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THE SCSTPE ORGANIC RANKINE ENGINE

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ABSTRACT

This paper describes the Organic Rankine cycle (ORC) engine under consideration for the PFDR solar thermal system being developed for JPL/DOE by FACC under Contract 955637. Design parameters, method of control, performance and cost data are provided for engine power levels up to 80 kWe; efficiency is shown as a function of turbine inlet temperature in the range of 149°C (300°F) to 427°C (800°F).

INTRODUCTION

Under the SCSTPE Program, FACC will develop a solar thermal PFDR, distributed generation system employing small Rankine-cycle Power Conversion Units (PCUs) mounted at the focus of parabolic dish concentrators. The baseline PCU is comprised of an organic Rankine cycle (ORC) engine, high speed AC generator and a ground-mounted AC/DC converter (rectifier). The Rankine cycle was selected for the SCSTPE Program on the basis of highest performance for least program risk (compared with other heat engine cycles). The ORC engine was selected over a steam Rankine engine on the basis of programmatic and technical factors, although a steam system is currently under consideration for a parallel development effort.

The PCU has not yet been selected; proposals are currently being solicited from a number of engine manufacturers, including Sundstrand, Garrett/AiResearch, Barber-Nichols, Thermo-Electron and General Electric. During the Phase I Small Power Systems study, however, FACC contracted with Sundstrand to provide a preliminary high performance ORC design (Ref 1). The design is an outgrowth of Rankine engine studies carried out by Sundstrand for NASA (Ref 2); it currently serves as the baseline SCSTPE engine until final ORC engine selection and is described below.

SYSTEM DESCRIPTION

The prototype ORC engine is a regenerative, hermetically-sealed 22 kW_e unit with a single-stage axial-flow turbine; supercritical toluene is the working fluid, with a turbine inlet temperature (TIT) of 427°C (800°F) and a maximum system pressure of 4.52 MPa (656 psia). A high-speed, 4-pole homopolar inductor alternator is direct-coupled to the turbine and cooled by the working fluid; variable-frequency AC power is converted to DC output by means of the solid state rectifier. Figure 1

