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SECOND LAW ANALYSIS OF FLASH-BINARY AND MULTILEVEL BINARY GEOTHERMAL POWER PLANTS

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ABSTRACT

The Second Law of thermodynamics is applied to a pair of advanced geothermal energy conversion systems - a flash-steam plant with a bottom binary cycle and a multi-level binary plant. Both plants are shown to be capable of excellent efficiencies. The key to this outstanding performance is the reduction of irreversibilities as revealed by several Second Law efficiencies. An exergy accounting system is used to highlight those processes which result in excessive losses. This Second Law methodology can lead to system improvements through further reductions in exergy destruction.

INTRODUCTION

Second Law analysis (exergy or availability analysis) is a powerful tool for assessing the thermodynamic performance of energy conversion systems [1-3]. Given the increasing variety of geothermal power systems coming into use, Second Law analysis is an excellent method for comparing alternatives. Furthermore, it can be of great help in designing energy conversion systems by identifying those processes with the greatest exergy loss.

The basic principles, working equations and some applications of this technique to geothermal systems have been reported, e.g., in refs. [4-6]. The method involves the use of basic principles of thermodynamics, i.e., the First and Second Laws applied to open systems in steady-state operation. The key quantity is the exergy rate,

$$\dot{E} = \dot{m}e, \qquad (1)$$

where $\dot{m}$ is the mass flow rate and e, the specific exergy, is given by

$$e = h - h_o - T_o(s - s_o). \qquad (2)$$

The significant point is that the specific exergy represents the maximum possible specific output from a fluid existing at any given state when used in an open steady system in contact with surroundings at a temperature T_o. The value of e is easily found using property tables given the conditions of the inlet state and of the surroundings.

The thermodynamic properties of geofluids (or "brines") will be assumed to be those of pure water [7]; those for other working fluids will be taken from ref. [8].

We will now apply Second Law analysis to two advanced geothermal power systems.

SINGLE-FLASH STEAM PLANT WITH BOTTOM BINARY CYCLE

The single-flash plant is one of the standard systems used with liquid-dominated reservoirs [9]. Fairly simple in concept, it has a relatively low utilization efficiency, η_u, defined as:

$$\eta_u = w/e, \qquad (3)$$

where w is the specific plant output. The theoretical optimum utilization efficiency for a single-flash plant fed from a hot-water reservoir at, say, 260 C (500 F) and having a condensing temperature of 52 C (126 F) is about 35 percent [9]. That is, about 35 percent of the exergy of the in-coming geofluid is converted into useful output.

The addition of a low-temperature bottom cycle improves the thermodynamic performance. Figure 1 is a simple schematic showing such a plant. Note that the bottom binary cycle captures some of the heat (actually, some of the exergy) of the waste brine leaving the separator. Usually a hydrocarbon (in this example, isopentane) is the working fluid in the binary cycle. Plants of this general type have been proposed [10], and in fact put into operation [11], but the analysis presented here is generic rather than specific to any particular plant or proposal. Furthermore the results given are merely illustrative and not intended as an optimization.

Table 1 lists the assumptions defining the situation. An exergy accounting reveals the sources of irreversibility, i.e., losses of efficiency. Table 2 shows these losses.

For the single-flash plant alone, i.e., with the waste brine going directly from the separator to the injection well, the major sources of exergy loss are the

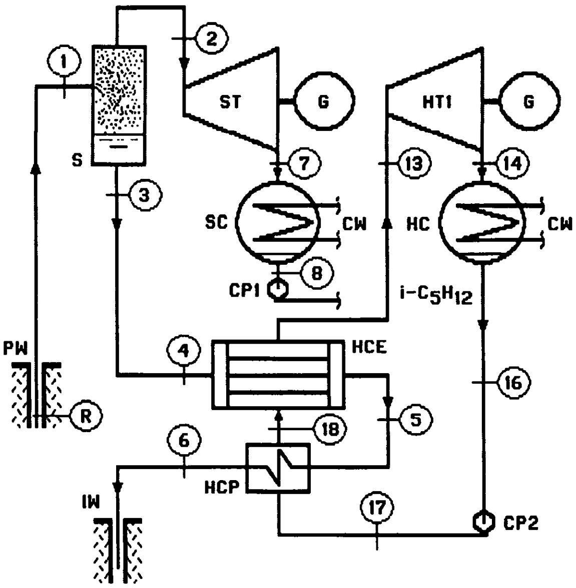

Fig. 1. Simplified schematic of a single-flash steam plant with a bottom binary cycle. Nomenclature: PW = production well; S = separator; ST = steam turbine; G = generator; SC = steam condenser; CW = cooling water; CP1, CP2 = condensate pumps; HCE = hydrocarbon evaporator; HCP = hydrocarbon preheater; HT1 = hydrocarbon turbine; IW = injection well.

