N84 28243

Testing of the United Stirling 4-95 Solar Stirling Engine on Test Bed Concentrator

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Abstract:

Testing of the improved 4-95 solar Stirling engine in a parabolic dish system has been going on in Test Bed Concentrators at Edwards Air Force Base since May 1982. This paper presents the objectives with the testing, test set-ups and component designs and the results of the testing.

Different type of tests have been performed, among the most important have been characterization of receivers, full day performance of complete system, cavity and aperture window test including influence from windeffects, control system tests, radiator system tests and special temperature measurements with infrared camera.

The maximum output from the system — 24 kW module power output, 28% overall conversion efficiency solar to net electric — and the full day performance — 13.5 hours of operation generating over 250 kWh — shows the system capability. Other important results are the influence on performance of flux distribution depending on concentrator alignment, and the optimum receiver operating criteria when balancing flux and temperatures on cooled receiver surface while avoiding flux on uncooled surfaces.

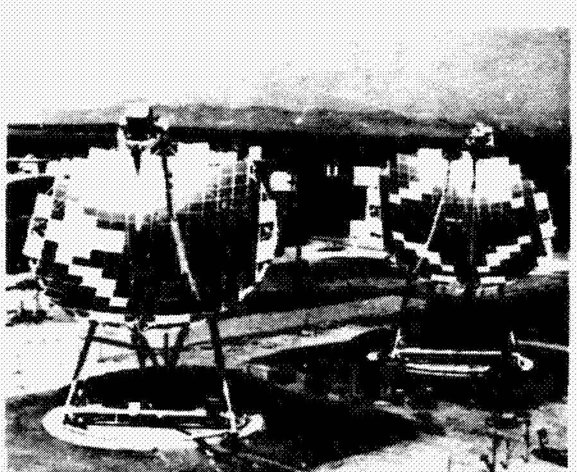

Fig 1 TBC's with Stirling Modules

Introduction

The testing of the solar Stirling engine in Test Bed Concentrator at Edwards Air Force Base started in early 1982 with the first version of engine with receiver system. An improvement of the engine followed as well as an improvement of the concentrator flux distribution and in May 1982 the testing of the new system started.

A second engine was installed in the second concentrator at Edwards Air Force Base in February 1983 and since then parallel testing of the two solar Stirling engines has been going on almost continuously. (Fig 1.)

The engine used in the testing has been the United Stirling model 4-95, the 4-cylinder double acting Stirling engine with a maximum output of 25 kW in solar application and compatible with an 11 m concentrator. The Stirling engines under testing have been integrated with other components, which are special for the solar application such as receiver system, generator, radiator and electrical and electronic controls.

Test sequence

The testing in the Test Bed Concentrator No 2 has aimed at the improvement of performance and the development of new components. The concentrator was first realigned to improve input characteristics. Special engine mounting as well as receiver cavity and cone were installed to establish optimum operating conditions. New components including receivers, cavities, aperture window and cone material were installed for development testing. Characterization of engine with these components during different operating conditions has been performed with different temperatures, different ambient conditions and also during different operating sequences such as start, stop, cloud passages, etc.

The testing in the Test Bed Concentrator No 1 has aimed at the installation of a complete, selfsustaining unit including engine, generator, radiator and control system, and to endurance test such a system (Fig 2.). Also characterization of the radiator system was to be performed.

