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COMPOUND HYBRID GEOTHERMAL-FOSSIL
POWER PLANTS

By
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MASTER

June 1979

Work Performed Under Contract No. EY-76-S-02-4051

Division of Engineering
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U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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COMPOUND HYBRID GEOTHERMAL-FOSSIL POWER PLANTS:

Thermodynamic Analyses and Site-Specific Applications

by

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June 1979

Performed under

Department of Energy

Division of Geothermal Energy

Contract EY-76-S-02-4051.A002

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ABSTRACT

The analysis of hybrid fossil-geothermal power plants is extended to compound hybrid systems which combine the features of previously analyzed systems: the geothermal-preheat and the fossil-superheat systems. Compound systems of the one- and two-stage type are considered. A compilation of working formulae from earlier studies is included for completeness. Results are given for parametric analyses of compound hybrid plants. System performance was determined for wellhead conditions of 150, 200, and 250°C, and for steam fractions of 10, 20, 30 and 40%. For two-stage systems an additional cycle variable, the hot water flash fraction, was varied from 0 to 100% in increments of 25%. From the viewpoint of thermodynamics, compound hybrid plants are superior to individual all-geothermal and all-fossil plants, and are shown to have certain advantages over basic geothermal-preheat and fossil-superheat hybrid plants. The flexibility of compound hybrid systems is illustrated by showing how such plants might be used at six geothermal sites in the western United States. The question of the optimum match between the energy resources and the power plant is addressed, and an analysis given for a hypothetical geothermal resource.

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1. BACKGROUND

This report extends the work of the Brown group in hybrid geothermal-fossil power plants to so-called compound hybrid systems. A number of reports and papers have been produced dealing in detail with geothermal-preheat systems [1,2] and fossil-superheat systems [3,4], and describing qualitatively other possible hybrid arrangements [5,6]. A plant of the geothermal-preheat type has been studied from an economic viewpoint [7], and a preliminary design has been prepared for the City of Burbank [8].

Geothermal-preheat hybrid systems are essentially conventional fossil-fired plants which use geothermal hot water in place of a number of extraction-steam-fed feedwater heaters. A simplified flow diagram is shown in Fig. 1. The thermodynamic advantages of this type of arrangement have been shown to be significant [2]. The reason for the improvement lies in the reduction of losses associated with the use of superheated steam bled from the turbines to provide sensible heating of boiler feedwater in conventional plants [6]. The elimination of the lower-temperature feedwater heaters in favor of a geothermal-hot-water/boiler-feedwater heat exchanger results in a more favorable match between the two fluids and a consequent reduction in the rate of entropy production. Furthermore, the steam flow through the low-pressure stages of the turbine is enhanced because of the elimination of the lower-pressure extraction points, resulting in a greater power output.

Fossil-superheat hybrid systems, on the other hand, are basically geothermal steam power plants with an added fossil-fired superheater [3,4]. One- and two-stage systems are illustrated schematically in Fig. 2a and 2b, respectively. The advantage of this type of plant stems mainly from two features. First, the fossil-fuel portion serves to increase the mean-effective temperature at which heat is added, resulting in an increased energy utilization efficiency. Second, the addition of superheat to the geothermal steam (which is typically saturated

or only slightly superheated at the turbine inlet) leads to completely dry expansion through the turbine, and consequently results in a higher machine efficiency according to the well-known Baumann rule [9], i.e., one percent moisture in the turbine exhaust means a one percent reduction in turbine efficiency.

2. JUSTIFICATION FOR COMPOUND HYBRID SYSTEMS

Neither a geothermal-preheat nor a fossil-superheat system, by itself, is particularly suited to the case where the geothermal fluid emerges from the wellhead as a two-phase mixture of steam and hot water. It is common for self-flowing geothermal wells to produce mixtures with a dryness fraction (or quality) of between 5-40% at the wellhead. The use of such a mixture for feedwater heating in a geothermal-preheat system would be thermodynamically inefficient. The vapor fraction of the geothermal fluid would suffer the same type of losses as the steam which is extracted from turbines for feedwater heating in conventional fossil plants. On the other hand, if one attempted to use fossil-superheat systems with this type of resource, one would have to separate the vapor fraction from the liquid, superheat the vapor, and discard the liquid (as in a one-stage system, Fig. 2a), thereby wasting a considerable fraction of the available work of the geofluid. Alternatively, one might use a two-stage system (Fig. 2b), and generate secondary steam by flashing the separated liquid to a lower pressure. However, one would have to tolerate significant losses associated with the irreversible liquid-throttling process.

The compound hybrid plants described in this report may be designed to take full advantage of two-phase geofluids. Furthermore, these designs will be shown to be sufficiently flexible to accommodate a variety of types of resources and a variable market demand for electric power.

3. DESCRIPTION OF COMPOUND HYBRID PLANTS

3.1 One-Stage Systems

The simplest compound hybrid power plant designed to utilize efficiently two-phase geothermal fluids is shown schematically in Fig. 3. We denote plants of this type as "one-stage" compound plants because there is only one stage of geothermal steam generation. This takes place by means of a natural flashing process, usually in the wellbore but sometimes (although undesirably) in the reservoir formation.

With reference to Fig. 3, the two-phase geofluid emerges from a number of production wells (PW) and is processed in cyclone separators (S). The separated steam is scrubbed (scrubbers not shown) and fed to a superheater (FSH) located in the boiler section of the power house. After leaving the superheater, the steam follows a route which is essentially identical to that of, say, the geothermal steam used at The Geysers geothermal installation, i.e., through a low-pressure turbine (GT), a condenser (GC), and finally through booster pumps to a number of injection wells (IW).

