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THE SCSE ORGANIC RANKINE ENGINE

by

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ABSTRACT

This paper describes the Organic Rankine Cycle (ORC) engine currently under development for the Small Community Solar Thermal Power Experiment (SCSE) for JPL/DOE under Contract 955637. This engine is the heart of a Power Conversion Subsystem (PCS) located at the focal point of a sun-tracking parabolic dish concentrator. The ORC engine employs a single-stage axial-flow turbine driving a high speed alternator to produce up to 25 kW electrical output at the focus of each dish. The organic working fluid is toluene, circulating in a closed-loop system at temperature up to 400°C (750°F).

Design parameters, system description, predicted performance and program status are described. The first SCSE Organic Rankine Power Conversion Subsystem will be delivered to the JPL/Edwards test site in May 1981.

INTRODUCTION

Under Phase II of the SCSE Program, FACC will develop a solar thermal, point focusing, distributed receiver, distributed generation system employing a small Rankine-cycle power conversion subsystem (PCS) mounted at the focus of a parabolic dish concentrator. This paper describes only the Rankine-cycle PCS. The overall system and the solar receiver (boiler) are addressed in companion papers by R. Pons and H. Haskins, respectively.

The PCS converts the thermal energy of superheated vapor from the receiver into shaft horsepower which drives a direct-coupled alternator at the focal point. This high frequency ac power is converted to dc by a ground-mounted rectifier, combined with the outputs from other dishes, then inverted to 60 Hz ac electrical power supplied directly to the utility grid.

The Rankine cycle was selected for the SCSE program on the basis of highest performance for least program risk (compared with other heat engine cycles). The organic Rankine cycle (ORC) engine was chosen over a steam Rankine engine on the basis of programmatic and technical factors. FACC has selected Barber-Nichols Engineering Company (B-N) of Arvada, Colorado, to design and build the PCS. B-N is currently in the hardware fabrication phase and assembly of the first unit is scheduled for completion next month.

SYSTEM DESCRIPTION

The power conversion subsystem is comprised of a very compact turbine-alternator-pump assembly, an air-cooled condenser, a regenerator, boost pump, start pump, various valves, plumbing and instrumentation. The PCS also includes certain ground-mounted electrical support equipment, such as the rectifier, overspeed brake controller, relays, etc.

Figure 1 is a cutaway view of the PCS configuration, shown attached to the FACC cavity-type receiver assembly. The cylindrical condenser shape results in an efficient PCS packaging arrangement about 1.1 m (44") dia x 1.5 m (60") long. The power conversion assembly shown in Figure 1 is designed to attach to the mounting rings of the General Electric Low Cost Concentrator (LCC) and provide minimum shadowing of the mirror surface. PCS weight at the focal point is about 322 Kg (710 lbs.).

A cutaway view of the turbine-alternator pump (TAP) assembly is shown in Figure 2. The TAP is an extremely compact device -- about the size of a football. It has one rotating shaft with the turbine wheel mounted at one end, the alternator rotor in the middle and the feed pump impeller at the other end. The shaft spins on hydrodynamic fluid-film bearings fed by toluene lubricant passages through the shaft itself. Salient features of the TAP are listed below.

TURBINE	ALTERNATOR
Single stage, axial flow	Permanent magnet (PMA) type
Full admission, 10 nozzles	Rotor: 6 Samarium Cobalt magnets
Inconel 718, 110 blades	Stator: 9-tooth, copper wound
Tip diameter 125 mm (4.92")	72 mm (2.8") OD x 127 mm (5.0")
Blade height 10.7 mm (0.42")	3 Ø, 3000 Hz AC at 60,000 rpm
Turbine efficiency 75%	95.0% peak efficiency

Turbine speed is nominally 60,000 rpm. It varies over a narrow range (55,000 to 60,000) as a function of input power. 60,000 rpm is not an excessive speed for turbomachinery (automotive turbochargers run twice as fast). It is this relatively high operating speed which makes the small TAP hardware size possible. As an example, the SCSE alternator is about one-twentieth the size and weight of more conventional generators associated with reciprocating-type heat engines. This turbine speed also allows the main feed pump to supply the full system flow at pressures up to 5.9 MPa (855 psi) with a centrifugal impeller only 33 mm (1.3") in diameter.