Fig 2 Module with radiator system

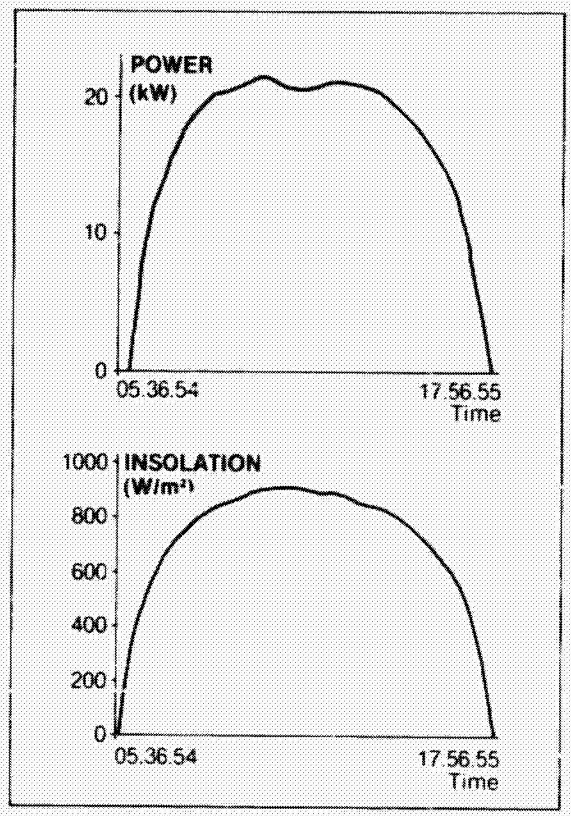

Fig 3 Insolation and power from a full day test

Test results

Module output

The present power conversion system has shown excellent performance. The module output is the highest so far for any parabolic dish system. The highlights are:

- 24 kW module output
- 28% overall conversion efficiency — solar to net electric
- 13.5 hours of operating with positive power output over a day
- generation of more than 250 kWh over a day

Figure 3 shows the output over a full day with corresponding solar input.

Of special interest is the mean daily efficiency for the system. The Stirling engine has a very high part load efficiency. For example already 1 hour after start, the system efficiency is very close to daily maximum, (Fig. 4). The mean daily efficiency is around 95% of the maximum.

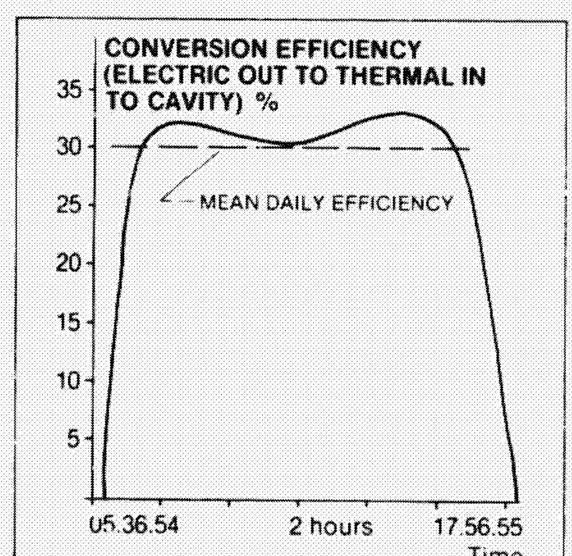

Fig 4 Mean daily output

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Flux distribution

The testing has so far been performed with two different aligments of the concentrator. The initial alignment strategy used a single focal point, giving heat flux to all areas in the cavity at nonuniform levels. The realignment strategy used was to allow insolation to fall only on cooled surfaces and to get as uniform distribution as possible. This improves overall performance for the power conversion unit. The basic improvement is the increase in cavity efficiency when limiting cavity wall temperatures. Figure 5 shows a comparison of performance with different flux distributions (March and June/July) for two receivers as well as for helium and hydrogen as working gases.

EDWARDS TEST DATA

RECEIVER TYPE	TIME	WORK GAS	INSOLATION (W/m^2)	EL OUTPUT (kW)	EFFICIENCY (%)
ESOR II A	March	He	915	19.5	28.4
ESOR II B	March	H_2	980	20.7	28.2
	March	He	973	19.5	26.7
ESOR II A	July	H_2	960	24.2	33.6
	July	He	906	20.7	30.5
ESOR II B	June	H_2	898	22.4	33.2
	June	He	922	20.6	30.0

Fig 5 Performance comparison at different flux distributions

Receiver performance

Three different receiver designs have been tested. Also testing at different distances from the focal point to vary the heat flux input, has been performed to optimize the operating conditions for the receiver.

The different receivers used have conflicting design criteria based on concentrator and engine requirements. The concentrator flux distribution calls for a wide diameter heater cage to achieve uniform, low flux levels on the tubes, but this results in excessive tube lenght which reduces engine performance. The engine calls for relatively short tube lenght which optimizes engine performance.

One receiver type has long tubes, wide diameter and the surface completely covered with tubes. Another receiver has the opposite, short tubes, small diameter, clearance between tubes. Both engines and cavity performance are involved in overall performance.