Table 1
SINGLE-FLASH PLANT WITH i-C5 BINARY CYCLE
Plant Specifications and Assumptions

Reservoir conditions: $T_R = 229.4^oC$, sat

Separator conditions: $T_1 = 151.1^oC$, sat

Steam condenser: $T_7 = T_8 = 37.8^oC$

Brine into HCE: $T_6 = 76.7^oC$

Total well flow rate: $\dot{m}_R = \dot{m}_1 = 229.7$ kg/s

Binary cycle working fluid: isopentane

i-C5 turbine conditions: $T_{13} = 103.8^oC$, sat
$P_{14} = 141.4$ kPa

i-C5 condenser: $T_{16} = 37.8^oC$

HCE pinch-point temp. diff. = 5.6^oC

Turbines obey Baumann rule for efficiency, dry efficiency = 85 %

Pump efficiencies = 80 %

See Fig. 1 for state-point notation.

following: some exergy is destroyed in the flashing process between the reservoir and the separator, and in the turbine expansion process; some is carried away with the cooling water, and some is discarded with the waste brine. The single-flash plant utilization efficiency comes to 36.1 percent. It can be seen that the largest loss is associated with discarding the brine; over 35 percent of the incoming exergy is lost in the process. It might be argued that this exergy serves to replenish the reservoir, but while it <u>might</u>, there is no quarantee that it <u>will</u>. From the point of view of the plant, it constitutes a major loss. The purpose of the bottom binary cycle is to recover some of this exergy loss.

With reference to Fig. 1, the preheater (HCP) and evaporator (HCE) constitute what might be called an "Exergy Recovery Unit", ERU. The transfer of <u>heat</u> from the brine to the isopentane is essentially perfect, neglecting minor losses through the heat exchanger insulation. However, not all of the <u>exergy drop</u> of the brine is delivered to the isopentane; some of it is lost owing to the irreversibility of heat transfer across a finite temperature difference. The larger the average temperature difference, the greater the exergy loss.

Table 2
SINGLE-FLASH PLANT WITH i-C5 BINARY CYCLE
Exergy Rate Accounting

--- Basic Single-Flash Plant ---	
Exergy delivered by well	53.19 MW
Exergy lost: well-separator	5.16
turbine	4.71
cooling water	4.98
waste brine	19.04
Exergy produced by turbine	19.19
Utilization efficiency (gross)	36.1 %
--- Exergy Recovery Unit ---	
Brine side:	
Exergy: into ERU	17.06 MW
out of HCE	9.53
out of HCP	5.99
Exergy drop: in HCE	7.53
in HCP	3.54
i-C5 side:	
Exergy: into ERU	0.065
out of HCP	2.85
out of HCE	9.14
Exergy increase: in HCP	2.785
in HCE	6.29
Exergy efficiency:	
HCP	78.7 %
HCE	83.5
ERU (Overall)	82.0
--- Overall Plant ---	
Exergy produced by turbines	23.83 MW
Utilization efficiency (gross)	44.8 %

The exergy transfer efficiency of a heat exchanger may be defined as follows:

$$n_e = \frac{\text{exergy increase, cold fluid}}{\text{exergy decrease, hot fluid}}. \qquad (4)$$

Table 2 summarizes these losses and efficiencies for the HCP, HCE and ERU.

We define the utilization efficiency of the bottom binary cycle as follows:

$$n_{bc} = \frac{\text{net power output, bottom cycle}}{\text{brine exergy decrease rate}}, \qquad (5)$$

which in this case is 42.1 percent. The overall plant utilization efficiency is 44.8 percent.

In arriving at these results, we have allowed for a temperature drop along the brine line between the separator and the hydrocarbon evaporator to simulate field conditions. This accounts for the difference of about 2 MW between the exergy values of 19.04 and 17.06 MW in Table 2.

It is interesting to note that the bottom cycle efficiency (42.1 %) is greater than the efficiency of the basic single-flash plant (36.1 %). We see also that the ERU is quite efficient: the evaporator section transfers 83.5 percent of the brine exergy drop to the isopentane, while the preheater section transfers 78.7 percent, for an overall efficiency of 82.0 percent.

