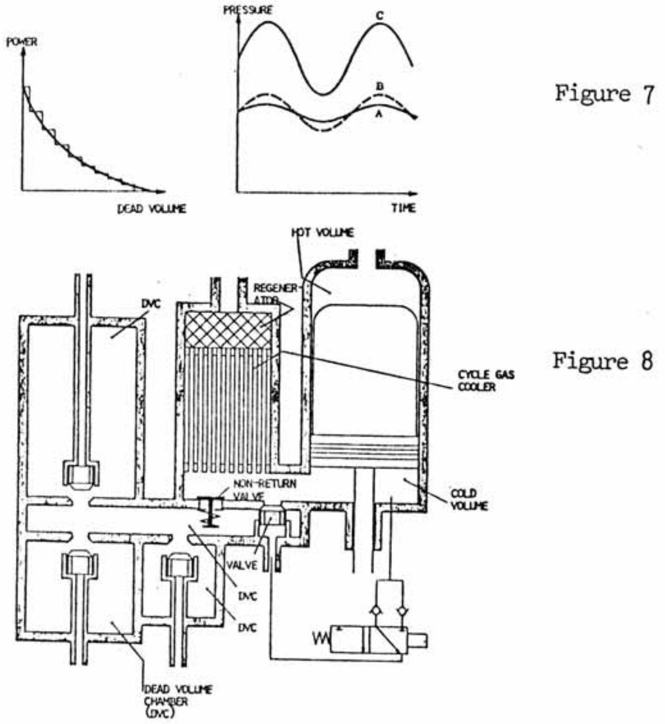


FIGURE 5. Power and pressure variation at 2000 r/min for a power control system based on combination of pressure amplitude and mean pressure variation

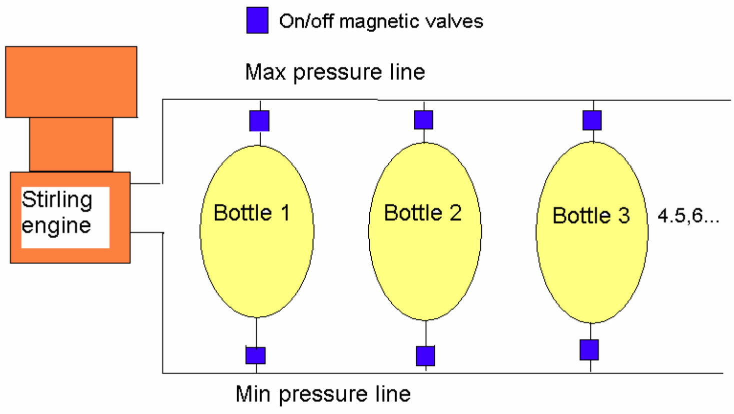


Increased mean cycle pressure (level C, figure 7) is obtained in figure 8. The non-return valve provides minimum cycle pressure in all dead volume chambers.

**Figure 6. Principle of dead volume control system in V4X31 engine.**

Another control system considered, but not chosen because of its too big volume requirements, was the TURK system conceived by Yngve Göthberg. It is a mean pressure control system without gas compressor. It was built for a Philips 4-235 engine and demonstrated without problems to the astonished Philips people around 1971. A schematic is shown below in fig. 7. The 4-235 system used 7 bottles to get down to idling pressure. Function is simple: Reducing pressure – bottle 1 is filled from max pressure line, the bottle 2, the bottle 3, and so on. Increasing pressure – engine is filled into the min pressure line in the reverse order ending with bottle 1. More bottles can of course be used. This is an ideal system for a stationary engine which needs a simple and inexpensive mean pressure control system.

