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FIRST PHASE TESTING OF SOLAR THERMAL ENGINE AT UNITED STIRLING

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INTRODUCTION

During 1980 United Stirling of Malmö, Sweden, (USS) has been under contract from the Jet Propulsion Laboratory, for the modification of one of their series of laboratory test engines, known as the model 4-95 (formerly P40), for operation as a solar power plant in a parabolic dish concentrator. The engine with its receiver (solar heat exchanger), alternator and control system is to be installed on the Test Bed Concentrator, located at the JPL Parabolic Dish Test Site at Edwards, California, in June 1981.

The objective of the program is to demonstrate that the Stirling engine is a practical, efficient and reliable energy converter when integrated with a parabolic dish concentrator, and that it has the potential of being cost competitive with fossil fueled electric generating systems of today.

Also during 1979-1980, United Stirling has been supporting the Fairchild Stratos Division of Fairchild Industries in a team effort to design a "direct coupled" hybrid receiver for the 4-95 engine to be installed in the above mentioned test. It will permit the engine to operate at constant load on either a "solar only" mode, or with a fossil fuel burner in a "combustion mode" during cloud cover or at night. The receiver is being fabricated by Fairchild Stratos and is to be integrated with the engine by United Stirling and the Advanco Corporation. The Stirling receiver activity (DSSR) is described in another paper at this Review.

Recent studies have shown that a Dish/Stirling system employing mass produced components has the potential to produce electricity for 50-70 mils/kWh and at a capital cost of under $1000/kW (1,2,3). Contributing to this is the relatively high thermal efficiency of the Stirling and its projected low selling price (4). The importance of thermal efficiency is related to the concentrator/engine production cost ratio. This ratio is not yet certain, but is believed to be between 2.5 and 4. Since concentrator mirror area is inversely proportional to thermal efficiency, power plant thermal efficiency has a leverage effect on overall system cost.

UNITED STIRLING IN-HOUSE PROGRAM

The Stirling engine being modified for the program has its roots in the USS development program going back to 1972 when the decision was made to concentrate all efforts on double-acting four cylinder designs, rather than the classical displacer type engines. Double-acting engines have proven to be lighter, more compact and less costly compared to multi-cylinder displacer engines.

In 1975 a new double-acting 40 kW engine was designed and first tested in 1976. It was originally termed the P40 but more recently designated the 4-95, having a displacement of 95 cc/cylinder. The design objective was to achieve a reliable experimental engine for the development of specific components such as the heater head (the high temperature heat exchanger receiving heat from an external source), piston rod seals, piston rings and control systems. In combination with a requirement of high cycle efficiency and high power density, this called for a concept with parallel cylinders placed in a square, a heater head with rotational symmetry, and a twin crank shaft drive unit. The 4-95 cross-section is shown in figure 1. The involute heater head is seen in figure 2, and the engine on a dynamometer is shown in figure 3.