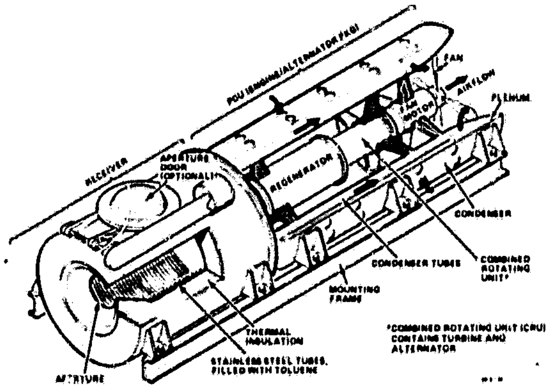

FIG. 1. ORC POWER CONVERSION ASSEMBLY

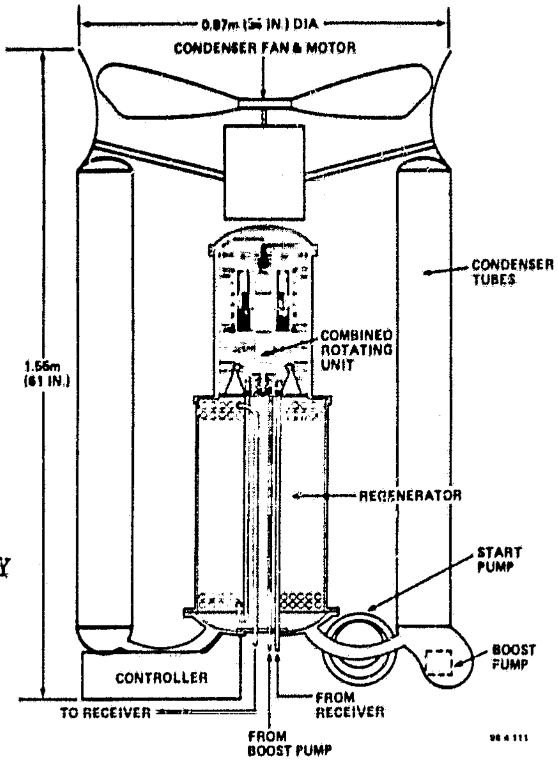

FIG. 2. BASELINE (22 KW_e) ORC POWER CONVERSION UNIT

is a cutaway view of the power conversion assembly, i.e., the PCU and the receiver*, showing the arrangement of the major engine components; the assembly is pallet-mounted for ease of installation/removal. A cross-section of the PCU is shown in Figure 2; the condenser is configured in a cylindrical shape surrounding the regenerator and the combined rotating unit (CRU), i.e., the hermetically-sealed turbine/alternator/feed pump components. This makes for a very compact PCU, measuring 0.87m (34 in.) in diameter by 1.55m (61 in.) in length. Forced draft cooling of the condenser is accomplished with an electrically-driven fan whose speed is varied (in 3 steps) as a function of cooling load and ambient air temperature to minimize parasitic losses. A dry-cooling arrangement was selected because of the lack of water in the high-insolation regions of the U.S. A PCU system schematic diagram is shown in Figure 3; note that the working fluid is used to cool the bearings and the controller as well as the alternator. The pertinent thermodynamic state points are identified on the figure and specified in Table 1. A pressure-enthalpy diagram for toluene is given in Figure 4,

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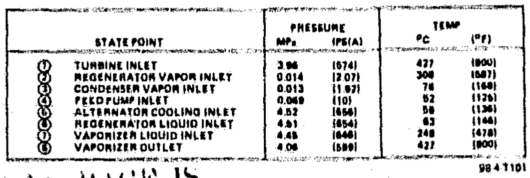
*The receiver shown is an alternate Garrett/AiResearch-designed unit of the direct-heated type, based on a steam receiver design currently under development for JPL/DOE; in the companion systems paper by Pons and Grigsby the baseline receiver is shown as the indirect-heated type, designed by FACC.

TABLE 1. PCU THERMODYNAMIC STATE POINTS

	STATE POINT	PRESSURE MPa	(PSIA)	TEMP. °C	(°F)
1	TURBINE INLET	3.96	(574)	427	(800)
2	REGENERATOR VAPOR INLET	0.014	(2.07)	308	(587)
3	CONDENSER VAPOR INLET	0.013	(1.92)	76	(168)
4	FEED PUMP INLET	0.069	(10)	52	(125)
5	ALTERNATOR COOLING INLET	4.52	(656)	58	(136)
6	REGENERATOR LIQUID INLET	4.5ı	(654)	63	(146)
7	VAPORIZER LIQUID INLET	4.45	(646)	248	(478)
8	VAPORIZER OUTLET	4.06	(589)	427	(800)



	STATE POINT	PRESSURE MPa	(PSIA)	TEMP °C	(°F)
①	TURBINE INLET	3.96	(574)	427	(800)
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⑦	VAPORIZER LIQUID INLET	4.45	(646)	248	(478)
⑧	VAPORIZER OUTLET	4.06	(589)	427	(800)

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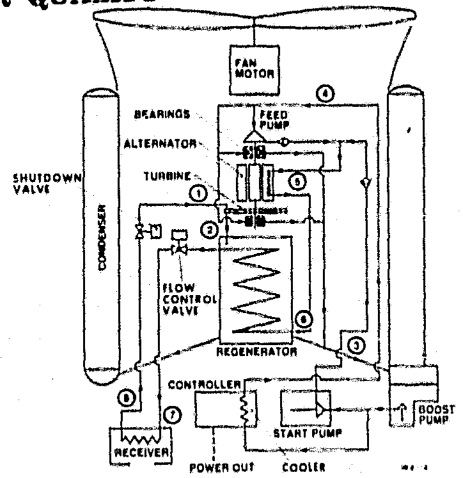