**Fig. 7. TURK mean pressure control system**



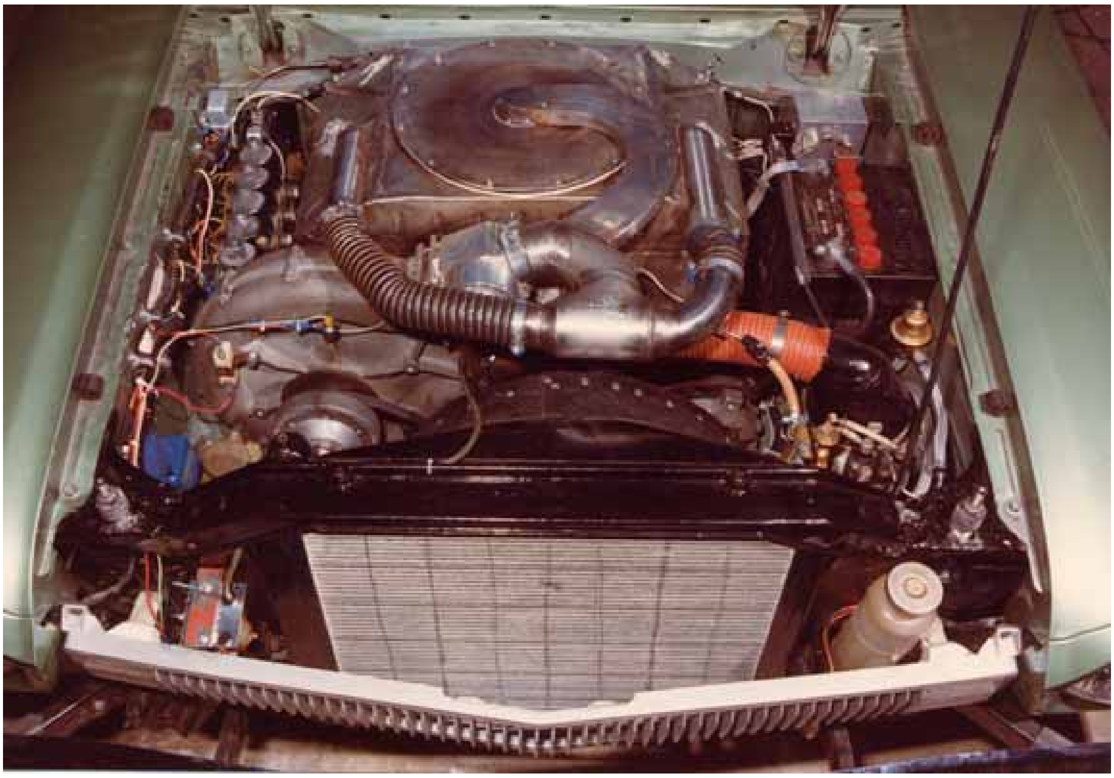


**Fig. 8. The V4X31 engine in the Ford Pinto car.**

Main problem with the dead volume control system was the valve control. It was done applying max or min cycle pressure to the valves, but the pressure difference was not always sufficient to close and open the valves. - In 1974 the Ford Pinto was demonstrated to a Ford delegation. The Ford project manager at the time, Norman D. Postma sat down in the car, put his left foot on the brake, stalled the engine to wide open throttle, and released the brake. Off the car went to his satisfaction! No racing car acceleration, but enough to get the feeling for a Stirling-engined car. (The temperature into the preheater was controlled < 920 deg C because it was more critical than the heater temperature.) Roelof Meijer was also present and got a chance to drive the car, see fig 9. As known to the author, *this was the first direct-driven Stirling engine car in the world*. GM Research had developed electrically driven hybrid cars, Stir-Lec 1 and 2 with Stirling battery chargers.

**Figure 9. Left: Unknown person, Norman D. Postma, Olle Jarnhammar, Torbjörn Lia and Lars Henriksson. Right: Roelof Meijer drives the car, Lennart Lundström in background.**

The demonstrations of the Ford Pinto car were the end of the V4X31 project. The car is now stored in parts in Malmö Museum. The engine is on display.