The third version of the receiver has a medium diameter, mean tube lenght and a surface nearly covered with tubes resulting in optimum receiver performance.

Varying the location of the receiver in relation to the focal point results in varying output if other parameter values are equal. The optimum output is, however, not the only parameter used in evaluation of optimum location. Flux and temperature distribution influencing component life should be involved in the evaluation.

Cavity, cone and aperture window tests

The cavity and cone are important components in the dish system (Fig 6). The performance of the cavity influences the overall system performance. Losses from cavity, both optical and thermal, depend very much on the design. For example a back up of insulation behind the receiver tubes improves performance and makes controlling more stable. Taking away the cone and cavity totally increases the losses to about twice the base cavity losses which are in the magnitude of 8 kW. Also an introduction of an aperture window can minimize the thermal losses by reducing convection currents. However, when introducing an aperture window, transmission losses are introduced. Depending on the magnitude of the two losses, the system can be optimized. The result from the testing with a flat quartz window shows a lower power output of up to 1 kW at full load. The result depends also on the temperature level used in the cavity system.

Wind direction and speed with respect to the open cavity can have an influence on the output power. When evaluating the two effects together, wind and transmission losses due to aperture window, actual testing has to be made to optimize the system. At present analythical methods are not accurate enough to permit selecting a final design without field testing.

Potential destruction of components in the focal area due to the high flux intensity also influences the design. During the short aperture window tests no damage of the window could be found. Also the cone material is critical when spot traverses the cone during slew off. Successful testing with cast silica has been performed and survival at full insolation under normal tracking was achieved. Lower grade material like ceramic board and Nextel Cloth cannot survive.

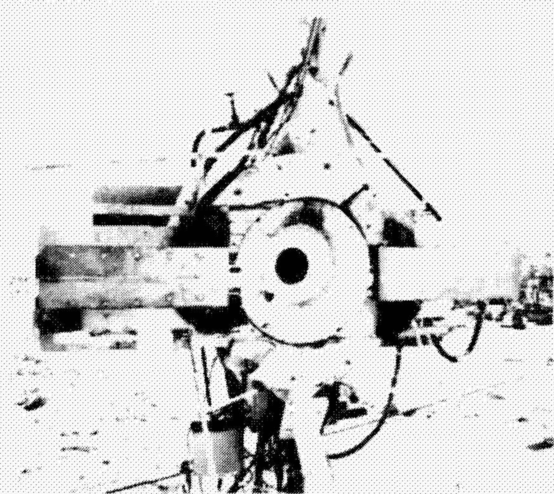

Fig 6 Aperture cone design

Radiator system tests

A complete radiator system installed up in focal mount has been tested. It was built up of 4 matrices in a square form, a radial fan and a waterpump. Performance at full load conditions resulted in a 20°C temperature difference between ambient and coolant temperature.

The parasitic power consumption ranges from 800 W to 1250 W for the fan and 200 W for the water pump. The fan motor has a low and a high power level, which permits the parasitic consumption to be minimized during all operating conditions.

Control system tests

The USAB microcomputer has been used for controling the module during all operating modes. The microcomputer allows an automatic operation. Numerous emphirical values of different parameters are included in the logics for optimized sequencing and operation. During the past year many tests have been performed to evaluate the control parameters and their optimum values. Figure 7 shows a transient curve corresponding to a start at fairly high insolation level. Shown are temperatures, pressure, speed and power output.

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Temperature measurement

Evaluation of all temperatures in the receiver system is very important, because the temperature level influences the receiver life and performance. The temperature varies somewhat over the heater surface and also around the tube itself, because of the solar input to the front face of the tube only. Temperatures have been measured with 40 thermocouples over the receiver and cavity.

Thermocouples however, cannot cover the entire surface and therefore are limited in measurement of temperature distribution. An infrared camera has been used, which gives information over all the receiver surface facing the sun, and testing can be made during normal operation. The most interesting results from the testing are:

- that no critical hot spots can be found on the receiver surface.
- that all tubes per quadrant show a uniform temperature at the same radial distance
- that the temperature distribution along the tube — warmer at the outer diameter — depends both on internal conditions (gas flow) and external conditions (heat-flux distribution)

Results are shown in figure 8.