The liquid fraction of the geofluid is piped from the outlet of the separator (S) to a heat exchanger (BH) in the feedwater heating train of an otherwise more-or-less conventional Rankine power cycle. The main difference in this case is the elimination of most of the feedwater heaters, typically 5 to 7 in conventional plants, in favor of a single, open, deaerating-type heater (FWH) in addition to the brine heat exchanger (BH). The spent brine may be injected directly using the excess pressure in the waste liquid (which should be only somewhat less than the separator pressure) or by means of an injection booster pump.

3.2 Two-Stage Systems

As may be seen from Fig. 3, a second stream of geothermal steam may be

generated by flashing a fraction of the hot water from the separator (S) before it arrives at the feedwater heater. Figure 4 shows a flow diagram for a two-stage system. A flash vessel (F) receives a portion of the separated hot water, throttles it to lower pressure, thereby generating secondary steam and another stream of hot water. The additional steam is mixed with the primary geothermal steam from the first geothermal turbine (GT1) after the primary steam from the turbine exhaust has passed through a steam-steam regenerator (R). Under most conditions of operation for two-stage systems, a regenerator turns out to be thermodynamically feasible. (For none of the conditions studied is a regenerator possible for one-stage systems.) The merged streams of geothermal steam then enter a low-pressure turbine (GT2), and generate additional power.

The residual hot water produced at the flash vessel is mixed with the main geothermal hot water leaving the brine heater (BH1) before entering the lowest temperature feedwater heater (BH2). A small (negligible) loss is encountered because of the mixing process because the two fluids are at different pressures and temperatures. Finally, as in the case of the one-stage systems, all of the geofluid is eventually reinjected by means of injection wells (IW).

4. THERMODYNAMIC ANALYSES

4.1 Figures of Merit and Design Parameters

Definitions of various figures of merit and design parameters for hybrid plants in general have been given elsewhere [1, 6], and working equations for these terms have been established [1-3, 10]. Since the performance factors are generally valid, they may be applied to compound hybrid systems. A summary of the definitions and working equations is included here for the sake of completeness.

F = combined figure of merit

$$= W / (W_f^* + W_g^*) \quad (1)$$

F_f = fossil-fuel figure of merit

$$= (W - W_g^*)/W_f^* \quad (2)$$

F_g = geothermal-energy figure of merit

$$= (W - W_f^*)/W_g^* \quad (3)$$

F_o = overall figure of merit

$$= 1 + (F_f - 1)/(1 + R), \text{ for } \Delta < 1 \quad (4)$$

$$= 1 + R(F_g - 1)/(1 + R), \text{ for } \Delta > 1. \quad (5)$$

The terms used in these equations have the following meanings:

W = net work of hybrid power plant.

W_f^* = net work of a state-of-the-art, fossil-fueled power plant (typically a supercritical reheat cycle with seven feedwater heaters).

W_g^* = net work of a state-of-the-art, geothermal power plant (typically an optimized double-flash plant).

Δ = relative depletion parameter

$$= F_f/F(\psi - 1) \quad (6)$$

$$= 1/F(\psi - F_g). \quad (7)$$

R = resource ratio

$$= W_g^o/W_f^o \quad (8)$$

ψ = work amplification factor

$$= W/W_g^* \quad (9)$$

$$= F(F_g - 1)/(F - 1). \quad (10)$$

The resource ratio, R , is the ratio of the total amount of work, W_g^o , that could be extracted from the geothermal resource on which the hybrid plant is built if a state-of-the-art geothermal plant were to be built instead, and a similar work term, W_f^o , for the fossil resource that is committed to the hybrid plant.

The terms W_g^* and W_f^* are obtained in the following manner:

$$W_g^* = \eta_g^* E_g, \quad (11)$$

where $\eta_g^* = 0.50$ (fixed).

$$\begin{aligned} E_g &= \text{available work (exergy) of the geofluid at the wellhead} \\ &= h_a - h_o - T_o (s_a - s_o), \end{aligned} \quad (12)$$

where h_a, h_o = geofluid enthalpy at the wellhead and the sink,

s_a, s_o = geofluid entropy at the wellhead and the sink,

T_o = absolute temperature of the sink,

= 300°K (540°R).

$$W_f^* = \eta_f^* (\Sigma Q_i), \quad (13)$$

where $\eta_f^* = 0.43$ (fixed).

ΣQ_i = sum of all fossil-derived heat delivered to hybrid plant.

There are two factors which characterize the savings in fossil fuel afforded by the hybrid plant [10].

$$\begin{aligned} \phi_h &= \text{fossil-fuel savings factor} \\ &= 1 - (W_f^*/W) \end{aligned} \quad (14)$$

$$= F_g/\psi. \quad (15)$$

$$\begin{aligned} \phi_d &= \text{fossil-fuel displacement factor} \\ &= 1 - \{W_f^*/(W_f^* + W_g^*)\} \end{aligned} \quad (16)$$

$$= (F_g - F)/\psi. \quad (17)$$

The first of these factors, ϕ_h , gives the savings in fossil fuel (as a fraction) that a hybrid plant is capable of over an all-fossil plant of the same net work output. The second factor, ϕ_d , takes into account the possibility that a geothermal plant of capacity, W_g^* , might be built on the site, and that an all-fossil plant of capacity, $W - W_g^*$, would then need to be built to generate the same total output as the hybrid plant. The factor ϕ_d gives the savings of a hybrid plant in such a case.

4.2 Systems Analysis

The compound hybrid systems were analyzed using standard thermodynamic

methods for systems operating in a steady-flow mode. The state points and cycle of operations for one-stage and two-stage systems are shown in temperature-entropy (T-s) coordinates in Figs. 5 and 6, respectively. The brine heater portion is shown in finer detail in Fig. 7 in the case of two-stage systems.