## THE V4X32, V4X33 AND V4X34 – HEATER DEVELOPMENT

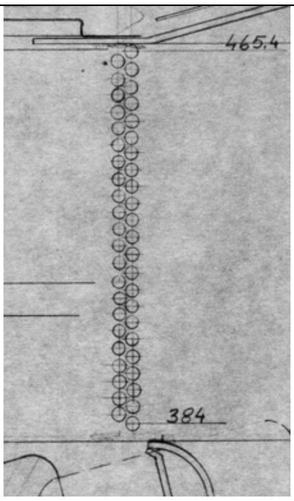
All these three test rig engines were devoted to heater head development, mainly to try to overcome the power drop. Different combinations of manifolds and tube configuration were tried:

V4X32 – very like the V4X2, see figure to the right. It was never run because of the bad experience with the V4X2 engine performance. Front row is the right one and the second row to the left of it was believed to get heat conduction from the front row which together with the heating from the combustion gases would heat it enough. It did not. (Theoretically the heater was very favourable with its large number of thin tubes.)

V4X33 – very like the V4X31 but without any heater tube surface enlargement

V4X34 – an attempt to reduce the dead volume of the tower manifold by substituting it with seven course tubes

No major breakthrough with the "power drop" was achieved with these heaters.



## THE V4X35 AND THE FORD TAUNUS TRIALS

Per Grahn, the design manager, conceived a novel heater for this engine, called the "temple heater". It had features from the V4X1 engine. It had individually bent tubes, now surface enlarged by a rolling thread tool instead of the brazed-on wire which tended to separate more or less from the tube after long time running. The cold-rolled 4.5/3.0 mm diameter Multimet tubes were only reduced to 2.85 mm inner diameter. The heater had a smaller manifold than the V4X1 because it was on a smaller diameter, fig. 10. Like for the other V4X engines, this engine had also the combustor placed inside the V to keep engine height down as much as possible.

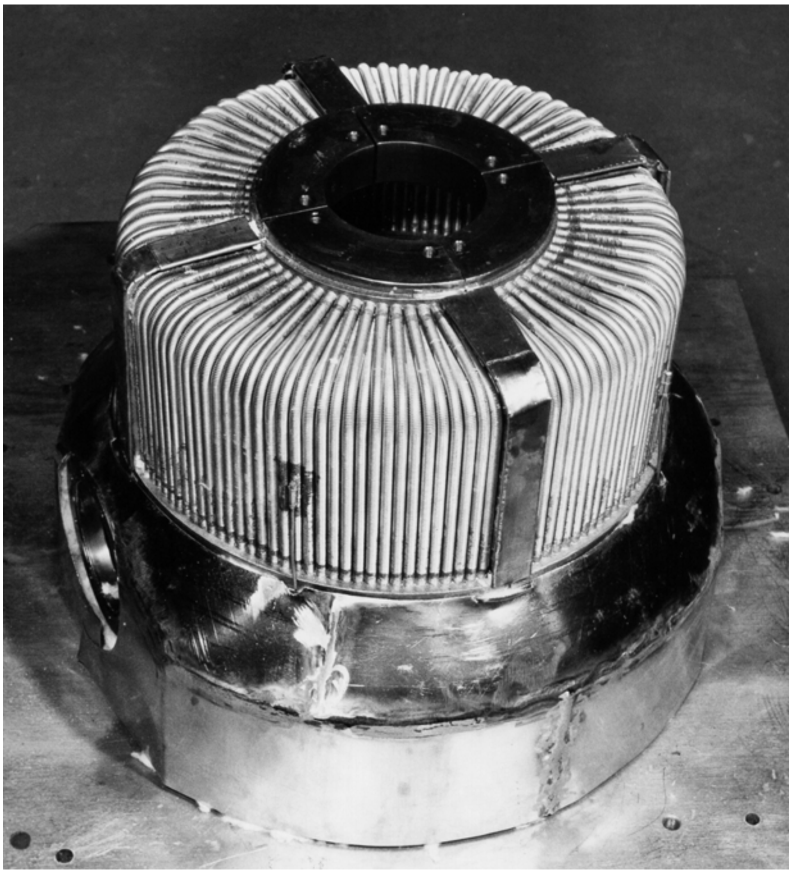


**Fig. 10. The V4X35 "temple heater".**

This heater shown in fig. 10 was a big step forward compared to the previous ones, mainly because of its design. The only remaining drawback was its insufficient heat transfer capacity. Λ=2 was desired, this heater only had Λ=1.3, however better than the previous V4X heaters. This showed also up in the power of the engine.
Below in Fig. 11 is the engine before car installation.