FIG. 3. BASELINE PCU SYSTEM SCHEMATIC

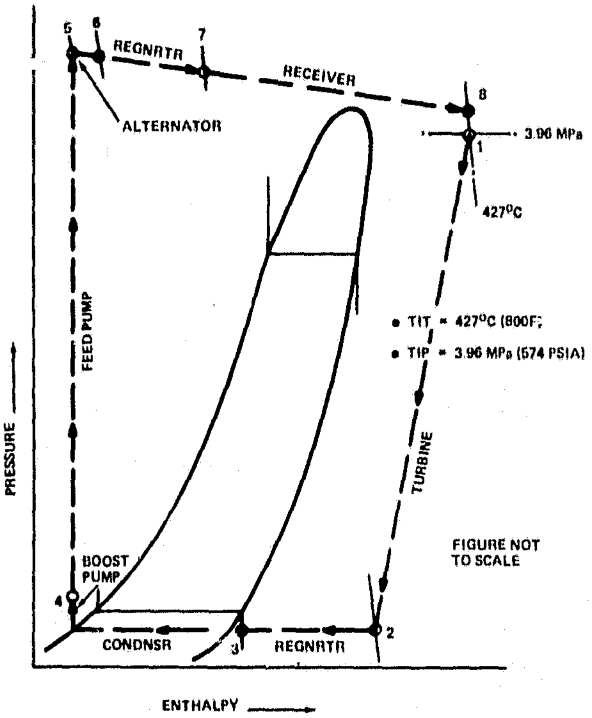

FIG. 4. PRESSURE-ENTHALPY DIAGRAM FOR TOLUENE SHOWING ORC STATEPOINTS

also showing the cycle operating path and the aforementioned state points. Gross weight of the PCU is estimated at 296 kg (653 lb); a weight breakdown of the 22 kW_e unit is given in Table 2.

TABLE 2. BASELINE (22 kW_e) PCU WEIGHT BREAKDOWN

	WEIGHT	
COMPONENT	kg	(lb)
CONDENSER	96	(16)
FAN/MOTOR	44	(212)
COMBINED ROTATING UNIT	85	(96)
REGENERATOR	17	(37)
START PUMP	16	(35)
ELECTRONIC CONTROLLER	9	(20)
FLUID (INVENTORY)	15	(33)
BOOST PUMP, VALVES, MISC	14	(32)
TOTAL	296	(653)

CONTROL

The PCU control scheme is designed both for stable operation under varying solar input and for high part-load efficiency, a highly desirable feature in a solar power system. As the solar input to the receiver varies, the turbine inlet temperature is held constant by varying the toluene flow rate; this is achieved by slaving an electro-mechanical flow control valve (which controls the output of the shaft-driven toluene feed pump) to a turbine inlet temperature sensor. In addition, a controller located at the power module provides turbine speed (and power) control by varying the alternator field excitation, thereby regulating output voltage and delivering variable amounts of power into the grid in direct proportion to the solar input. The local controller is under supervisory control by the plant central microprocessor, which contains command look-up functions to permit operation at the optimum turbine speed for each load value. As mentioned earlier, condenser fan speed is also varied with load (under central control) to maximize system efficiency.

