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Standard Guide for Specifying Thermal Performance of Geothermal Power Systems[1]

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INTRODUCTION

The following sections describe a guide for determining the thermodynamic excellence of geothermal power systems. This guide may be used to establish and compare performance levels of alternative geothermal plant designs using equal or different resource conditions and is intended as a means for supplying information in support of geothermal plant optimization.

It is also the purpose of this guide to promote the common use of pertinent comparison criteria for geothermal power systems, and to discourage the use of some criteria which may range from less useful to misleading.

1. Scope

1.1 This guide covers power plant performance terms and criteria for use in evaluation and comparison of geothermal energy conversion and power generation systems. The special nature of these geothermal systems makes performance criteria commonly used to evaluate conventional fossil fuel-fired systems of limited value. This guide identifies the limitations of the less useful criteria and defines an equitable basis for measuring the quality of differing thermal cycles and plant equipment for geothermal resources.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Significance and Use

2.1 Thermal efficiency and heat rate are frequently utilized to evaluate the thermodynamic quality of fossil fuel-fired power plants.[2] Evaluation of geothermal systems using similar definitions of thermal efficiency and heat rate is inappropriate, except for plants which operate on a cycle, such as binary plants. A utilization factor, defined as the ratio of net work output to the ideal work available from the geofluid, provides a more equitable basis for evaluation of the thermodynamic excellence of geothermal systems.

3. Calculations

3.1 *Fossil Fuel-fired Power Plants*—Thermal efficiency and heat rate are useful and valid criteria for evaluation and comparison of fossil fuel-fired power plants. Thermal efficiency is the ratio of net work generated to the heat that is theoretically available from the fuel. Conventional usage within the electric generating industry defines thermal efficiency (in dimensionless form) as:

$$\eta_t = 3600/HR \tag{1}$$

where:

3600 = kJ equivalent of 1 kWh, and
HR = heat rate, the ratio of energy supplied to the net output, kJ/kWh.

3.1.1 For fossil fuel-fired power plants heat rate is expressed as:

$$HR = (M_F \times FC/W) \tag{2}$$

where:

M_F = fuel flow rate, kg/h,
FC = fuel higher heating value, kJ/kg, and
W = net output, kW.

3.1.2 Thermal efficiency and heat rate are applicable to plants which operate on a cycle, and include the effectiveness of energy conversion associated with the fuel combustion, the effect of heat rejected in exhaust gases and condensate, and allowance for equipment and balance of plant auxiliary power

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[2] Kestin, J., DiPippo, R., Khalifa, H.E., and Ryley, D. J., "Source Book on the Production of Electricity From Geothermal Energy," DoE/RA/28320-2, U.S. Department of Energy, 1980, pp. 243–257.

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losses. Thus, thermal efficiency and heat rate provide an equitable basis for ranking and comparing fossil fuel-fired plants of alternative design.

3.2 *Geothermal Power Plants*—Geothermal plants using flashed steam (see Fig. 1a and Fig. 1b) do not operate on a cycle but involve a series of energy conversion processes. Therefore evaluation of such plants using a similar definition of thermal efficiency and heat rate is inappropriate and will lead to erroneous conclusions regarding the effectiveness of the plants. The exception to this is the case of binary plants (see Fig. 1c) which operate on a cycle and which receive a heat supply. (See Sect. 3.2.2)

3.3 *Utilization Factor*—A thermodynamically valid basis for comparing the thermodynamic excellence of geothermal energy conversion processes is provided by the utilization factor. The utilization factor is defined as the ratio of net work output to the ideal work available from the geofluid between its initial state (supply condition) and the sink condition (lowest temperature available for heat rejection). Utilization factor (U) can be expressed (in dimensionless form) as:

$$U = \frac{W}{Q_o E_1} \tag{3}$$

where:

E_1 = ideal specific work available to the process within the natural bounds of the environment, kJ/kg,
Q_o = well head mass flow rate, kg/s, and
W = net useful power, kW.

3.3.1 Utilization factor fulfills the objective of evaluating the quality of thermal cycles and for ranking the power potential of geothermal resources. It is important that the power be explicitly defined as net power, as there may be significant differences in auxiliary power requirements, and differing methods of providing auxiliary power, in the cases being evaluated. This applies particularly to auxiliary power allowances for venting gases or for transporting working fluids.