Pressure losses through the various heat exchangers are denoted by broken isobars in the case of one-stage systems, Fig. 5. Pressure losses are also accounted for in the case of two-stage systems, although broken isobars are not shown in Fig. 6 so as to avoid unnecessarily complicating the figure. The detailed T-s diagram of the brine heater section (Fig. 7) does, however, show the appropriate pressure losses.

The regenerator (R) shown in the case of two-stage systems is not always feasible. The temperature of the exhaust from the first geothermal turbine (state e) must be greater than the wellhead temperature by an amount at least equal to the minimum acceptable temperature difference.

A summary of the working equations for all work and heat terms is given below for two-stage systems. It should be observed that the proper equations are obtained for one-stage systems when the hot water flash fraction, r_f , is set equal to zero. The notation used in the equations which follow is taken from Fig. 4.

Heat derived from fossil fuel:

$$Q_{SG} = \dot{m}_1(h_1 - h_{10}) \quad (18)$$

$$Q_{RH} = \dot{m}_3(h_3 - h_2) \quad (19)$$

$$Q_{FSH} = \dot{m}_d(h_d - h_c). \quad (20)$$

Work output of turbines:

$$W_{FT1} = \dot{m}_1(h_1 - h_2) \quad (21)$$

$$W_{FT2} = \dot{m}_3(h_3 - h_4) \quad (22)$$

$$W_{GT1} = \dot{m}_d(h_d - h_e) \quad (23)$$

$$W_{GT2} = \dot{m}_k(h_k - h_l) \quad (24)$$

Work required for pumping:

$$W_{CP} = \dot{m}_5(h_6 - h_5) \quad (25)$$

$$W_{BFP} = \dot{m}_1(h_{10} - h_9) \quad (26)$$

$$W_{RP} = \dot{m}_m(h_n - h_m). \quad (27)$$

Heat rejected in condensers:

$$Q_{FC} = \dot{m}_5(h_4 - h_5) \quad (28)$$

$$Q_{GC} = \dot{m}_m(h_\ell - h_m). \quad (29)$$

Since the entire analysis was done for a unit mass of geofluid emerging from the well, the mass of steam leaving the separator (S) is simply x_a , the dryness fraction of the geofluid. Furthermore, if we define the hot water flash fraction, r_f , as follows,

$$r_f = \dot{m}_i / \dot{m}_g, \quad (30)$$

then the mass flow rates at various points around the plant may be determined.

Mass flow rates of geofluid:

$$\dot{m}_a \equiv 1 \quad (31)$$

$$\dot{m}_b = \dot{m}_c = \dot{m}_d = \dot{m}_e = \dot{m}_f = x_a \quad (32)$$

$$\dot{m}_g = 1 - x_a \quad (33)$$

$$\dot{m}_h = \dot{m}_q = \dot{m}_r = (1 - r_f)(1 - x_a) \quad (34)$$

$$\dot{m}_i = r_f(1 - x_a) \quad (35)$$

$$\dot{m}_j = x_i, r_f(1 - x_a) \quad (36)$$

$$\dot{m}_k = \dot{m}_\ell = \dot{m}_m = \dot{m}_n = x_a + x_i, r_f(1 - x_a) \quad (37)$$

$$\dot{m}_p = r_f(1 - x_i,)(1 - x_a) \quad (38)$$

$$\dot{m}_s = \dot{m}_t = (1 - r_f x_i,)(1 - x_a). \quad (39)$$

Mass flow rates of clean water substance:

$$\dot{m}_2 = \dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}_8 = \quad (40)$$

$$= (1 - x_a) \{ (1 - r_f)h_h + r_f(1 - x_i,)h_p - (1 - r_f x_i,)h_t \} / (h_9 - h_7)$$

$$\dot{m}_{2'} = \dot{m}_2(h_9 - h_8) / (h_2 - h_9) \quad (41)$$

$$\dot{m}_1 = \dot{m}_9 = \dot{m}_{10} = \dot{m}_2 + \dot{m}_{2'}. \quad (42)$$

Thus the figures of merit, F , F_f , and F_g , from eqs. (1-3) may be calculated using

$$W = W_{FT1} + W_{FT2} + W_{GT1} + W_{GT2} - W_{CP} - W_{BFP} - W_{RP}, \quad (43)$$

$$W_f^* = 0.43 (Q_{SG} + Q_{RH} + Q_{FSH}), \quad (44)$$

together with eqs. (11) and (12) for W_g^* .

5. FORTTRAN COMPUTER CODES

5.1 Properties of Water Substance

For the purpose of the parametric computer studies of the hybrid plants, the working fluids, i.e., the clean water substance and the geothermal fluid, have been taken to be pure water substance. That is, the results of the parametric studies do not reflect the impact of dissolved solids and noncondensable gases that may have an effect on the output of the geothermal side of the plant in particular. However, in the site-specific applications we have incorporated a correction factor to account roughly for the effect of dissolved solids. (See Section 6.3.1.)

The properties of water in the liquid and vapor phases were computed according to the fundamental equation of state devised by J. H. Keenan, *et al* [11]. A set of subroutines, coded by H. E. Khalifa and used in our earlier studies of hybrid systems [1-3], were employed by the main program.

Appendices A-F list the five subroutines needed to find the thermodynamic properties at each of the state points for each cycle. Subroutine PROPS (Appendix A) contains five arguments: pressure, P ; temperature, T ; specific enthalpy, H ; specific entropy, S ; and specific volume, V . The value of the control variable, IN , determines which of these variables are taken as independent and which are dependent; i.e.,

when $IN = 0$, P and T are the independent variables,

when $IN = 1$, P and S are the independent variables,

and when $IN = 2$, P and H are the independent variables.