PERFORMANCE

427°C (800°F) is generally considered to be the upper limit for operating with toluene and was picked as the baseline TIT to maximize PCU efficiency and reduce overall system energy cost. At the (rated) ambient temperature of 27°C (80°F), overall PCU efficiency, i.e., from thermal input to DC electrical output, is 28.5%. In consideration of the possibility of toluene breakdown at elevated temperature, PCU performance was also determined for lower values of TIT; Table 3 summarizes design point characteristics for TIT values of 371°C (700°F) and 399°C (750°F) as well as for the baseline design. Note that the penalty for operation at 371°C is two points in efficiency, i.e., 26.5% compared with 28.5% baseline value; as shown in the companion systems paper by Pons and Grigsby, this corresponds to about a 7% increase in (operational) system energy cost. Operation at reduced temperature may, of course, not be necessary. For example, it is projected that the rate of toluene degradation will actually be quite low, since the bulk of the inventory is not at peak temperature most of time. Sundstrand estimates that the toluene will have to be changed only about every 30,000 hours, or about twice in the 30 year life of the solar plant. Note further that

TABLE 3. PCU DESIGN POINT CHARACTERISTICS

PARAMETER		371°C (700 F)	399°C (750 F)	427°C (800 F)
DC POWER OUT	kW	22	22	22
THERMAL POWER IN	kW	83	79.7	77.2
PCU EFFICIENCY*	%	26.5	27.6	28.5
FAN POWER	kW	1.7	1.8	1.9
PARASITIC POWER**	kW	0.12	0.12	0.12
RECTIFIER EFF'Y	%	97	97	97
ALTERNATOR EFF'Y	%	92	92	92
PUMP EFF'Y	%	54	53	52
TURBINE EFF'Y	%	74	73	73
REGENERATOR EFFY	%	95	95	95
BEARING LOSSES	kW	0.1	0.1	0.1
FLUID FLOW RATE	kg/hr	519	494	461
	(lb/hr)	(1144)	(1090)	(1021)

*TO DC OUTPUT

**INCLUDES CONTROLS AND BOOST PUMP

the use of a hermetic-sealed system minimizes oxide formation and attendant scale deposition on the plumbing. Figure 5 shows the general trend in efficiency for small (20-50 kW_e) ORC power conversion units, over the range $300^oF < TIT < 800^oF$.

Figure 6 shows the effect of engine size on PCU efficiency for the specified three values of TIT. There is a substantial drop in efficiency below about 20 kW_e. Figure 7 shows the efficiency of the 22 kW_e PCU as a function of thermal input and ambient air temperature. Note the excellent part-load performance, which is the major reason for the system's high annual capacity factor (ACF = 0.418) at the Barstow, CA site.

COST

For system economic projections, both capital and maintenance costs for the PCU are essential inputs. Figure 8 is an estimate of these PCU costs over the power output range of 5 to 80 kW_e, based on annual production rates of 100,000 units/year. At this stage in the development of the system, however, there is considerable uncertainty over the accuracy of these data; a possible error of ±40% is not an unreasonable assumption at the present time.

CONCLUSIONS

A carefully-designed ORC power conversion unit can achieve good efficiency at relatively low temperature, i.e., compared with Brayton, Stirling or steam Rankine cycle engines. The low temperature assures high solar collection efficiency (which contributes to high overall system efficiency), lower risk and lower cost, since less critical materials and lower-stress equipment designs can be used.

Many thousands of operating hours exist on ORC systems/components, albeit at different sizes than for the components of the baseline system. Nevertheless, the ORC-PCU should be considered a state-of-the-art device. In addition, 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.

REFERENCES

1) Anon, "Phase I of the First (Solar) Small Power System Experiment (Experimental System No. 1)" Final Report, No. V-6529, Ford Aerospace & Communications Corp., Aeronutronic Division, Newport Beach, CA, 5 May 1979.

2) Bland, T., "15 kW_e (Nominal) Solar Thermal Electric Power Conversion Concept Definition Study - Steam Rankine Turbine System," Sundstrand Corp., Report DOE/NASA/0061-79/1, NASA CR-159589, AER 1713.