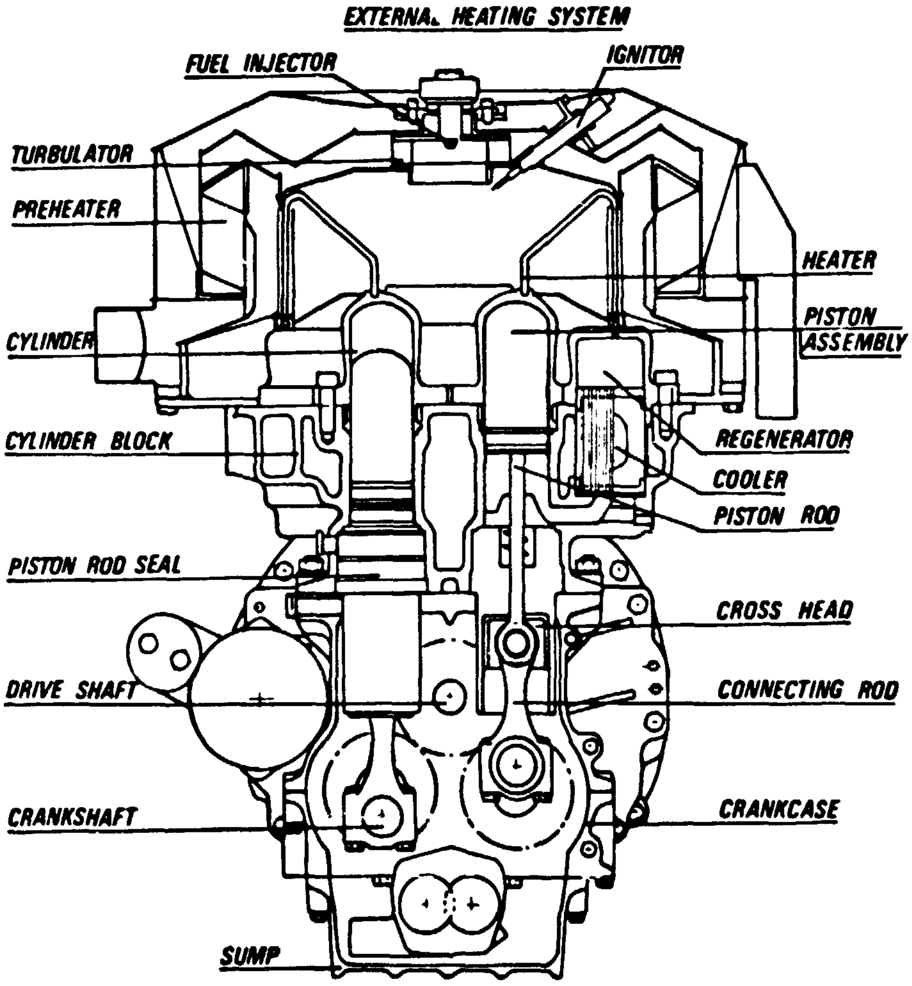

Fig1. Cross-section 4-95 engine.

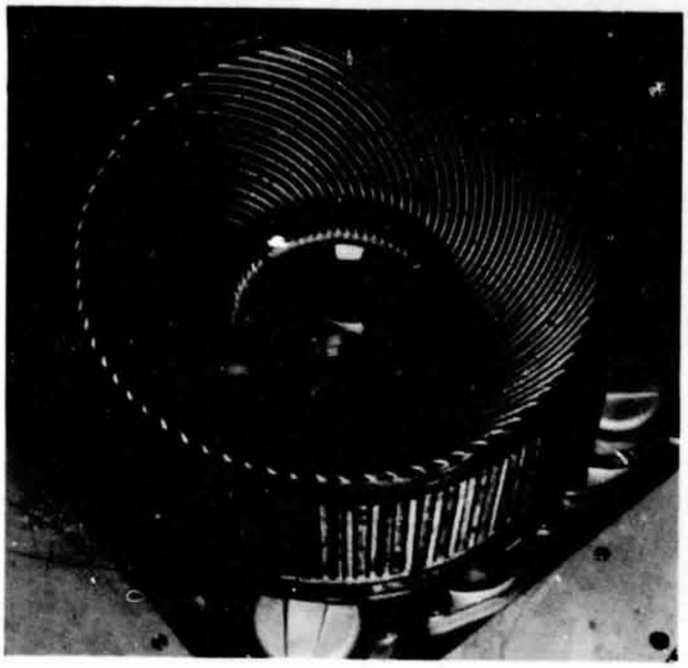

Fig2. 4-95 involute heater head.

The engine is structurally built up from three main assemblies, the drive unit, block and heater head. It is possible to split the engine between block and drive unit without disassembling the heater head. This option minimized the effort and time needed for assembling and disassembling in conjunction with modifications and servicing.

Twentyone 4-95 engines have been built for in-house use as well as for special testing by government agencies and private organizations in the United States, Britain and West Germany. The 4-95 is playing a key role as a baseline engine in the DOE/NASA Automotive Stirling Engine (ASE) program. Three passenger cars, so far, have been operating with the 4-95 engine.

Several conceptual and design features give the 4-95 engine a potential for long life between overhauls. Such unique features include:

- absence of sharp pressure impulses within cylinders
- inherent low linear and torsional vibration
- absence of valve gear
- lubrication system operates in non-contaminating atmosphere
- piston rings and seals operate in cool region
- cross head design eliminates side forces on piston assembly

As of December 1980, total test time for all 4-95 engines on dynamometers and in demonstration programs exceeds 13,000 hours. One engine operating on a special high temperature (820 °C) endurance cycle has been running over 5800 hours. The critical piston rod seal, known as the new PL design, has achieved approximately 120,000 hours of successful running on all seal units, with one seal exceeding 7000 hours without failure. Additionally, about 150,000 hours of separate component and accessory testing contribute to overall reliability of the 4-95.