In each case, the other three variables are computed.

Subroutines PETE (Appendix B) and TRUMP (Appendix C) are aids to subroutine PROPS. Subroutine BOILT (Appendix D) computes the saturation temperature for a given vapor pressure, and subroutine SATUR (Appendix E) is used to find the saturation enthalpy, H , for a specified vapor pressure. When the control variable, IS , in SATUR is equal to 0, the value of H is for saturated liquid; when $IS=1$, the value of H is for saturated vapor.

5.2 Main Program for Systems Analysis

Appendix F contains a listing of the FORTRAN code used as the main program for the two-stage system analysis, and, when the flash fraction $r_f = 0$, for the one-stage analysis as well. The basic structure of the program consists of three nested DO-loops. The inner loop varies the hot water flash fraction r_f ; the middle loop varies the wellhead quality x_a ; and the outer loop varies the wellhead temperature T_a . No attempt was made to optimize the program for minimum running time since the program is relatively short. Rather, it was written in a simple, straightforward, block format to facilitate debugging. The program was executed in an interactive mode through a keyboard and a CRT terminal, with the final output being printed off-line.

6. RESULTS AND APPLICATIONS

6.1 System Configurational Assumptions

The computer analyses were performed on systems with specific configurational parameters. The fixed system parameters are listed in Table 1; the ranges of the variable parameters are given in Table 2. The characteristics of the geofluid at the wellhead were chosen to cover a wide range of values that might be expected at typical liquid-dominated geothermal fields.

A subcritical Rankine cycle was selected for the fossil side of the plant in accordance with a growing trend in the power industry [12]. The extraction pressure was set at 25% of the main steam pressure, also in accordance with practice. The temperature of the superheated geothermal steam was held to a conservative 510°C (950°F) instead of the 540°C (1004°F) that is customary for pure steam in order to allow for possible difficulties because of impurities that may elude the scrubbers. More exotic materials may thus be required in the geothermal steam superheater, and such materials generally have poorer heat transfer characteristics than mild steel.

In the case of two-stage systems, no attempt was made to determine an optimum flash pressure (state points i' , j , p). Instead, a fixed value of 0.2 MPa (29 lbf/in²) was selected. This pressure being above atmospheric will assure that the waste hot liquid will flow under its own head from the flash vessel, through the brine heater, and into the injection well. (See Fig. 4.) According to the so-called "equal-temperature-split" rule [13], this choice of flash pressure should give nearly optimum results for a wellhead temperature of 200°C (392°F). However, the rule-of-thumb was devised for pure flash systems, not hybrid systems. In any event, earlier studies have shown that considerable latitude exists in the choice of flash point relative to the optimum without seriously affecting the thermodynamic performance of a hybrid plant [4].

Both condensers were chosen to operate at the same pressure, 5.6 kPa (1.9 in Hg), on the assumption that each condenser would be supplied from a common cooling water source. While somewhat on the low side for geothermal plants, this pressure is consistent with the design values for large central stations served by wet cooling towers. Such operating conditions ought to be attainable with surface-type condensers in conjunction with cooling techniques including wet or wet/dry cooling towers or phased-storage with cooling ponds

and/or spray modules [14]. Finally we have allowed for a 10% pressure loss in all heat exchangers, including the steam generators. The results of the thermodynamic analyses presented in this report thus should reflect the realities of practical power plant design considerations.

6.2 Results of Parametric Studies

The results of the computations are given starting in Table 3 where the combined, fossil, and geothermal figures of merit and the net plant work (per unit mass of geofluid at the wellhead) may be found for one-stage systems. Values are listed for all combinations of wellhead temperature (150, 200, 250°C) and wellhead quality (10, 20, 30, 40%). The calculations were performed for the system shown in Fig. 3 whose thermodynamic cycle is sketched in Fig. 5.

Similar results are given for two-stage systems in Tables 4-7; each table corresponds to a particular value for the hot water flash fraction, and shows results for the same combinations of wellhead temperature and quality as Table 3.

Selected families of curves are plotted in Figs. 8-16. The first three graphs (Figs. 8-10), show the figures of merit, F , F_f , and F_g , as a function of flash fraction r_f for a fixed wellhead quality of 20% and wellhead temperatures of 150, 200, and 250°C, respectively. The values of F and F_f increase with increasing flash fraction, the dependency growing stronger for higher wellhead temperatures. At the lowest temperature studied, F_g depends weakly on r_f ; an inverse relation exists between F_g and r_f for higher temperatures, again with the dependency being greatest at the highest temperature. In all cases, all figures of merit exceed unity, indicating that the hybrid plant holds a thermodynamic advantage over two, separate state-of-the-art geothermal and fossil power plants receiving the same input as the hybrid plant. This

advantage ranges from 50-75% from the geothermal viewpoint (i.e., F_g), from 5-33% from the fossil viewpoint (i.e., F_f), and from 5-20% from a combined viewpoint (i.e., F), for the particular conditions selected for Figs. 8-10.

Figure 11 shows a cross-plot of the figures of merit versus wellhead temperature for $r_f = 0.5$ and $x_a = 20\%$. The geothermal figure of merit passes through a maximum at about 210°C (410°F), whereas F and F_f increase monotonically with T_a .