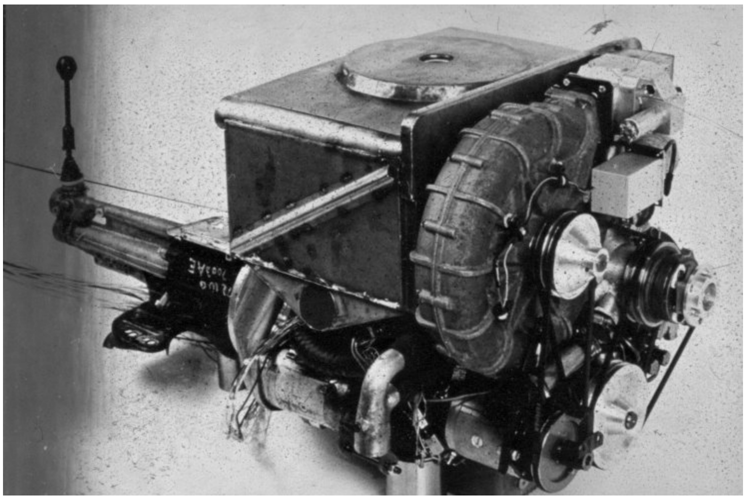


**Fig. 11. The V4X35 engine with manual gearbox fitted.**

A mean pressure control system was developed by Sten-Håkan Almström and designed by Ulf Bergman. It incorporated a compressor, a hydraulically controlled spool valve, and a supply system which avoided the Philips 4-235 supply problem mentioned on page 6. The V4X35 engine could be supplied to 90% torque in 0.5 seconds! How? By supplying around max cycle pressure when piston is in bottom, see fig. 12.

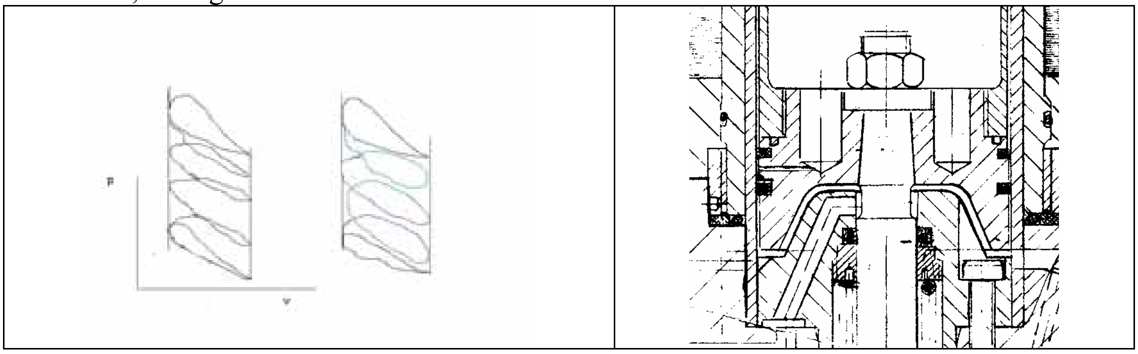


**Figure 12. Left: Schematic of min and max pressure supply. Low transient power when supplying at min pressure line, high at supplying at max pressure.Right: Gas supply to diameter reduction in piston rod.**

**Fig. 13. Jan Erik Everitt works with the V4X35 installation under the Ford Taunus hood.
He was the person driving the car 10 000 kilometers.**