The condenser consists of 369 finned aluminum tubes in parallel, arranged in three concentric layers. Cooling air is drawn in axially by the two-speed fan and exhausted radially outward across the condenser tubes. This direction of air flow prevents stalling of the fan motor during high winds.

The regenerator is simply a heat exchanger designed to recover waste heat energy from the turbine exhaust vapor and use it to pre-heat the liquid before it enters the receiver (boiler), thereby enhancing overall system efficiency. The regenerator core is constructed of stainless steel tubing with aluminum fins. The liquid follows one continuous path (in the counterflow direction) through the finned tubing which makes 112 passes through the hot vapor flow.

The PCS is designed to operate at all solar-related elevation angles from 5° to 90° above the horizon. For this reason, the hotwell (liquid collection reservoir) is located at the low point of the PCS. The total working fluid inventory is about 15 litres (4 gal). The low pressure side of the system operates at sub-atmospheric pressure to optimize turbine performance, so a small electrically-driven centrifugal boost pump is used to provide a moderate positive pressure to feed liquid to the main pump and the bearings. The boost pump obtains liquid from the hotwell.

The temperature of the vapor at the exit of the solar receiver is maintained near a constant 399°C (750°F) by means of a vapor throttling control valve between the receiver outlet and the turbine inlet. The constant temperature can be maintained by controlling the mass flow rate of the working fluid to compensate for variations in solar flux vel. The vapor control valve is a pintle-type valve operated by a hydraulic actuator which is powered by high pressure working fluid. Valve command signals are keyed to temperature sensors at the receiver outlet.

Figure 3 is a simplified schematic diagram of the PCS showing the major components and the plumbing loop. The Remote Control Interface Assembly (RCIA) box shown in the figure is a FACC-designed controller/computer located near the base of each dish. Each RCIA communicates with a Master Power Controller (MPC) which performs central control and monitoring functions for a large array of SCSE power modules.

TOLUENE

The organic working fluid is reagent grade toluene ($C_6H_5CH_3$), a clear liquid similar to common paint thinner. The thermodynamic properties of toluene are ideally suited for use in small ORC turbines for solar applications. It yields high performance at relatively lower temperatures and pressures, compared to steam, and its freezing point is minus 95°C (minus 139°). Toluene is a fully characterized substance and its toxicity, flammability and other environmentally sensitive parameters are quite well known and safe handling procedures are well established.

For any given working fluid, efficiency increases with temperature; however, all organic fluids have an upper temperature limit beyond which they tend to decompose, evolve noncondensible gases, etc. Some existing toluene systems have operated at 427°C (800°F) and beyond, but 399°C (750°F) is planned as the upper limit for SCSE to promote long fluid life (years). The maximum temperature may be adjusted up or down as more experience is gained with the system. Adding 28°C (50°F) is worth about 1% gain in overall subsystem efficiency.

A few ORC systems in the field have experienced problems related to leakage, i.e., fluid degradation caused by air, moisture or oil contaminating the working fluid. For this reason, the SCSE system was designed as a hermetically sealed, closed-loop system to avoid the possible pitfalls associated with high speed shaft seals. Gearboxes, pipe threads, rust, etc. The PCS has no external moving seals. The toluene acts to lubricate all bearings.

