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Selection of Working Fluid for an Organic Rankine Cycle Based Concentrating Solar Thermal Power Plant

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Line-focusing concentrating solar collectors such as parabolic trough collector (PTC) and linear Fresnel reflector (LFR) may be employed for power generation through organic Rankine cycle (ORC). Dry fluids are the most preferred working fluids for an ORC. It offers higher thermodynamic efficiency and better part load performance compared to steam Rankine cycle (SRC) up to medium scale applications with medium temperature heat sources. In this paper, thermo-economic comparisons between SRC and ORC based concentrating solar power (CSP) plants are presented. An approximate methodology for these power generating cycles is proposed to generate selection diagram. Selection diagram helps in selecting appropriate power generating cycle and corresponding working fluid, for the CSP plant.

1. Introduction

With growing energy demand and green-house gas emissions, the worldwide interest for medium grade heat recovery, using modular organic Rankine cycle (ORC) based power plant, has increased significantly (Mavrou et al., 2014). Small scale power plants (less than 2 MWe), based on conventional steam Rankine cycle (SRC), have much lower efficiency. SRC needs higher temperature and higher plant capacity to be economical (Desai and Bandyopadhyay, 2015a). In case of an ORC with dry working fluids, the state point after expansion in the turbine lies in the superheated vapor region, resulting more efficient turbines for modular plants with medium temperature heat sources (Hung et al., 1997). The use of an appropriate dry organic fluid improves turbine isentropic efficiency at design condition (up to 90 %) and part-load characteristics, eliminates the problem of turbine blades erosion, reduces mechanical stress, and improves turbine life (Algieri and Morrone, 2012). The basic ORC can be modified by incorporating both regeneration and turbine bleeding to improve its thermal efficiency (Desai and Bandyopadhyay, 2009). ORC has been used as a power generating cycle for heat sources like, biomass, waste heat, geothermal, solar thermal, etc. (Quoilin et al., 2013). Currently, there is one parabolic trough collector (PTC) based CSP plant (in MW range) with n-Pentane as working fluid (Quoilin et al., 2013). Analysis of a parabolic trough collector (PTC) based concentrating solar power (CSP) plant using ORC have been reported in the literature (He et al., 2012).

Several studies on working fluid selection for the ORC have been reported. Working fluids should have low ozone depletion and global warming potentials, low toxicity and freezing point, high flash point, low cost, good material compatibility and fluid stability limits (Rayegan and Tao, 2011). Thermodynamic properties of various working fluids affect the system efficiency and economic viability of the ORC. High vaporization and low condensation latent heat, high critical temperature, and low liquid specific heat of the working fluid have positive impact on thermodynamic efficiency of the cycle (Bao and Zhao, 2013). Fluids with low vapor density have higher volume flow rate, resulting in higher pressure drops in the heat exchangers and the size of expander also increases (Bao and Zhao, 2013). Macchi and Perdichizzi (1981) reported that the turbine size parameter (SP), a function of volumetric flow rate at the turbine outlet and isentropic enthalpy change in turbine, represents size and cost of the ORC turbine.

In case of an ORC, the improved design point and part-load characteristics of the turbine results in lower collector aperture area requirement, compared to modular scale SRC based CSP plants of same capacity. On the other hand, the cost of power block for ORC is higher compared to the SRC power block. In this paper, the thermo-economic comparisons between SRC and ORC based CSP plants are presented. The best possible

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way for power generating cycle selection (between SRC and ORC) is based on the condition of equality of levelized cost of energy (LCOE). An approximate, but simple methodology and approximate selection diagram for these power generating cycles based CSP plants are proposed. ORC with different working fluids is also compared with SRC using this selection diagram. The applicability of the proposed methodology is demonstrated through illustrative case studies of PTC and LFR based CSP plants with SRC and ORC.

2. CSP plants using ORC

Line-focusing concentrating solar systems (PTC and LFR) are capable of giving temperature up to 400 °C and ORC can be used as a power generating cycle in CSP plants with these systems.