MULTI-LEVEL BINARY POWER PLANT

While one of the advantages often claimed for binary plants is their simplicity, some binary plants in fact sacrifice simplicity to gain higher efficiencies. It was recognized early on that simple binary plants had relatively low efficiencies, and the earliest commercial plants were not simple cycles. The first commercial size binary plant, the Magmamax plant (later re-named B.C. McCabe and and then GEM-1) was a dual-fluid, dual-loop, interconnected cycle [12]. The Raft River pilot plant was a dual-pressure, single-fluid cycle [13]. Recently, the ORMESA plants (I, IE, IH and II) and others employ cycles based on the cascade principle involving several temperature levels [14].

The intent of all advanced binary cycles is to reduce the irreversibility associated with the transfer of heat across a finite temperature difference, as described earlier. The irreversibility can be reduced by a careful matching of the brine cooling curve to the heating/boiling curve(s) of the cycle working fluid(s).

The analysis given here is generic in nature and is not intended to pertain directly to any particular plant, existing or planned. We consider a three-tiered binary plant depicted schematically in Fig. 2. Each tier consists of a simple binary cycle (I, II and III), comprised of a preheater (PH), evaporator (EV), turbine-generator (TG), condenser (C) and feedpump (P). Since each loop is separate, different working fluids could be selected for each one as appropriate. In this analysis, however, we will adopt a single working fluid for all three loops for simplicity.

The geofluid is pumped as a hot liquid under pressure from the well(s) and passes first through the evaporator of each cycle, sequentially from Cycle I to Cycle III. Then it is divided into three parallel streams which are directed to the three preheaters. The mass flow rates in the three parallel streams are determined by thermodynamic considerations. Finally the cooled geofluid, still in the liquid state, is reinjected.

The cycle working fluid leaves each evaporator as a saturated vapor, while each preheater provides a portion of the sensible heat needed to bring the fluid to the boiling point. In the case of Cycle III, the preheater can supply all of the required sensible heating.

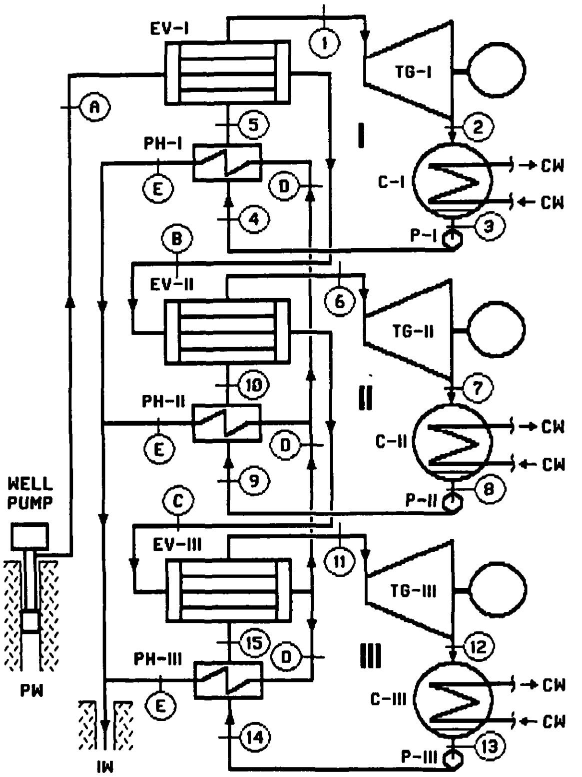

Fig. 2. Simplified schematic of a three-tiered binary plant. Nomenclature: See Fig.1; also, EV = evaporator; PH = preheater; TG = turbine/generator; C = condenser; P = pump.

The efficiency of exergy transfer in each preheater/evaporator depends on the pinch-point temperature difference (i.e., the difference in temperature between the two fluids at the point of closest approach). The advantage of a tiered system over a simple cycle is illustrated in the temperature versus heat-transfer diagrams, Figs. 3 and 4. The former is for a three-tiered plant while the latter is for a simple cycle. Both diagrams have the same brine temperature drop and pinch-point temperature differences. The average temperature difference (related to the shaded area) is smaller for the tiered cycle which translates into lower irreversibilities and higher efficencies.