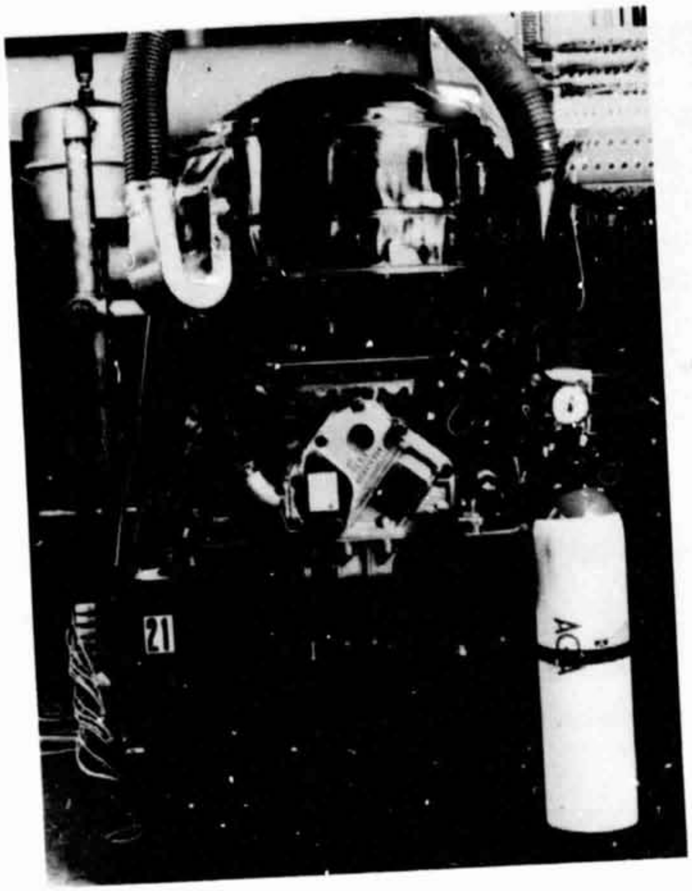

Fig3. 4-95 no 21, JPL engine in test rig.

PROGRAM SCHEDULES AND ACCOMPLISHMENTS

Under the JPL Program, procurement of components for the baseline 4-95 Stirling solar engine (number 21 in series) began September 1, 1980, with engine assembly later that month. Acceptance testing was to be done using a conventional fossil fuel combustion system and with the engine up-right rather than inverted. The program schedule is shown in figure 4.

The engine began its initial dynamometer "run-in" for checking out engine functions on November 13. The test included constant speed operation on helium at 1800 rpm and half load for about 11 hours. Following this, acceptance tests requiring about 12 hours were run between idle and full load (3 MPa to 15 MPa mean pressure) and between 600 and 4000 rpm, at 720 °C nominal tube temperature and 50 °C coolant temperature. Data logging include usual temperatures and pressures and all parameters required to determine power and thermal efficiency over the load and speed range. Final tests included control system measurements, requiring 8 hours.

During the acceptance and control tests, check out of data indicated higher than normal friction especially at the lower speeds. At the end of 31 hours the engine was disassembled for inspection. One cross head and its cylinder liner were found scuffed as the result of improper clearance and, possibly, lube oil contamination with machining residues from fabrication. After cleaning and replacing the parts, a second run-in test was made for 11 hours, followed by 6 hours of acceptance testing between 1000 and 4000 rpm, under all load conditions. Data indicated no further problems, and the tests were completed after a total of 48 hours running time on December 8th, ahead of schedule.

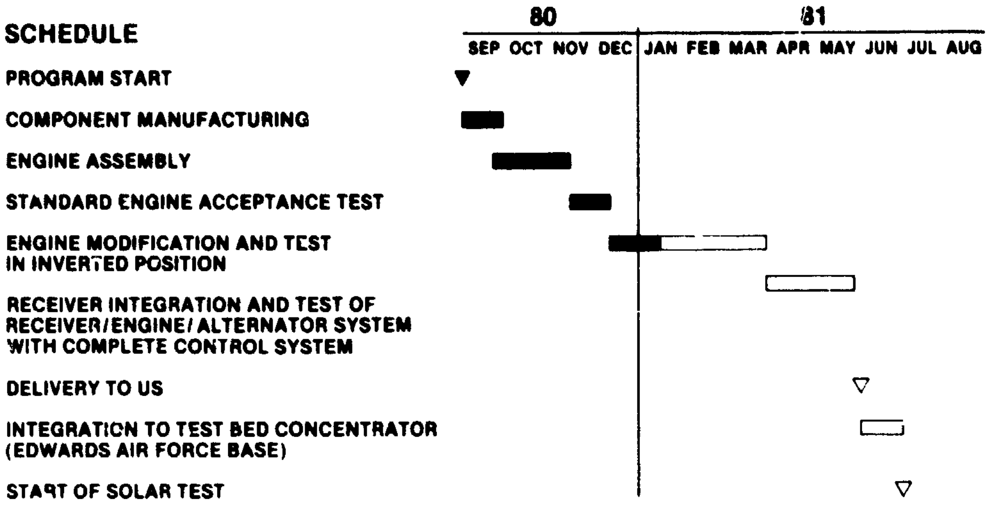

Fig4. Program schedule.