3.3.2 Utilization factor is presented as a guide for design evaluations and the selection of suitable design conditions for equipment specifications. Utilization factor for a typical single flash steam cycle is presented as a function of rejection temperature in Fig. 2, the rejection temperature that results in the highest utilization is referred to as the optimum temperature. For multiflash cycles (including flash-binary) optimum values can be identified for each flash level. For binary cycles, optimum temperatures tend to vary with the secondary fluid selected. Optimum rejection temperature can also be identified for hybrid cycles such as those employing total flow machines with steam bottoming cycles.

3.3.3 Binary plants of the simple or hybrid type can be evaluated on the basis of the utilization efficiency. The cyclic portion of such plants may also be evaluated by the familiar thermal efficiency or heat rate. The heat supplied to a geothermal cycle (in kW_t) is in general:

$$Q_o(h_o - h_r) \tag{4}$$

and the heat rate (in kW_t/kW_e) becomes:

$$HR = Q_o(h_o - h_r)/W \tag{5}$$

where:

Q_o = total mass flow rate of the geothermal fluid (geofluid) to the cycle, kg/s,
h_o = specific enthalpy of the total two-phase or single-phase well flow, kJ/kg, and
h_r = specific enthalpy of the fluid rejected from the cycle and returned to the reservoir or environment, kJ/kg.

3.4 *Ideal Specific Work*—The ideal specific work (E_i), is the theoretical maximum work that can be obtained from a system at an initial state at pressure (P_o) and enthalpy (h_o) and sink conditions (P_a and T_a). The ideal specific work can be calculated using the second law of thermodynamics.