2.1 PTC based CSP plant using ORC

Simplified schematic of a PTC based CSP plant using regenerative ORC is shown in Figure 1(a). Solar radiation incident on the PTC field is used to generate high temperature HTF (from state 1P to state 2P). The evaporator produces high temperature and high pressure organic fluid vapor (from state 4a to state 5) using high temperature HTF from the PTC field. It may be noted that the condition of organic fluid at the inlet of the turbine may be saturated or superheated for dry fluids. High temperature and high pressure organic fluid vapor is expanded through an organic turbine to generate power. The HTF coming out of the evaporator (state 3P) is re-circulated back to the PTC field. The heat from high temperature fluid vapor (in case of dry fluids) at the turbine outlet is transferred (from state 6 to state 6a) to the evaporator feed (from state 4 to state 4a) using a regenerator. Finally, the organic fluid vapor coming out of the regenerator is condensed in the condenser (from state 6a to state 7).

2.2 LFR based CSP plant using ORC

Simplified schematic of a LFR based CSP plant using regenerative ORC is shown in Figure 2. The organic liquid (at state 1L) directly enters into LFR field and at the outlet of LFR field a two-phase mixture (state 2L) is obtained. The mixture enters into a separator, where saturated organic fluid vapor (at state 5) is directed towards the turbine to generate power. The liquid organic fluid coming out of the separator (at state 3L) is re-circulated back into the LFR field using Pump-I. The other state points are same as explained earlier. It may be noted that superheating of working fluid is typically avoided in LFR field.

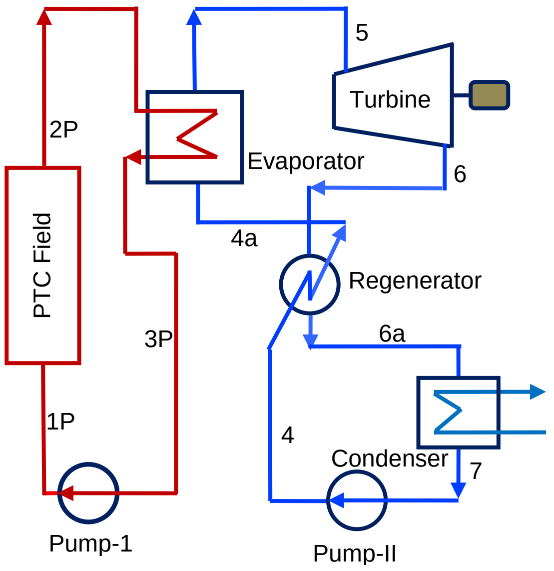

Figure 1: Simplified schematic of a PTC based CSP plant using regenerative ORC.

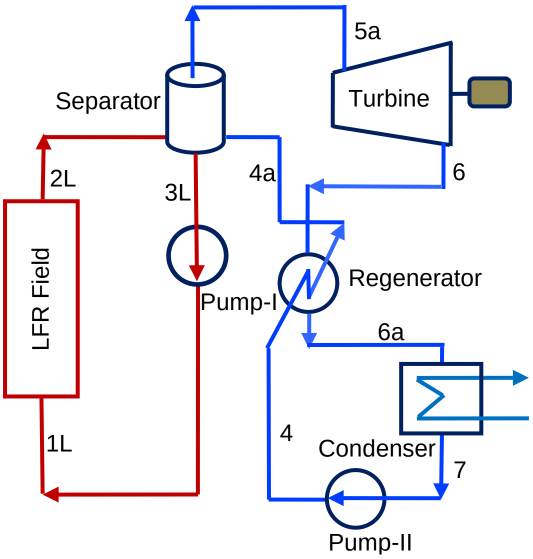

Figure 2: Simplified schematic of a LFR based CSP plant using regenerative ORC.

2.3 Approximate thermo-economic analysis

The condition when levelized costs of energy for SRC and ORC based plants are equal, is written as:

$$\mathrm{LCOE_{ORC}} = \mathrm{LCOE_{SRC}} \tag{1}$$

$$\frac{C_{\mathrm{CL}} \times A_{p,\mathrm{ORC}} \times \mathrm{CRF} + \beta_{0,\mathrm{ORC}} \times \mathrm{CRF} + \beta_{1,\mathrm{ORC}} \times \mathrm{CRF} + \beta_{2,\mathrm{ORC}}}{E_{\mathrm{ORC}}} = \frac{C_{\mathrm{CL}} \times A_{p,\mathrm{SRC}} \times \mathrm{CRF} + \beta_{0,\mathrm{SRC}} \times \mathrm{CRF} + \beta_{1,\mathrm{SRC}} \times \mathrm{CRF} + \beta_{2,\mathrm{SRC}}}{E_{\mathrm{SRC}}} \tag{2}$$