Results of testing engine 4-95-021 with a standard involute heater, figure 2, are presented in the curves, figure 5, 6. To summarize, it can be noted that the engine power at 1800 rpm ranges from 20 kW at 11 MPa to 27 kW at 15 MPa. Auxiliaries include the lube oil pump and the helium pump, which are the only ones to be engine driven at the Edwards Test Site. The water pump will be at ground level and is the responsibility of JPL.

TEST DATA — JPL ENGINE
SOLAR ENGINE PERFORMANCE

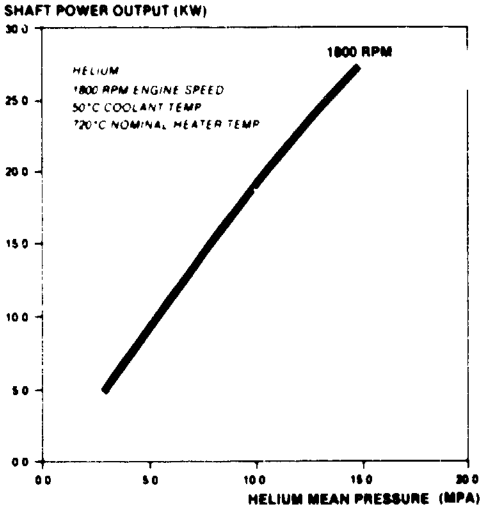

Fig5.
Acceptance test data- power.

TEST DATA — JPL ENGINE
SOLAR ENGINE PERFORMANCE

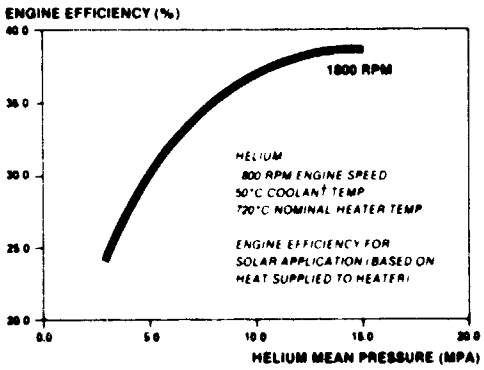

Fig6.
Acceptance test data- efficiency.

Engine thermal efficiency for solar applications is based on net heat into the heater, rather than on gross heat (from fuel) as in automotive applications. The net heat value is the result of 2 measurements -- the overall brake thermal efficiency and the so-called "furnace" or external heat system efficiency, η_b. The latter is equal to:

$$\eta_b = \frac{\dot{Q}_H \cdot (\dot{Q}_{eg} + \dot{Q}_{rad})}{Q_H}$$

$$\eta_{ST} = \frac{\eta_e}{\eta_b}$$

η_b = external heat system efficiency
$\dot{Q}_H$ = heat input from fuel and air
$\dot{Q}_{eg}$ = heat losses in exhaust gases
$\dot{Q}_{rad}$ = heat losses through radiation
η_e = overall brake thermal engine efficiency
η_{ST} = solar thermal efficiency

The difficulty lies in the accurate determination of the bracketed term, which is the result of measurements (temperatures in the exhaust gas and insulated spaces of combustor) and calculations. However, the end result is believed to be conservative. The curves in figure 6 show the solar thermal efficiency ranging from 37% at 11 MPa to 39% at 15 MPa, on helium. On hydrogen the efficiency at 15 MPa is estimated to be 41%.

The estimated performance with the Fairchild hybrid receiver installed, in place of the present involute heater, is shown in figure 7. The efficiencies are lower by about 2 percentage points because the heater tubes in the hybrid receiver are approximately 50% longer than for the standard heater, which casues higher internal flow losses.

Coolant Temp. 50°C **Mean pressure 15 MPa**	**Nominal outer tube wall temp.**			
	710°C		**810°C**	
	He	**H_2**	**He**	**H_2**
Max. power, kW	**24**	**26**	**27**	**28**
Max. efficiency, %	**36**	**38**	**40**	**41**

Fig7. Predicted engine performance in a solar application.