$$E_i = (h_o - h_a) - T_a(S_o - S_a) \tag{6}$$

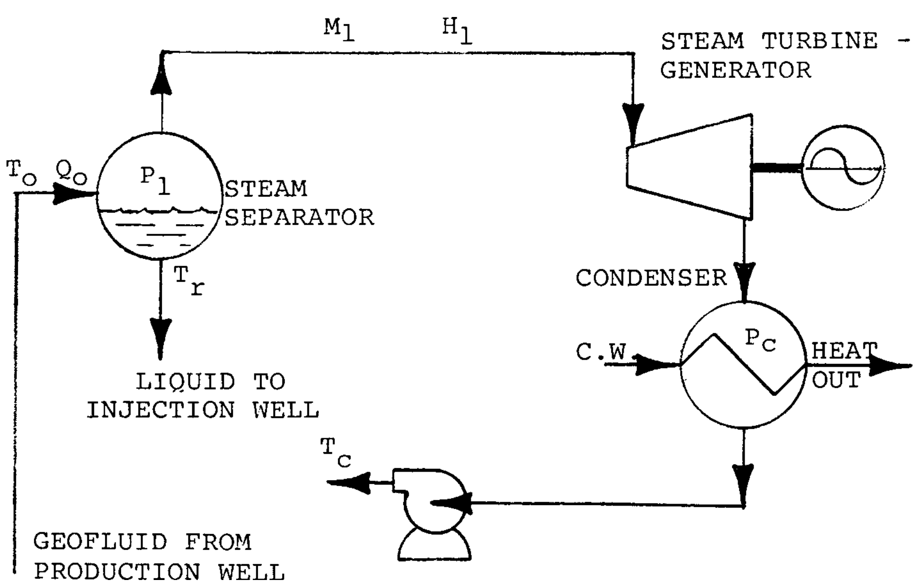

FIG. 1 a Schematic of Single-Flash Steam Cycle

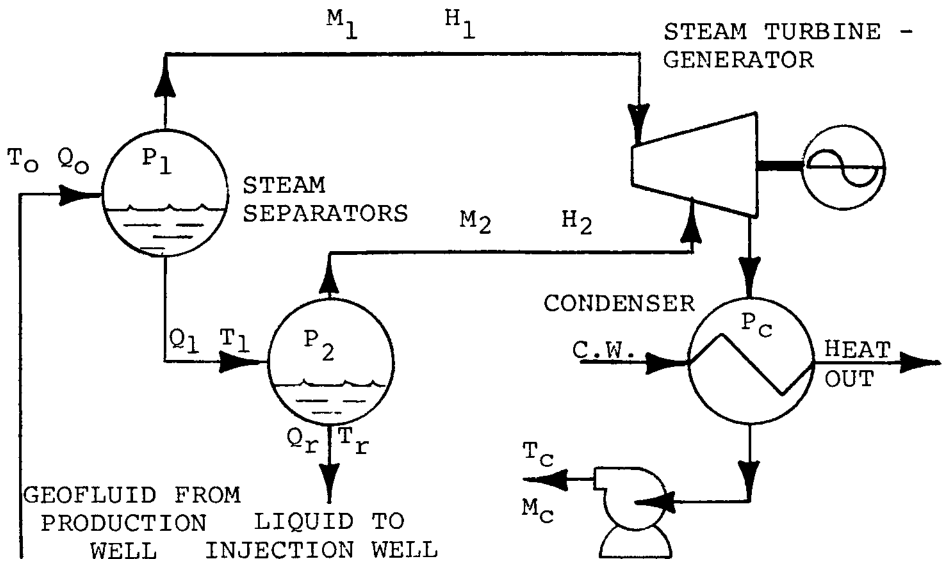

FIG. 1 b Schematic of Dual-Flash Steam Cycle *(continued)*

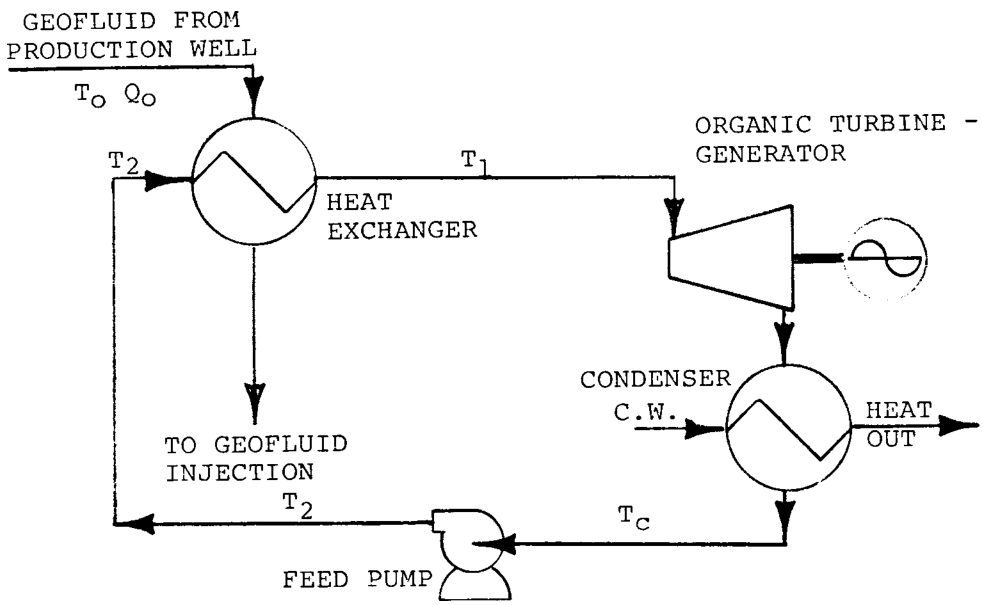

FIG. 1 c Schematic of Geofluid/Organic Rankine Cycle *(continued)*

where:

h_o and h_a	=	geothermal fluid enthalpies at the inlet and sink conditions, kJ/kg,
S_o and S_a	=	geothermal fluid entropies at inlet and sink conditions, kJ/kg·K, and
T_a	=	sink (or dead-state) temperature, K.

3.4.1 The use of thermal properties for pure water in the calculation of E_I is acceptable for low concentrations of impurities: Total dissolved solids (TDS) < 20000 mg/kg and non-condensable gases (NCG) < 1 % (wt. of steam). Corrections should be applied to account for the effects of impurities when they exceed these limits[3].

3.5 *Sink Condition*— Unless special environmental conditions exist, in deriving the ideal specific work, the sink condition of saturated water at 15.6°C (60°F) is recommended.