The net work output, W , per unit mass of geofluid at the wellhead is plotted against flash fraction for each value of quality in Figs. 12-14, for $T_a = 150$, 200 , and 250°C , respectively. The dependence is linear in all cases. Interestingly, the results for 200 and 250°C exhibit a focal point at which the net work is independent of quality. This occurs roughly for a flash fraction equal to 67% at 200°C , and to 37% at 250°C . The net work ranges from about 0.6 - 1.4 kJ/g (260 - 600×10^6 Btu/lbm).

Figure 15 is a cross-plot of W versus wellhead temperature for $x_a = 20\%$ and with r_f as a parameter. The net work is seen to fall off with flash fraction and with wellhead temperature, except for the case of one-stage systems (i.e., $r_f = 0$). Two curves are shown in this case, a and b. The curve labeled b corresponds to the case where the two-stage system (Fig. 4) was simply analyzed for $r_f = 0$. In such a case, the regenerator is not feasible and would not be included in the physical plant. However, the computations were done consistently with the cases when $r_f \neq 0$, and a pressure loss was taken from state b to c and from e to f, even though $T_c = T_b$ and $T_f = T_e$. Curve a, on the other hand, was obtained from a separate program (not listed in the Appendices) that was used to analyze one-stage systems only.

The same discrepancy was evident in the earlier figures (Figs. 8 - 10) for $r_f = 0$ in which the circles were obtained from the separate one-stage

program.

Figure 16 shows F , F_f , F_g , and W as a function of wellhead quality for $T_a = 200^\circ\text{C}$ and $r_f = 50\%$.

Tables 8 - 11 list the design factors: ψ , the work amplification factor, and $\dot{m}_1$ and $\dot{m}_2$, the mass flow rates (per unit mass flow of geofluid at the wellhead) of clean, main steam and bleed steam, respectively.

Fuel conservation factors are given in Tables 12 - 15. These include: the overall figure of merit, F_o , that takes into account the finite size of the geothermal and fossil resources committed to a given hybrid plant; the hybrid fossil-fuel savings factor, ϕ_h , that gives the savings over an all-fossil plant of the same output; and the displacement factor, ϕ_d , that gives the savings over a properly matched geothermal plant and an all-fossil plant sized to make up the difference between the capacity of the hybrid plant and that of the geothermal plant. For most cases included in the last four tables, the conditions are such that the relative depletion parameter, Δ , exceeds unity (except for the entries denoted by an asterisk), i.e., the geothermal resource is depleted before the fossil resource.

The question of resource depletion is treated in more detail in Section 6.4.

6.3 Site-Specific Applications

In the following sections we apply the concept of the compound hybrid plant to six promising liquid-dominated geothermal resource areas in the western United States. The sites were chosen to cover a wide range of resource conditions. The plants chosen for each site are not intended to be "optimal" in any absolute sense, but rather illustrate certain advantageous features of hybrid plants.

The geothermal resource characteristics, the type of plant for each

site, and the general objective governing the choice of plant are given in Table 16.

6.3.1 Salton Sea (Niland), CA

This resource has the highest temperature and the highest concentration of dissolved solids (TDS) of any geothermal field in the United States. Owing to the extremely high levels of solids, $\sim 250,000$ ppm or 25%, it was necessary to correct the work output terms from our computer calculations that were based on pure water. The net work output from the geothermal turbines was reduced by 0.8% for each 1% of TDS [15], or by a total of 20% in this case.

A two-stage plant with a 100% flash fraction was selected in order to achieve high figures of merit for fossil-fuel usage and for combined resource usage.

6.3.2 Baca No. 1 (Valles Caldera), NM

The first, large geothermal demonstration plant, supported in part by the Department of Energy, is under construction at this site. The resource is relatively hot and quite clean. The two-stage plant with a 50% flash fraction was chosen to yield a high figure of merit for geothermal energy utilization.

6.3.3 Roosevelt Hot Springs, UT

Earlier studies commissioned by the City of Burbank, CA showed that this site was advantageous both technically and economically as a location for a hybrid plant of the geothermal-preheat type [8]. A number of coal fields lie in relatively close proximity to the KGRA. Since the wellhead geofluid characteristics are similar to those at Baca No. 1, the same type of plant was selected and should yield a high F_g .

6.3.4 Brawley, CA

The Brawley site is characterized by a moderate-temperature geofluid carrying about 100,000 ppm or 10% dissolved solids. The same correction factor for geothermal work output was applied as in the case of the Salton Sea KGRA, i.e., work output for pure water was reduced by 8% to account for the presence of the dissolved solids. The goal of the two-stage plant with a 75% flash fraction was to achieve a balance of good values for the utilization factors F , F_f , and F_g .

6.3.5 Coso Hot Springs (China Lake), CA

Preliminary results of exploration studies indicate that Coso may be a valuable geothermal resource. Technical proposals are being sought by the U. S. Navy for energy conversion systems capable of 30-year operation [16]. The temperature is moderate and the dissolved solids are low. A two-stage plant with a 25% flash fraction was selected to give high values for F_g and net specific work output W .

6.3.6 East Mesa, CA

This example was selected to illustrate the application of hybrid plants to resources of moderate-to-low temperature and low wellhead quality. The concentration of dissolved solids was taken as less than 1% although one well (Mesa 6-1) contains about 2.5% TDS. Other wells reveal TDS concentrations that lie below 1%. In light of the relatively low wellhead temperature of 150°C (302°F), a one-stage plant was chosen, i.e., a 0% flash fraction. This should yield a high value for the net specific work output and result in a minimum geofluid flow rate for a given plant capacity.

6.3.7 Summary of Results

Table 17 lists a number of performance characteristics for each of the compound hybrid plants for the six KGRAs. The mass flow rates of the geofluid and the clean steam, $\dot{m}_a$, $\dot{m}_1$, and $\dot{m}_2$, and the required number of geothermal wells, are given per 100 MW of hybrid plant net capacity, and may be scaled up or down for plants of other sizes. The entry, W_g/W_{net} , shows the geothermal contribution to the total plant output, and ranges from 3.5% for the East Mesa plant to 47% at the Salton Sea.