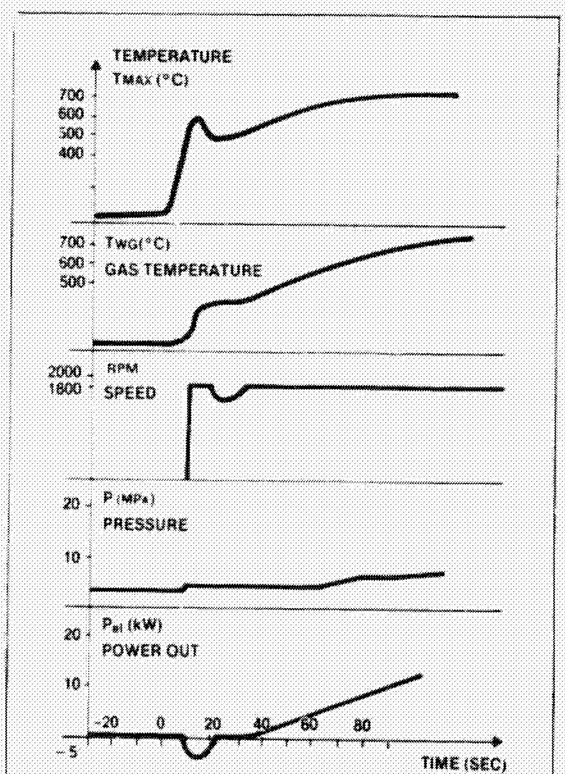

Fig 7 Transient — start time

Fig 8 Infrared camera picture of receiver with quadrants — Isotherm shown

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Conclusion

The testing at Edwards Air Force Base has been very succesful. Testing has been going continously, except during periods of bad weather. Unfortunately 1983 has been unusual in the respect, causing a severe loss in running hours.

The testing which started in March 1983 with Stirling engines in both concentrators was very impressive. It was the first time when two solar Stirling engines were in solar operation at the same time. (Fig 9).

We now have a much better understanding of solar parabolic dish system and the influence of different parameters. However, more testing is needed and it will continue at Edwards Air Force Base. This testing will include further development of receivers, shutters, cone and aperture window, control system and eventually endurance testing of an optimized system.

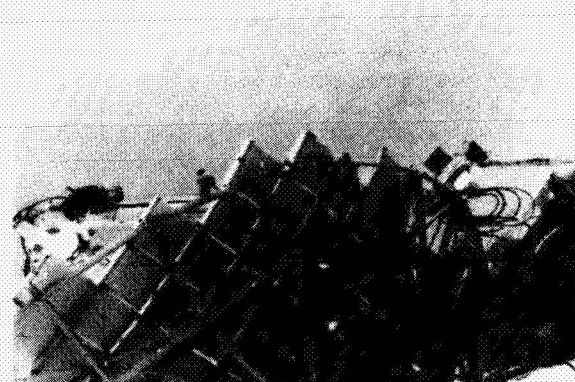

Fig 9 Two Stirling modules under testing

Future action

Additional testing will also go on in Palm Springs within the Vanguard project. This activity is als. ponsored by the US Department of Energy under a cost sharin., contract. This testing will be done with the second generation of Solar Stirling engines, the Mark II engine, figure 10. This new design had as objectives compared to the Mark I engine to reduce production cost, to increase reliability and to keep the performance level.

The development effort resulted in a simplified design including all experience from the Edwards testing as well as new inventions and development from laboratory testing. The most important new design solutions are:

- the oil system with only internal oilflow
- the build up of cold moving parts allowing accurate alignment of components resulting in improved reliability for seals and piston rings
- the design and material selection of receiver resulting in a cheap receiver with simplified fabrication and improved performance
- the special design of gas control system, guided by the installation of modules together in a farm using one hydrogen compressor and gas storage system including feed lines to each module in concentrators, instead of each module having its own compressor and gas storage and beeing a self-sustaining unit up in focal mount.