3.6 *Geofluid Rate*— For comparisons of alternative cycles or apparatus for a specific site or resource, where ideal specific work, (E_i), is constant, the comparison can proceed on the basis of specific power, W/Q_o, or its reciprocal which is usually termed, water-rate or geofluid-rate. The geofluid-rate measures

[3] DiPippo, R. and Ellis, P.F., II, *Geothermal Information Series, Part 2: Geothermal Power Cycle Selection Guidelines*, EPRI DCN 90-213-142-02-02, July 1990, Electric Power Research Institute, Palo Alto, CA, pp. 3-11, 3-12.

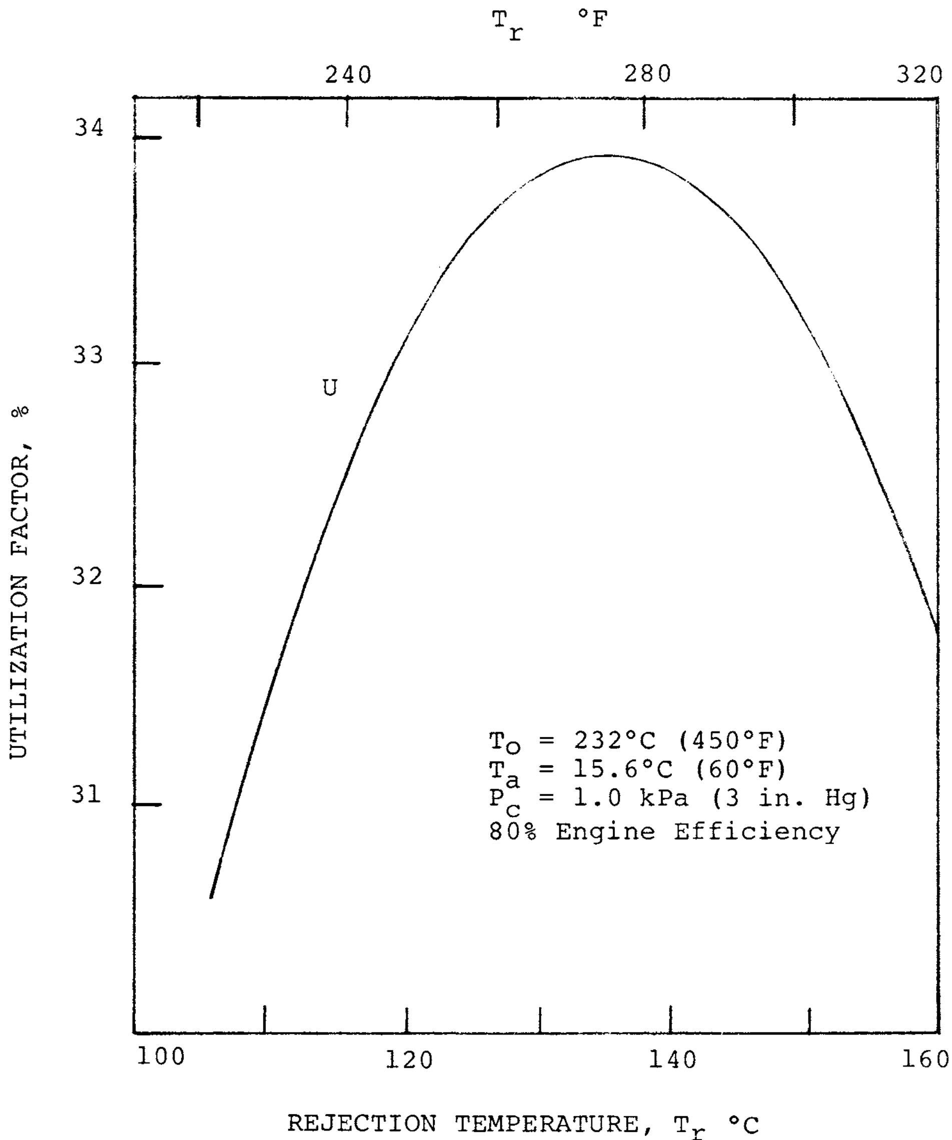

FIG. 2 Utilization Factor For Single-Flash Steam Cycle

the well flow rate to produce a kilowatt of power and is a major index of field development costs. For comparisons where auxiliary losses are presumed constant, the geofluid-rate calculation is often foreshortened to a basis of gross power generation; however, this should be used with caution.

4. Keywords

4.1 geothermal energy; geothermal energy conversion; geothermal power generation; geothermal power systems; power plant performance; thermal cycle

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