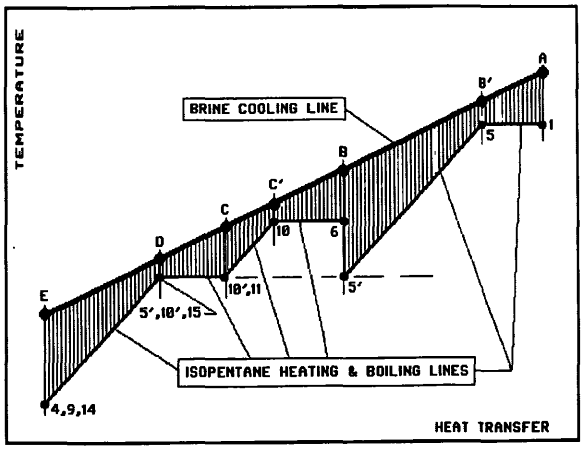

Fig. 3. Temperature/heat-transfer diagram for a three-tiered binary plant.

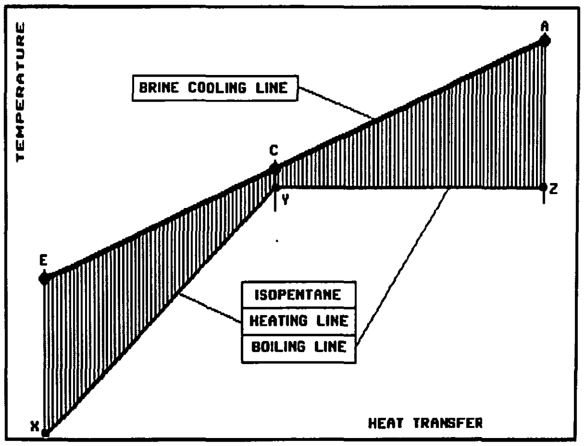

Fig. 4. Temperature/heat-transfer diagram for a simple binary plant.

Table 3 lists the conditions chosen for this example. The use of isopentane allows the turbines to run completely in the superheated vapor region, thereby achieving a higher isentropic efficency (assumed to be 85 %). Geofluid temperatures within the plant have been arbitrarily selected and are not intended to be optimum values. The brine inlet temperature is typical of moderate temperature geothermal resources and of waste fluids from the separators of many single-flash plants.

Table 3
THREE-TIERED ISOPENTANE BINARY PLANT
Plant Specifications and Assumptions

Geofluid temperatures:
$T_A = 151.9^oC$, $T_B = 115.6^oC$, $T_C = 87.8^oC$,
$T_D = 82.3^oC$, $T_E = 73.9^oC$

Geofluid mass flow rate: $\dot{m}_{br} = 0.4536$ kg/s

Binary cycle working fluid: isopentane

Turbine inlet temperatures:
$T_1 = 123.9^oC$, $T_6 = 87.8^oC$, $T_{11} = 76.9^oC$

HXer pinch-point temp. diff. = 5.6^oC

Turbines obey Baumann rule for efficiency, dry efficiency = 85 %

Pump efficiency = 75 %

See Fig. 2 for state-point notation.

A schematic temperature-entropy diagram (Fig. 5) is offered as an aid in visualizing the processes in the plant. The state points are keyed to Fig. 2. The diagram is not to scale; in particular, the liquid heating processes (i.e., 14-15, 9-10 and 4-5) are highly exaggerated for visibility, since really they are nearly indistinguishable from the saturated liquid line.

The results of the exergy accounting analysis are summarized Table 4. The utilization efficiency is very good for any kind of geothermal plant: 38.1 percent (net) based on the incoming exergy of the geofluid, or 45.9 percent (net) based on the change in the exergy of the geofluid as it passes through the plant.

The excellent performance stems from the high efficiency of exergy transfer in the heat exchangers. Figure 6 is a temperature/heat-transfer diagram for the preheater/evaporator combination in Cycle I. The isopentane heating and boiling lines are continuous (with a corner at the bubble point) but the brine cooling curve has a discontinuity, B-D, since the brine is routed to Cycle II when it reaches state B. Some of it returns at state D after leaving the evaporator of

Cycle III. The temperature drop of the brine between states B and D serves to reduce the irreversibility of heat transfer in Cycle I compared to the simple case where the brine would cool continuously through EV-I and PH-I. Thus, the adverse effect of the pinch-point is mitigated.