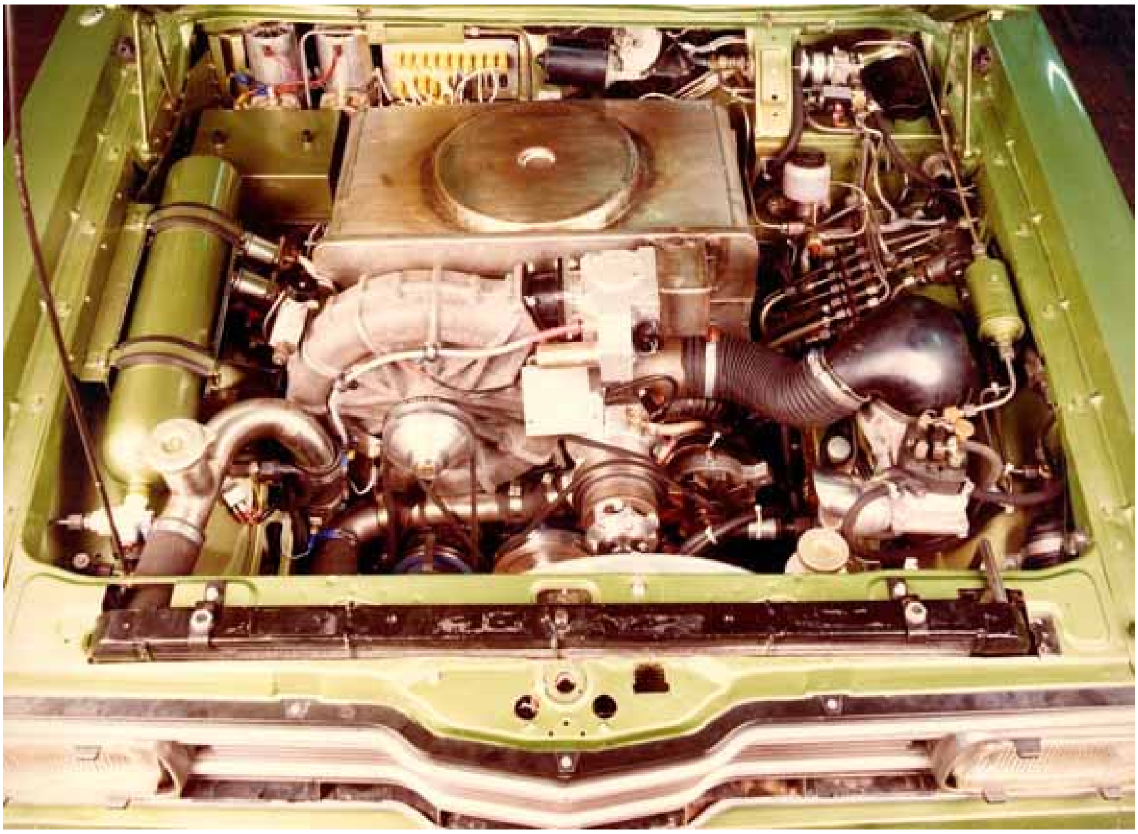


**Fig. 14. The V4X35 engine in the 1974 Ford Taunus.**

In the V4X35 car installation in fig. 14 the following can be seen in the engine compartment:

Far left - 7 litre hydrogen bottle
Upper left corner - two diaphragm compressors for atomising the gasoline fuel
Far centre - engine preheater with combustor flame inspection glass in the middle
Left front of preheater - the regenerative (also called side channel) air blower
Far right – Bosch K-Jetronic mechanical air/fuel system
Close in the middle – a 0.5 $m^2$ radiator which used ram air only except at idling

The car was used for evaluation of the control system (remember that the car had a manual gearbox!), the heater endurance, etcetera, etcetera. As endurance test the car was driven 10 000 km without major failures which proves that the design was robust.
The car with engine installed is now in the possession of Malmö Museum.

## THE V4X36 SETTING THE STIRLING CAR SPEED RECORD

With the V4X35 10 000 km endurance testing, the V4X project was coming to an end. It was only an experimental project created as a support to the 200 hp engine main project. The V4X engine was not part of United Stirling manufacturing plans. The main project of the company was still, as stated in the beginning of the introduction, a 200 hp engine for heavy-duty applications.
However, a V4X36 engine was also made to test a variation of the V4X35 heater, and to test a circular preheater to see if the heater temperature should become more uniform than with the previous rectangular preheater. The V4X36 heater had manifolds on the cylinders and regenerator housings for simpler manufacturing. The V4X36 was used for performance comparison with the V4X35. It turned out that they were very similar – and this was the end of the United Stirling V4X project.
But - this was not the end of the V4X36 story! Around 1982, Lennart Lundström got an opportunity to acquire the V4X36 engine from United Stirling. Lennart had the idea of trying to set a world speed record for Stirling engined cars. He had a welded tube frame from a late 50'ies Porsche Bergspider racing car which was extremely lightweight. Lennart's work with this car-engine combination is described in ref. 3.