There are two effective efficiencies listed, $\eta_{eff,f}$ and $\eta_{eff,g}$. These are computed as follows:

$$\eta_{eff,f} = F_f \eta_f^* , \quad (45)$$

$$\eta_{eff,g} = F_g \eta_g^* \quad (46)$$

These may be viewed as effective energy conversion efficiencies for fossil or geothermal energy, allowing for the maximum, presently-attainable utilization efficiency for the other resource. It has been shown [2, 17] that these efficiencies are essentially Second Law efficiencies, even in the case of fossil-fuel utilization since the available work (exergy) of a fossil fuel is essentially equal to its standard heat of reaction. Thus for fossil fuels, the so-called First and Second Law efficiencies, while different in concept, are nearly equal numerically.

The compound hybrid plants at the selected KGRAs have effective fossil-fuel efficiencies ranging from 44 to 58%, and effective geothermal efficiencies of from 79 to 84%.

The last entry in Table 17 is the percentage savings in fossil fuel when the hybrid plant is built instead of an all-fossil plant of the same net out-

put. The savings amount to 49% for the hybrid plant at the Salton Sea, roughly 20% for the plants at Baca No. 1, Roosevelt, and Brawley, 14% for Coso, and 7% for East Mesa.

6.4 Optimal Matching of Plant and Resources

We have established the fact that compound hybrid power plants have a thermodynamic advantage over either a pure fossil plant, a pure geothermal plant, or a combination of such plants. When one takes into account the finite nature of the two energy sources supplying a given plant, it becomes clear that the optimum use will be made of both resources when the plant is so matched to the resources that the two energy supplies are depleted at the same time. Otherwise, the one resource which remains would most likely have to be used in a conventional, non-hybrid plant at a lower utilization efficiency. This latter statement is almost certainly true in the case when the fossil fuel supply is depleted first, leaving the geothermal resource to be used on the site. In the other case, the rest of the fossil fuel could be transported elsewhere for use, and perhaps even to another geothermal site where it might be used in another hybrid plant, but it is probably true that the second site would be less advantageous than the one to which the fossil fuel was committed in the first place.

Therefore, as was shown in our earlier works [2, 3], the relative depletion parameter, Δ , eqs. (6, 7), should, if possible, be designed equal to unity, ensuring simultaneous depletion of the two resources and the maximum overall figure of merit, F_0 , eqs. (4, 5).

The variation of the relative depletion parameter and of the overall figure of merit were examined as a function of the resource ratio, R , for a family of two-stage compound hybrid plants (i.e., $0 \leq r_f \leq 1$), utilizing a hypotheti-

cal geothermal resource having 200°C (392°F) wellhead temperature and 20% wellhead quality. The results are plotted in Fig. 17.

It may be seen that for resource ratios less than about 0.14 there is little to choose among the family of plants although those with zero flash fractions hold a small advantage over the others. It is in this region where the geothermal resource gives out before the fossil resource, i.e., $\Delta > 1$.

On the other hand, for values of $R > 0.31$, the advantage lies with plants having $r_f = 1.0$, and the improvement in F_o is significant in comparison to, say, a plant with $r_f = 0.0$. In these cases, $\Delta < 1$, indicating that the fossil fuel resource is the first to be depleted.

For resource ratios lying between 0.14 and 0.31, it is possible to choose a compound hybrid plant with a particular flash fraction that leads to an optimum overall figure of merit. This selection will be determined by the condition that $\Delta = 1$. Figure 18 gives the upper envelope of the family of curves for F_o , starting with the case of $r_f = 0$, including the locus (broken line) of optimum F_o values for $r_f = 0.25, 0.50, 0.75$, and continuing with plants having $r_f = 1$. The portion over which $\Delta = 1$ is shown in rectilinear coordinates in Fig. 19 for ease of interpolation.

In practice a designer would likely be confronted with the case of a geothermal resource with a certain assessed electric generation capability of W_g^0 megawatts over, say, a 30-year lifetime (assuming conversion to electricity in a state-of-the-art geothermal power plant). If there is a fossil resource that can be justified on economic grounds to be committed to a hybrid plant at the geothermal site, then the designer should specify that an amount of fossil resource equivalent to $3.2 W_g^0$ (i.e., $W_g^0/0.31$) be contracted for to supply the hybrid plant having a hot water flash fraction of 100%. For the hypothetical resource under consideration (point f in Fig. 18), this will result in slightly

over 15% more electrical output over the lifetime of the energy resources than separate utilization of the resources in state-of-the-art geothermal and fossil plants.

There is no thermodynamic advantage to be gained by allotting more fossil fuel than $3.2 W_g^0$ since the excess will not be used at the highest possible effective efficiency. If for other reasons, one wishes to assign a greater amount of fossil fuel to the hybrid plant than the optimum value, then the flash fraction should be adjusted downward in accordance with Fig. 18 or 19. For example, if $5 W_g^0$ is assigned to the plant, then r_f should be set at 0.56 to achieve an optimal F_o (about 11.3% gain).

Furthermore, if it is not possible to commit at least the equivalent of $3.2 W_g^0$ of fossil fuel to the hybrid plant, then the designer should select a plant with a 100% flash fraction, and settle for a lower gain than the ultimate. For example, if only $2 W_g^0$ of fossil fuel can be obtained, then the fossil fuel will deplete before the geothermal resource ($\Delta = 0.62$, Fig. 17), and the overall gain will be limited to 13.3% (Fig. 18). Of course, the designer in such a case might opt to consider hybrid plants of a different generic type such as the gas turbine topping system described elsewhere [6], in an effort to obtain even higher values of the overall figure of merit.