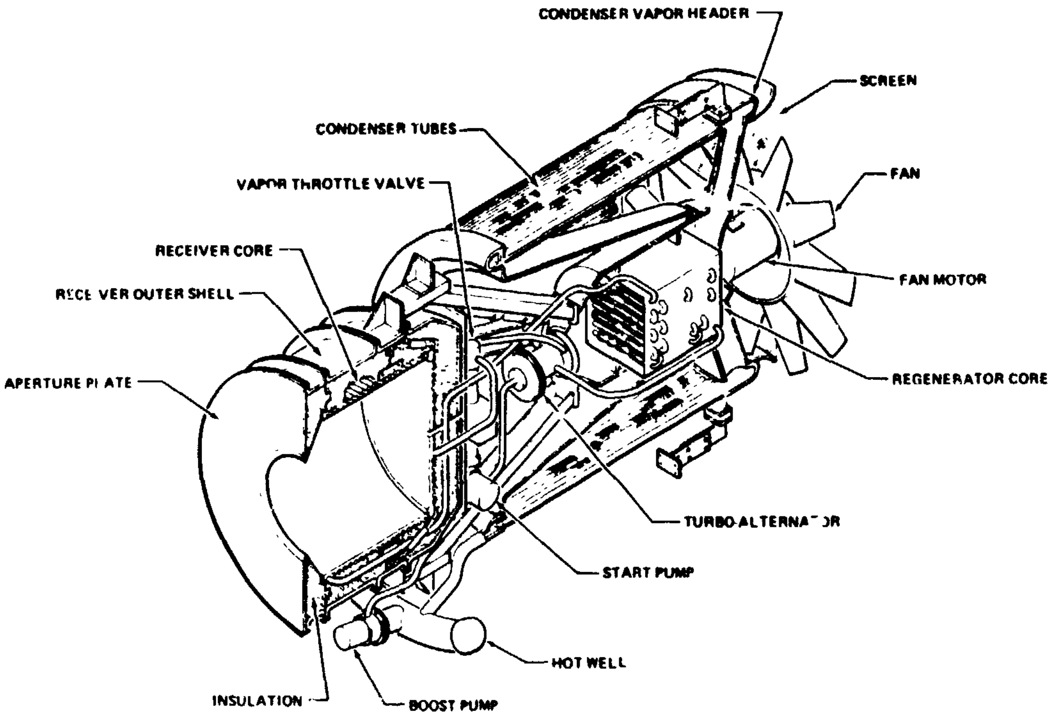

FIGURE 1. POWER CONVERSION ASSEMBLY

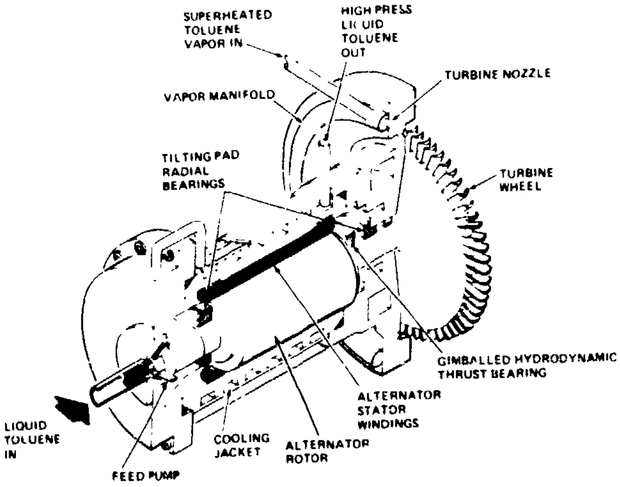

FIGURE 2. TURBINE-ALTERNATOR-PUMP (TAP)

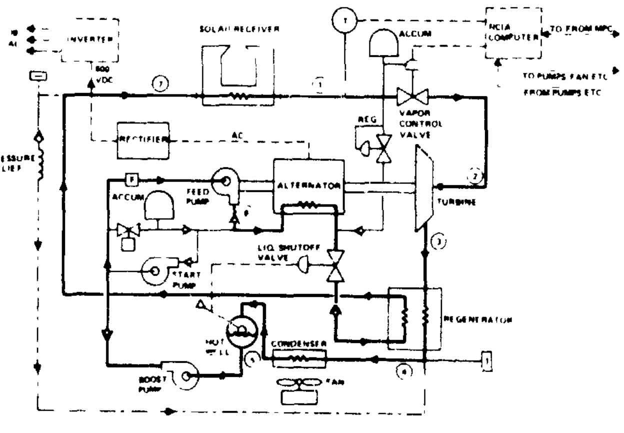

FIGURE 3. POWER CONVERSION SUBSYSTEM (PCA) SCHEMATIC

cool the alternator and pumps, and to operate the hydraulic actuator of the control valve (in addition to its primary function of powering the turbine).