The next major task in the program includes a functional test of about 100 hours using the same engine and heating system combined with the 25 kW induction alternator (to be used in the final system), operating at 3 or more angles from 90° to completely inverted. Components are on hand and modifications to the lubricating system have been made for gravity drainage in all positions. A preliminary test of a mock-up of the crankcase, with external plumbing and oil sump, was made recently at Ricardo in England, who have been fabricating the 4-95 engine crankcases and drive units. Gravity drainage was found to be satisfactory at all angles (figure 8).

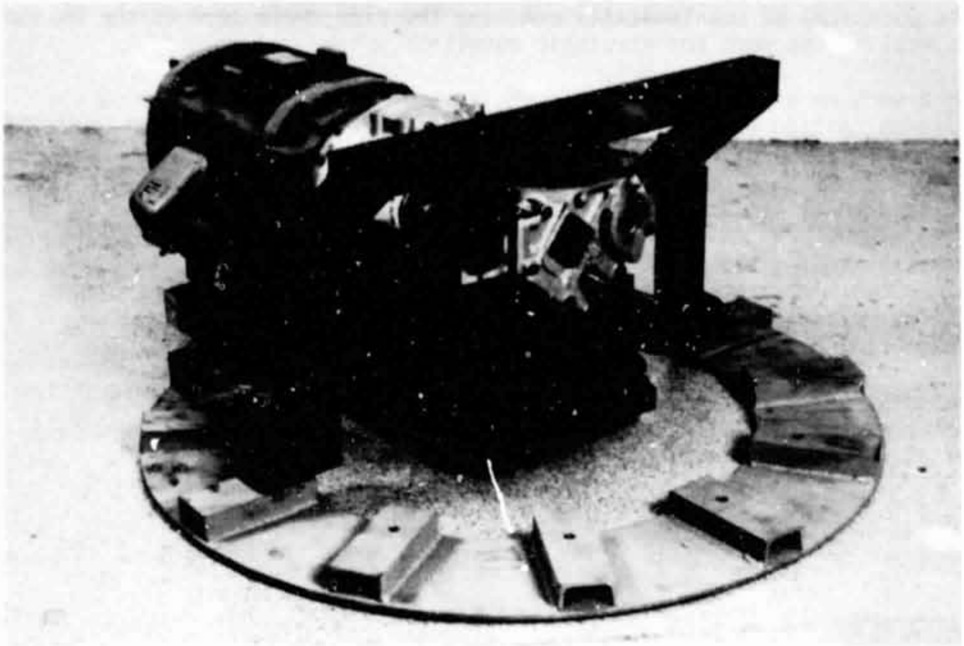

Fig8. Engine/alternator in mounting structure and TBC mounting ring (mock-up).

The new PL-seal unit has been tested in the inverted position in a separate test rig for 1500 hours. No oil was found to pass into the engine working spaces.

Numerous meetings between JPL, Fairchild and USS have been taking place during 1980 for coordination of the instrumentation and controls to interface with the new receiver and with the JPL test equipment at the Edwards Test Site.

The Fairchild receiver is scheduled for delivery to USS by March 1, 1981. Functional and performance testing of the receiver, integrated with the modified 4-95-21 engine, is scheduled for April and May, 1981. It will operate in the combustion mode only and at one inverted angle. The complete power package, including the modified engine equipped with the DSSR, alternator, controls and mounting structure, will be delivered to the TBC site at Edwards in late May, 1981.

FUTURE PLANS AND ADVANCED ENGINES

United Stirling has a continuing program for improvement of components and accessories for all engine designs. In particular, for solar designs, the extreme requirements for long unattended operation and time between overhaul, justifies further work to prolong the life of specific components, such as the piston rings. Progress is being made in this area. Present life of rings ranges from about 2500 to 4000 hours.

In addition, the introduction of the ceramic receiver/heater head has the potential of substantially reducing the life cycle cost of the engine, as well as the need for strategic materials.

At a working temperature of 1100 °C, ceramic components, such as a silicon carbide heater, will produce a 50% power increase and a thermal efficiency of about 49%.

In some solar applications a sodium cooled solar receiver will be advantageous, especially when thermal energy storage is included. The Stirling engine with a sodium heater head operates more efficiently since the heater tubes can be shorter and temperatures more uniform. Thermal efficiency increases about 3 percentages points in a sodium heated engine at the same nominal tube temperature.

Based on a relatively low-risk development program, United Stirling believes that for solar applications engine time between major overhauls of 30,000 hours is achievable.

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