$$\mathrm{CRF} = \frac{d \times (1+d)^{n}}{(1+d)^{n} - 1} \tag{3}$$

where C_{CL} is specific collector field investment cost (\$/m^2), β_0 is power block cost (\$), β_1 is balance of plant cost (\$), β_2 is annual O&M cost (\$/y), A_p is aperture area of collector field (m^2), E is annual generation (kWh/y), CRF is capital recovery factor, d is discount rate**,** and n is lifetime (y). It may be noted that the solar field and power block are the most expensive components of CSP plants and that has a significant impact on the overall cost as well as LCOE. Therefore, Eq(2) can be simplified using the following assumption,

$$\frac{\beta_{1,\mathrm{SRC}} \times \mathrm{CRF} + \beta_{2,\mathrm{SRC}}}{E_{\mathrm{SRC}}} \approx \frac{\beta_{1,\mathrm{ORC}} \times \mathrm{CRF} + \beta_{2,\mathrm{ORC}}}{E_{\mathrm{ORC}}} \tag{4}$$

Based on this assumption (Eq 4), Eq(2) may be simplified as,

$$\frac{C_{\mathrm{CL}} \times A_{p,\mathrm{ORC}}}{E_{\mathrm{ORC}}} + \frac{\beta_{0,\mathrm{ORC}}}{E_{\mathrm{ORC}}} = \frac{C_{\mathrm{CL}} \times A_{p,\mathrm{SRC}}}{E_{\mathrm{SRC}}} + \frac{\beta_{0,\mathrm{SRC}}}{E_{\mathrm{SRC}}} \tag{5}$$

Aperture area of the collector field is expressed as (Desai and Bandyopadhyay, 2015b):

$$A_p = \frac{P_D \cdot \Delta h}{\Delta_{\mathrm{CL}} \cdot \Delta h_{is} \cdot \eta_{is,D}} = \frac{P_D}{\Delta_{\mathrm{CL}} \cdot \eta_{cycle}} \tag{6}$$

$$\Delta_{\mathrm{CL}} = \left(\eta_o \cdot I_D - U_l \cdot \Delta T\right)_{\mathrm{CL}} \text{ and } \eta_{cycle} = \left(\frac{\Delta h_{is}}{\Delta h}\right) \cdot \eta_{is,D} \tag{7}$$

where η_o is optical efficiency of collector field, U_l is heat loss co-efficient based on aperture area of collector field (W/(m^2·K)), P_D is design power output (W), Δh_{is} is isentropic enthalpy change in turbine (J/kg), Δh is specific heat input to power generating cycle (J/kg), $\eta_{is,D}$ is isentropic efficiency of turbine at design condition, η_{cycle} is thermal efficiency of a power generating cycle (pumping work is neglected). I_D is aperture effective design radiation (W/m^2) and can be expressed as product of direct normal irradiance (DNI) and incidence angle modifier (IAM). ΔT is difference between T_m, mean temperature of collector field (°C) and T_a, ambient temperature (°C). Desai et al. (2014) proposed a methodology to determine thermodynamically and cost optimum design radiation for CSP plants. Design radiation for ORC based plant is expected to be slightly higher than the SRC based plants due to better part-load efficiency of the ORCs, resulting in lower aperture area requirement compared to SRC based plants of same capacity. Furthermore, using Eq(6), Eq(5) can be expressed as:

$$\left(\left(\frac{C}{\Delta}\right)_{\mathrm{CL}} \cdot \left(\frac{1}{\eta_{cycle}}\right) + \frac{\beta_0}{P_D}\right)_{\mathrm{ORC}} = \frac{E_{\mathrm{ORC}}}{E_{\mathrm{SRC}}} \cdot \left(\left(\frac{C}{\Delta}\right)_{\mathrm{CL}} \cdot \left(\frac{1}{\eta_{cycle}}\right) + \frac{\beta_0}{P_D}\right)_{\mathrm{SRC}} \tag{8}$$