PERFORMANCE

Electrical power output of the PCS is about 20 kW_e at rated conditions of 75.6 kW_t thermal input and 28°C (82°F) ambient air temperature. PCS output is about 25 kW_e at peak power conditions of 92.4 kW_t input.

Figure 4 shows PCS efficiency as a function of thermal input for various ambient temperatures. PCS efficiency is defined as the <u>net</u> dc electrical power out (accounting for parasitics) divided by thermal energy input from the receiver. Predicted efficiency at rated power is about 26 percent. Note the relatively flat shape of the curves, denoting high efficiencies across a very broad range of solar operating conditions. This excellent "part-load" characteristic helps maximize power output on an annualized basis and not just at a rated power point.

PROGRAM STATUS

Some PCS components are currently undergoing development testing at Barber-Nichols. B-N expects to complete assembly of the first deliverable unit in February, test it as a subsystem in March, test it combined with the FACC receiver and controller in April and ship it to the JPL test site in May of 1981.

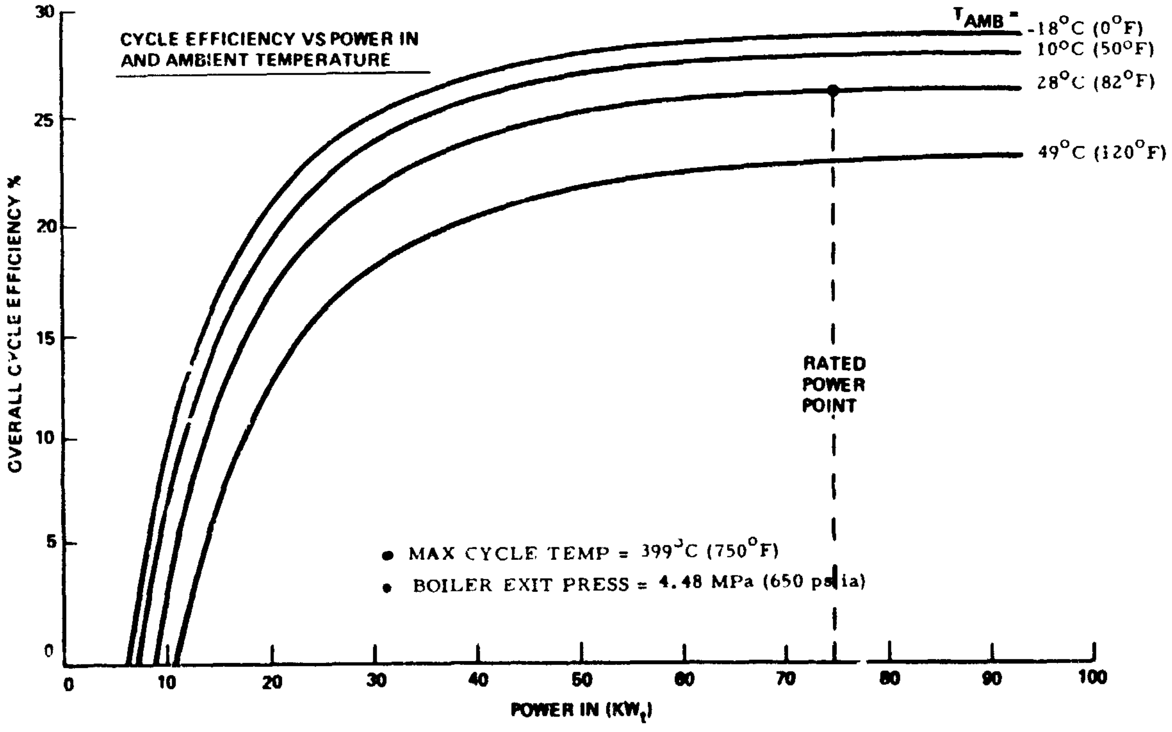

FIGURE 4. PCA PERFORMANCE