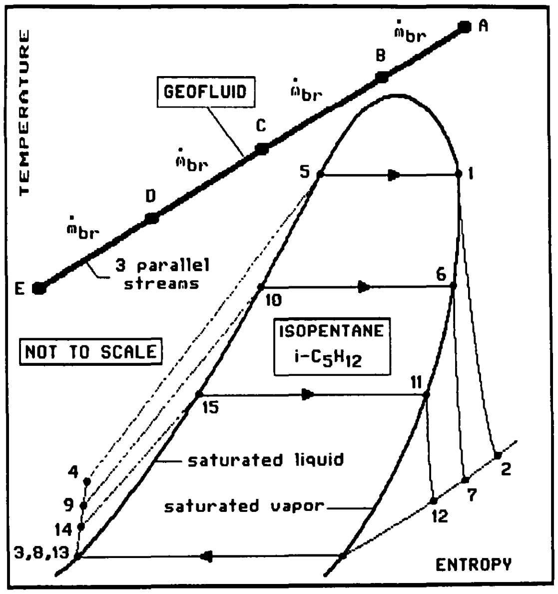

Fig. 5. Temperature/entropy diagram for a three-tiered binary plant.

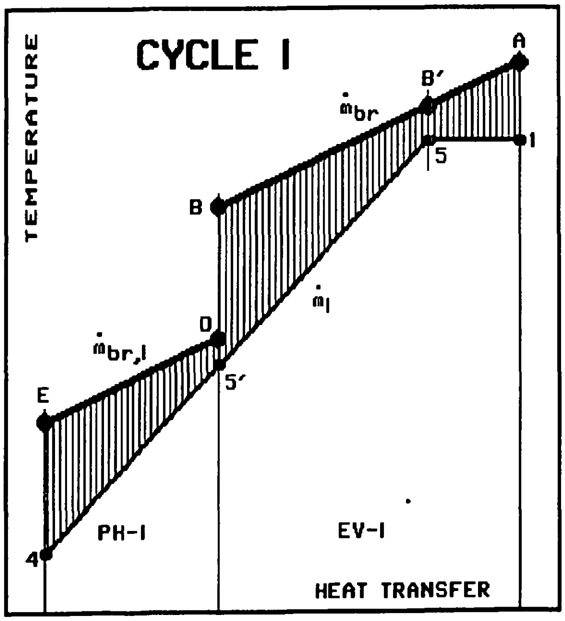

Fig. 6. Temperature/heat-transfer diagram for the Cycle I portion of a three-tiered binary plant.

The efficiency of exergy transfer can be determined separately for the preheater, PH-I, and the evaporator, EV-I:

$$\eta_{PH-I} = \dot{m}_I(e_{5'} - e_4)/\dot{m}_{br,I}(e_D - e_E) \quad (6)$$

$$\eta_{EV-I} = \dot{m}_I(e_1 - e_{5'})/\dot{m}_{br}(e_A - e_B). \quad (7)$$

The overall exergy efficiency of the combined preheater/evaporator is simply the ratio of the total increase in the exergy of the isopentane to the total decrease in the exergy of the brine as it passes through the PH/EV combination. Cycles II and III may be analyzed in a similar fashion and the results are included in Table 4.

CONCLUSIONS

With regard to a flash-steam plant with a bottom binary cycle, the use of an "exergy recovery unit" or ERU as a thermal bridge between the two conversion systems results in a synergistic gain in performance wherein the overall combined efficiency exceeds that of each system separately. In the case of a multi-level binary plant, the excellent overall plant efficiency comes about through a careful matching of the heating-boiling curves of the cycle working fluid with the brine cooling curve. Relative to a simple binary plant, the improvement in exergy transfer from the geofluid to the working fluid can be dramatic.

Table 4
THREE-TIERED ISOPENTANE BINARY PLANT
Exergy Rate Accounting

--- Overall Plant ---

Exergy:		
delivered to plant	40.810	kW
returned to injection wells	6.926	
delivered by Cycle I	9.947	
delivered by Cycle II	4.754	
delivered by Cycle III	0.857	
delivered by plant	15.558	
Utilization efficiency:		
based on:		
input exergy	38.1	%
change in geofluid exergy	45.9	

--- Heat Exchangers ---

Exergy efficiency for HXer's in:		
Cycle I: Preheater	70.3	%
Evaporator	85.0	
Overall	84.0	
Cycle II: Preheater	60.0	
Evaporator	81.7	
Overall	80.5	
Cycle III: Preheater	76.1	
Evaporator	88.1	
Overall	85.9	

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NOMENCLATURE

E ... Exergy rate
e ... Specific exergy
h ... Specific enthalpy
m ... Mass flow rate
n_e .. Exergy transfer efficiency
n_u .. Utilization efficiency
P ... Pressure
s ... Specific entropy
T ... Temperature
w ... Specific work

Superscript
˙ ... Time rate of quantity

Subscripts
bc .. Refers to bottom cycle
o ... Refers to the "dead state"