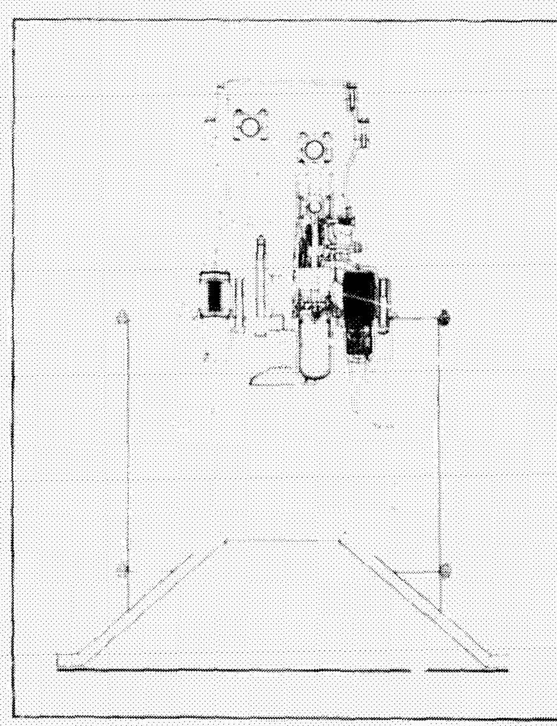

Fig 10 Mark II Cross-section

The Mark II engine has been fabricated and assembled and the first engine, intended for the Palm Springs installation, has been laboratory tested for about 200 operating hours (figure 11). The result from the testing shows a slightly better performance than for the Mark I engine. The Mark II engine has been converted for solar operation and assembled with radiator and solar control system, to a selfsustaining unit and is ready for continued solar testing in Palm Springs. (Figure 12).

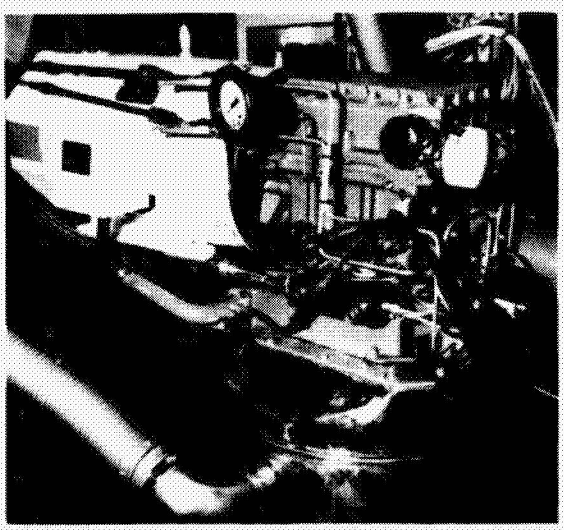

Fig 11 Mark II in test rig

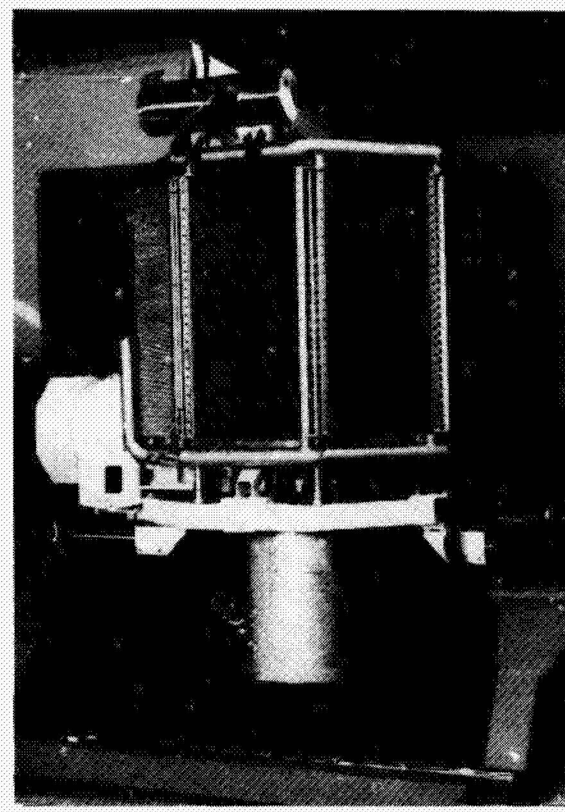

Fig 12 Mark II Solar module

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