$$\left(\frac{1}{\eta_{cycle}} + \left(\frac{\Delta}{C}\right)_{\mathrm{CL}} \cdot \left(\frac{\beta_0}{P_D}\right)\right)_{\mathrm{ORC}} = \frac{\left(\Delta_{\mathrm{CL}} \cdot E\right)_{\mathrm{ORC}}}{\left(\Delta_{\mathrm{CL}} \cdot E\right)_{\mathrm{SRC}}} \cdot \left(\frac{1}{\eta_{cycle}} + \left(\frac{\Delta}{C}\right)_{\mathrm{CL}} \cdot \left(\frac{\beta_0}{P_D}\right)\right)_{\mathrm{SRC}} \tag{9}$$

Eq(9) gives the condition of equality of the levelized costs for CSP plants with SRC and ORC.

3. Selection Diagram

Selection diagram captures the variations of power generating cycle efficiency, and costs of power block and collector field (\$/W), which are the important parameters that influences the choice of power generating cycle for a CSP plant. Figure 3 shows the selection diagram for SRC and ORC, generated for PTC based CSP plant using the data given in Tables 1–3. Thermodynamic properties of different dry organic fluids are calculated using the Refprop (Lemmon et al., 2002) and Coolprop (for Octamethyltrisiloxane) software (Bell et al., 2015).

DNI data are taken for Jodhpur, India. Line representing the condition of equality of the levelized costs for a SRC based and an ORC based CSP plant is shown in Figure 3. Right side of the line indicates that the optimal configuration of a CSP plant having ORC. Optimal configuration of a CSP plant with SRC lies on the left side of the separating line. It may be observed that there is no significant change in the optimum regions with different working fluids for ORC.

Table 1: Thermodynamic properties of different working fluids used in the analysis

Working Fluid	P_{crit} (MPa)	T_{crit} (°C)	P_{eva} (MPa)	T_{eva} (°C)	P_{cond} (MPa)	T_{cond} (°C)	PTC based CSP plant			LFR based CSP plant		
							VFR (v_6/v_5)	SP (m)	η_{cycle} (%)	VFR (v_6/v_5)	SP (m)	η_{cycle} (%)
Toluene	4.126	318.6	3.154	297	0.0099	45	362.8	0.2113	32.24	465.6	0.2214	29.21
Octamethyl-trisiloxane	1.415	290.9	0.882	260	0.005	66.6	214.6	0.409	26.3	258	0.4238	24.34
Cyclohexane	4.075	280.5	3.229	262	0.03	45	127.4	0.1413	30.1	172.9	0.1498	26.75
Heptane	2.736	267	2.087	248	0.0153	45	164.5	0.1995	28.86	219	0.2096	26.07
Benzene	4.894	288.9	3.583	264	0.0298	45	128.3	0.1366	29.34	154.8	0.1436	26.21
Hexane	3.034	234.7	2.308	216	0.0451	45	60.5	0.1352	26.06	78.9	0.1433	23.08
Isohexane	3.04	224.6	2.308	206	0.0608	45	45.5	0.1246	25.15	59.3	0.1323	22.19
R113	3.392	214.1	2.839	202	0.0929	45	34.8	0.1292	24.17	46.7	0.1393	20.8
Pentane	3.37	196.6	2.45	176	0.1361	45	20.8	0.0967	21.97	26.1	0.1035	18.96
Water	22.06	373.9	4.0	250	0.0096	45	214.3	0.1472	22.71	282.2	0.1944	15.27

Table 2: Data used for the analysis of PTC and LFR based CSP plants

Input Parameter	PTC based CSP plant	LFR based CSP plant
Collector field efficiency model parameters	η_o = 0.7; U_l = 0.1 W/(m^2·K)	η_o = 0.65; U_l = 0.1 W/(m^2·K)
Collector tracking mode	Focal axis N-S horizontal and E-W tracking	Focal axis N-S horizontal and E-W tracking
IAM effect	Euro Trough design (Schenk et al. 2014)	Novatech design (Schenk et al. 2014)
Collector field and HTF system cost, C_{CL} (\$/m^2)	280	167
Heat transfer fluid	Therminol VP-1	Water/Organic fluids
Superheating at turbine inlet condition (ΔT_{sup})	40 °C for ORC, 100 °C for SRC	0 °C
Collector outlet temperature (T_{2P})	T_{eva} + ΔT_{sup} + 40 °C	T_{eva}
Ambient temperature (T_a)	30 °C (design value)	30 °C (design value)
Plant capacity (P_D)	1 MWe	1 MWe
Auxiliary consumption	10 % of gross power output	10 % of gross power output
Temperature driving force (ΔT_{min})	For heat exchanger and regenerator = 10 °C; For condenser = 5 °C	For regenerator = 10 °C; For condenser = 5 °C
Isentropic efficiency of pump	0.6	0.6