7. Conclusions

Compound hybrid geothermal-fossil power plants are significantly superior to conventional, individual geothermal and fossil plants in regard to the thermodynamic utilization of the available energy resources. The margin of superiority depends on the particular configuration of the hybrid plant and the characteristics of the geothermal resource. The hybrid plants proposed in this paper use components that are familiar to designers and which are employed in fossil and geothermal power plants now in operation around the world. What is lacking, however, is long-term operating experience with certain of

the geothermal elements such as brine heat exchangers, superheaters carrying geothermal steam, piping systems to handle geothermal brines, and reinjection pumps.

Compound hybrid plants are flexible enough to be adapted to a wide range of geothermal resources over a full range of plant capacities. They may be designed to depend more or less upon either of the energy sources to accommodate the availability of the respective "fuels". Since hybrid plants are more efficient than conventional ones, the use of hybrid plants would result in considerable savings in fossil fuels required to generate the same output. Of course, it is obvious that the construction of an all-geothermal plant in lieu of an all-fossil one would also lead to savings in fossil fuel, but a hybrid plant produces a greater overall savings of the combined resources because of its synergistic characteristics. Thus, the useful lifetime of the non-renewable fossil fuel and of the depletable geothermal resource can be extended by the implementation of the hybrid geothermal-fossil concept in future power plants.

There appear to be several sites in the western United States where hybrid geothermal-fossil plants are technically feasible [10]. The applicability of such plants, however, will ultimately turn on the economics of each particular proposal. The results of such an assessment will be strongly site-specific and involve importantly the differential cost of transporting the fossil fuel to the proposed site of the hybrid plant (essentially coincident with the associated geothermal field) in comparison with the cost to ship it to the site of an alternate all-fossil plant designed to provide the same power. It is encouraging that such studies as have been done so far [7] indicate that reductions of about 10% in the busbar cost of electricity may be achievable under certain circumstances.

ACKNOWLEDGEMENTS

This work was performed with support from DOE/DGE Contract EY-76-S-02-4051.A002 to Brown University, Dr. J. Kestin, Principal Investigator, Mr. C. B. McFarland, Program Manager. Much of the earlier work on which this study is based was done in collaboration with Dr. H. E. Khalifa, now with the United Technologies Research Center, East Hartford, CT. In particular Dr. Khalifa contributed importantly to the development of the compound hybrid plant concept while he was at Brown University. The authors wish to extend their appreciation to Dr. Khalifa for the use of his FORTRAN code for the properties of water substance, and for his helpful suggestions during the course of this study. A major portion of the calculations for this study were performed on the DEC-20 computing system at Southeastern Massachusetts University (SMU). The bulk of the work reported herein was used to satisfy in part the requirements for the Bachelor of Science degree in Mechanical Engineering from SMU for one of the authors (E. M. Avelar).

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Table 1 Fixed system parameters

<u>Conditions</u>	<u>State*</u>	<u>Type of System</u>	
		<u>One-stage</u>	<u>Two-stage</u>
Fossil side:			
Main steam temperature, °C(°F)	①	540(1004)	540(1004)
Main steam pressure, MPa(lbf/in ²)	①	16.5(2400)	16.5(2400)
Extraction pressure, MPa(lbf/in ²)	②	4.1(595)	4.1(595)
Reheat steam temperature, °C(°F)	③	540(1004)	540(1004)
Reheat steam pressure, MPa(lbf/in ²)	③	3.9(565)	3.9(565)
Turbine isentropic efficiency:			
High-pressure turbine, FT1		82%	82%
Low-pressure turbine, FT2		85%	85%
Geothermal side:			
Main steam temperature, °C(°F)	④	510(950)	510(950)
Flash vessel pressure, MPa(lbf/in ²)	①' ④ ⑤	--	0.2(29)
Turbine isentropic efficiency		85%	85%
Regenerator effectiveness		--	80%
General:			
Condenser pressure, kPa(in Hg)	④ ⑤	5.6(1.9)	5.6(1.9)
Pump isentropic efficiency		80%	80%
Pressure loss in heat exchangers		10%	10%

*See Fig. 3 for one-stage systems and Fig. 4 for two-stage systems.

Table 2 Variable system parameters

<u>Conditions</u>	<u>State*</u>	<u>Type of System</u>	
		<u>One-stage</u>	<u>Two-stage</u>
Geofluid temperature, °C	(a)	150, 200, 250	150, 200, 250
Geofluid quality, %	(a)	10, 20, 30, 40	10, 20, 30, 40
Flash fraction, %	(i)/(g)	0	25, 50, 75, 100

*See Fig. 3 for one-stage systems and Fig. 4 for two-stage systems.

Table 3 Performance of one-stage compound systems

Wellhead quality	=	10%	20%	30%	40%
Wellhead temperature					
150°C(302°F)	F	= 1.032	1.045	1.059	1.074
	F _f	= 1.034	1.048	1.066	1.087
	F _g	= 1.612	1.562	1.535	1.517
	W	= 1.432	1.366	1.301	1.235
200°C(392°F)	F	= 1.066	1.083	1.102	1.123
	F _f	= 1.072	1.094	1.121	1.153
	F _g	= 1.759	1.696	1.657	1.631
	W	= 1.415	1.367	1.318	1.270
250°C(482°F)	F	= 1.095	1.116	1.138	1.163
	F _f	= 1.109	1.139	1.174	1.216
	F _g	= 1.745	1.707	1.681	1.663
	W	= 1.392	1.357	1.323	1.288

Note: Units of W are kJ/g. Multiply by 430 to obtain 10⁶ Btu/lbm.