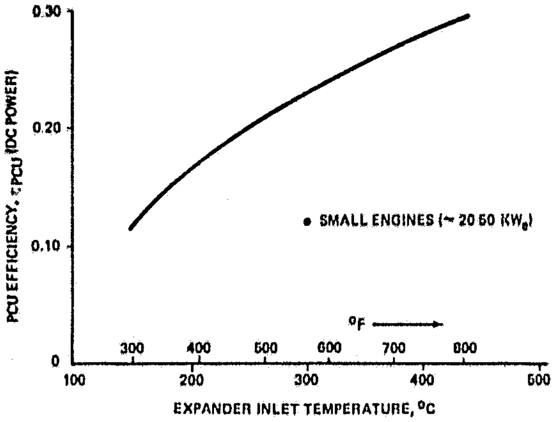

FIG. 5. INFLUENCE OF TEMPERATURE ON ORC POWER CONVERSION UNIT EFFICIENCY

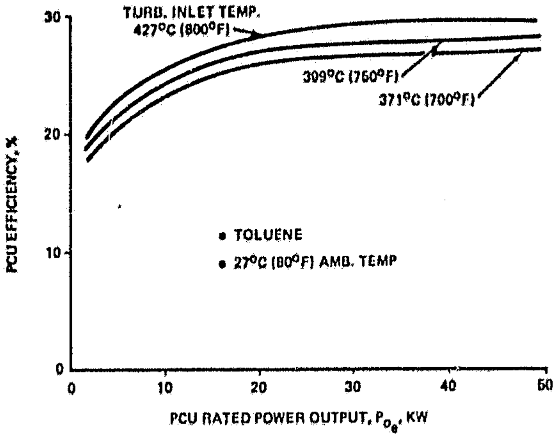

FIG. 6. EFFECT OF ENGINE SIZE ON PCU EFFICIENCY

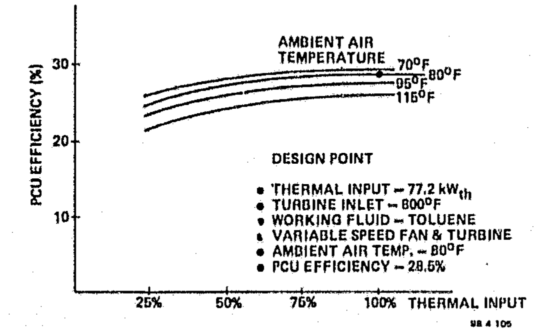

FIG. 7. PCU PART LOAD PERFORMANCE

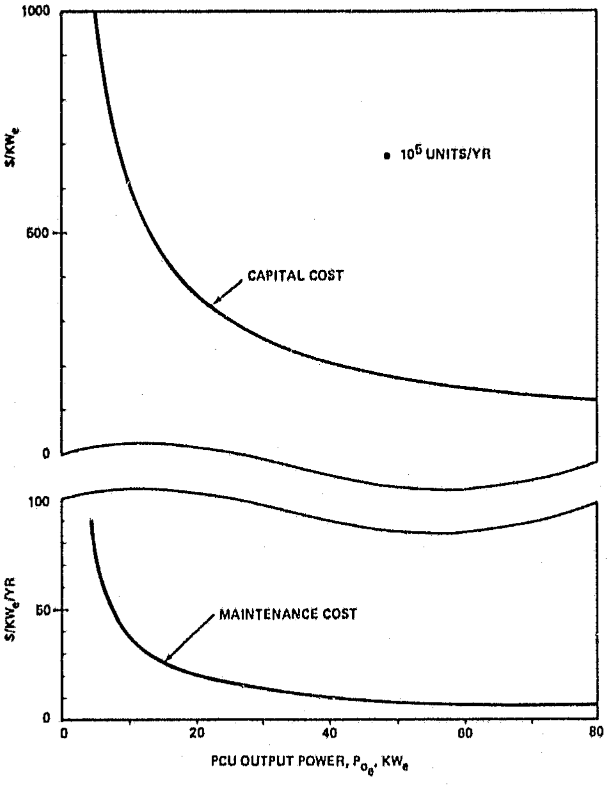

FIG. 8. PROJECTED PCU COSTS