Table 3: Data used for the analysis of SRC and ORC based CSP plants

Input Parameter	SRC	ORC
Power block cost (β_0/P_D)	900 \$/kW	n-Pentane:1,800 \$/kW; OMTS: 2,300 \$/kW
Isentropic efficiency of the turbine at design ($\eta_{is,D}$)	Superheated turbine: 0.65; Saturated turbine: 0.45	0.77
Turn down ratio of turbine (P_{min}/P_{max})	0.2	0.1
Willans' line equation: Turbine power output (P) = $a + b \cdot m$	$a = -y \cdot P_D$; y = 0.2; $b = (1+y) \cdot \Delta h_{is} \cdot \eta_{is,D}$	$a = -y \cdot P_D$; y = 0.1; $b = (1+y) \cdot \Delta h_{is} \cdot \eta_{is,D}$ (Desai et al., 2014)

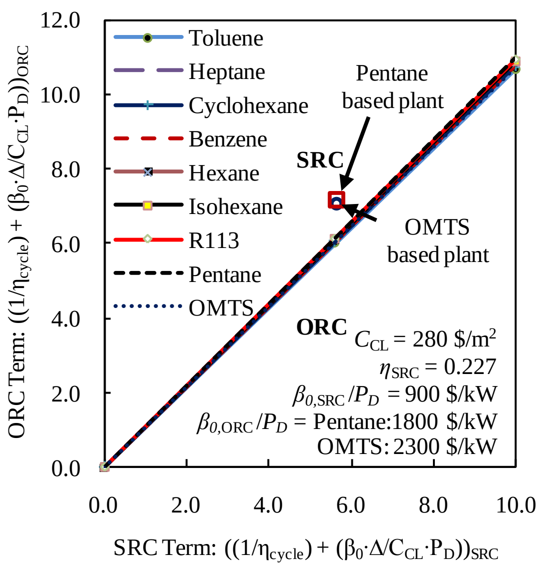

Figure 3: Selection diagram for SRC and ORC based plants (PTC based CSP plant).

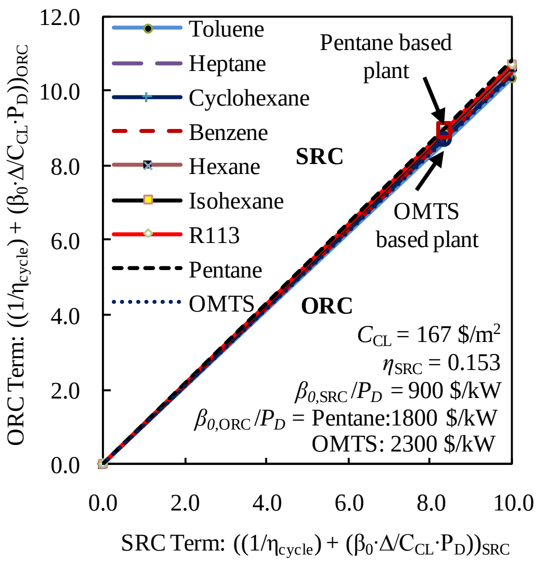

Figure 4: Selection diagram for SRC and ORC based plants (LFR based CSP plant).

To show the applicability of the proposed selection diagram, the costs of ORC power block available for working fluids n-Pentane (Arvay et al., 2011) and Octamethyltrisiloxane (OMTS) (Cofrancesco and Ronzello, 2011) are used for the analysis and the CSP plants using these working fluids are represented on selection diagram. It may be noted that the cost of ORC power block varies with working fluids and it is difficult to obtain the actual cost data for different working fluids. It may be observed that the PTC based CSP plant with ORC (both n-Pentane and OMTS), has slightly higher LCOE compared to SRC based plant. The cycle efficiency for OMTS is significantly higher compared to n-Pentane (see Table 1). However, SP is much higher for OMTS compared to n-Pentane (see Table 1). This leads to bigger size, complicated design (multi-stage), and higher cost of an ORC turbine.