The engine was rear-mounted; see figure 15 and the engine cooler was placed behind the engine. The engine had a motorcycle transmission. The new body panels of the car were made by the team in fibreglass. Height of the car was only 80 cm.

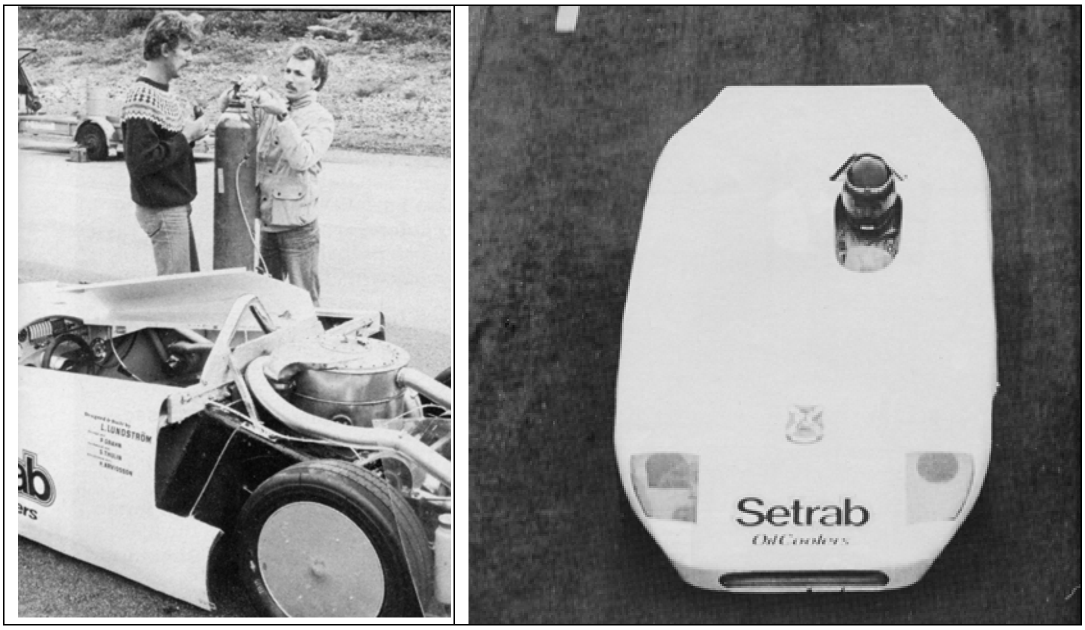


**Figure 15. Left, engine view. Staffan Thulin and Tommy Backheim is filling the engine with hydrogen. Right, Lennart Lundström on test trial.**

**Fig. 16. V4X36 racing car at the speed record trials. Persons: Staffan Thulin, official, Lennart Lundström, Håkan Arvidsson, 2 officials, and Per Grahn.**

A Stirling class was created by FIA, Féderation Internationale de l'Automobile, named Category A, Group 10, for Stirling cars only. On September 25, 1983 the record to the right in the table below was set at the racing track of Hällered near Borås, Sweden.

| **Vehicle data** | **Record data** |
|---|---|
| Length 3700 mm<br>Width 1550 mm<br>Height 800 mm<br>Weight 700 kg (300 front, 400 rear)<br>Engine power about 40 kW | 10 km standing start 135.88 km/hour |

Top speed of the car was about 200 km/hour during the record trials. - The car is now displayed at Malmö Museum aside with the Ford Pinto V4X31 engine.

## CONCLUSIONS FOR PRESENT STIRLING DEVELOPERS

1. The TURK mean pressure control system is useful for stationary engines.
2. With less space, a dead volume control system should be considered.
3. Providing cold rolled thread is a handy way of increasing heater tube surface.
4. The speed record of the V4X36 car is 20 years old and remains to be broken!

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2. Hargreaves, C. M.: The Philips Stirling Engine. Elsevier 1991.
3. Wheels (Swedish Car Magazine) No 1, pp. 26-30, January 1984.