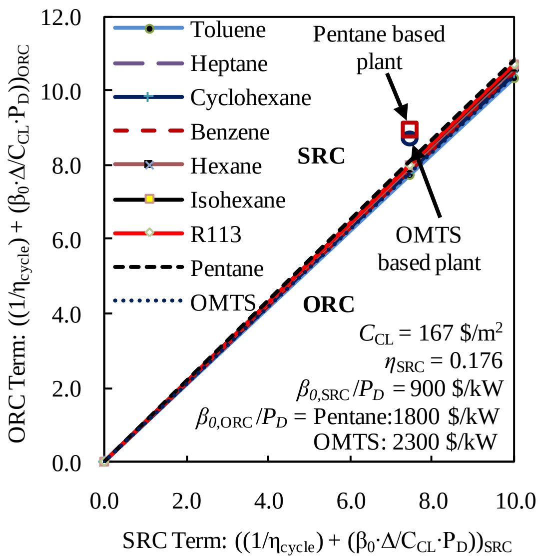

Figure 5. Variations in selection diagram with SRC efficiency (LFR based CSP plant).

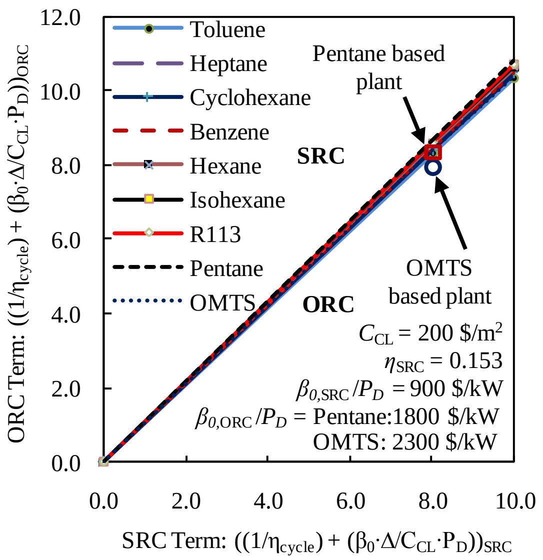

Figure 6: Variations in selection diagram with collector field cost (LFR based CSP plant).

Selection diagram for SRC and ORC, generated for LFR based CSP plant (capacity: 1 MWe), is shown in Figure 4. It may be observed that there is no significant change in the optimum regions with change in type of collector fields. The LFR based CSP plant with ORC (both n-Pentane and OMTS), has nearly same LCOE compared to SRC based plant. It may be noted that the cost of saturated turbine is taken to be same as superheated turbine. Figures 5 and 6 demonstrate that there is no significant variation in selection diagram with SRC efficiency and collector field cost. However, the decision of selection between SRC and ORC is influenced by these values. Increase in SRC efficiency reduces the possibility of selecting an ORC, as expected. However, increases in collector field and SRC power block costs help in choosing an ORC over SRC. Moreover, an organic fluid with higher cycle efficiency and lower SP of turbine can achieve lower LCOE.

4. Conclusions

SRC is the most widely used power generating cycle in CSP plants. However, SRC needs higher temperature and higher plant capacity to be profitable. ORC with dry working fluids gives more efficient turbines for modular plants with medium temperature heat sources. The improved design point and part-load characteristics of the ORC turbines results in lower aperture area of collector aperture, compared to modular scale SRC based CSP plants of same capacity. On the other hand, the cost of power block for ORC is higher compared to the SRC power block. The thermo-economic comparisons between SRC and ORC based CSP plants are presented in this paper. Using the condition of equality of LCOE, an approximate, but simple selection methodology and approximate selection diagram for these cycles based CSP plants are proposed. Selection diagram captures the variations of power generating cycle efficiency, and costs of power block and collector field for the CSP plants with SRC and ORC. Different working fluids of ORC are compared with SRC using this selection diagram. The decision of selection between SRC and ORC is influenced by collector field type and cost, SRC efficiency and power block cost.

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