Table 4 Performance of two-stage compound systems:
flash fraction = 25%

Wellhead quality		=	10%	20%	30%	40%
Wellhead temperature						
150°C(302°F)	F	=	1.036	1.051	1.068	1.088
	F _f	=	1.039	1.056	1.078	1.106
	F _g	=	1.628	1.578	1.552	1.536
	W	=	1.313	1.238	1.164	1.090
200°C(392°F)	F	=	1.075	1.098	1.123	1.151
	F _f	=	1.083	1.113	1.150	1.195
	F _g	=	1.751	1.713	1.690	1.673
	W	=	1.236	1.202	1.168	1.134
250°C(482°F)	F	=	1.104	1.130	1.157	1.185
	F _f	=	1.123	1.160	1.204	1.257
	F _g	=	1.691	1.679	1.671	1.666
	W	=	1.190	1.180	1.170	1.160

Note: See note for Table 3.

Table 5 Performance of two-stage compound systems:
flash fraction = 50%

Wellhead quality	=	10%	20%	30%	40%
Wellhead temperature					
150°C(302°F)	F	= 1.040	1.056	1.074	1.095
	F _f	= 1.042	1.061	1.085	1.115
	F _g	= 1.635	1.583	1.555	1.537
	W	= 1.213	1.150	1.087	1.023
200°C(392°F)	F	= 1.084	1.110	1.138	1.168
	F _f	= 1.095	1.131	1.173	1.225
	F _g	= 1.716	1.689	1.672	1.661
	W	= 1.059	1.045	1.031	1.016
250°C(482°F)	F	= 1.115	1.144	1.174	1.205
	F _f	= 1.141	1.187	1.240	1.302
	F _g	= 1.621	1.628	1.633	1.637
	W	= 0.982	0.995	1.008	1.021

Note: See note for Table 3.

Table 6 Performance of two-stage compound systems:
flash fraction = 75%

Wellhead quality	=	10%	20%	30%	40%
Wellhead temperature					
150°C(302°F)	F	= 1.044	1.061	1.080	1.103
	F _f	= 1.047	1.068	1.094	1.127
	F _g	= 1.641	1.587	1.557	1.539
	W	= 1.113	1.061	1.009	0.957
200°C(392°F)	F	= 1.097	1.127	1.157	1.190
	F _f	= 1.113	1.156	1.207	1.268
	F _g	= 1.682	1.665	1.655	1.649
	W	= 0.883	0.888	0.893	0.899
250°C(482°F)	F	= 1.131	1.166	1.199	1.232
	F _f	= 1.172	1.232	1.299	1.374
	F _g	= 1.552	1.577	1.595	1.609
	W	= 0.774	0.810	0.846	0.883

Note: See note for Table 3.

Table 7 Performance of two-stage compound systems:
flash fraction = 100%

Wellhead quality	=	10%	20%	30%	40%
Wellhead temperature					
150°C (302°F)	F	= 1.049	1.067	1.088	1.112
	F _f	= 1.053	1.076	1.105	1.141
	F _g	= 1.648	1.591	1.560	1.541
	W	= 1.013	0.972	0.931	0.890
200°C (392°F)	F	= 1.117	1.151	1.186	1.220
	F _f	= 1.143	1.198	1.262	1.335
	F _g	= 1.648	1.641	1.638	1.636
	W	= 0.707	0.731	0.756	0.781
250°C (482°F)	F	= 1.161	1.202	1.238	1.271
	F _f	= 1.242	1.327	1.415	1.506
	F _g	= 1.483	1.527	1.558	1.581
	W	= 0.567	0.625	0.685	0.744

Note: See note for Table 3.

Table 8 Design parameters for two-stage systems:
flash fraction = 25%

Wellhead quality	=	10%	20%	30%	40%	
Wellhead temperature						
150°C (302°F)	ψ	=	17.96	11.93	8.65	6.60
	$\dot{m}_1$	=	1.032	0.918	0.803	0.688
	$\dot{m}_{2'}$	=	0.199	0.177	0.153	0.133
200°C (392°F)	ψ	=	10.79	8.01	6.30	5.13
	$\dot{m}_1$	=	0.873	0.776	0.679	0.582
	$\dot{m}_{2'}$	=	0.099	0.088	0.077	0.066
250°C (482°F)	ψ	=	7.31	5.92	4.96	4.26
	$\dot{m}_1$	=	0.751	0.667	0.584	0.500
	$\dot{m}_{2'}$	=	0.0088	0.0078	0.0069	0.0059

Note: $\dot{m}_1$ = flow rate of clean, main steam per unit flow rate of geofluid.

$\dot{m}_{2'}$ = flow rate of bleed steam per unit flow rate of geofluid.

Table 9 Design parameters for two-stage systems:
flash fraction = 50%

Wellhead quality =		10%	20%	30%	40%
Wellhead temperature					
150°C(302°F)	ψ =	16.59	11.07	8.08	6.19
	$\dot{m}_1$ =	0.945	0.840	0.735	0.630
	$\dot{m}_{2'}$ =	0.182	0.162	0.142	0.121
200°C(392°F)	ψ =	9.25	6.96	5.56	4.60
	$\dot{m}_1$ =	0.724	0.644	0.563	0.483
	$\dot{m}_{2'}$ =	0.082	0.073	0.064	0.055
250°C(482°F)	ψ =	6.03	4.99	4.27	3.75
	$\dot{m}_1$ =	0.584	0.519	0.454	0.389
	$\dot{m}_{2'}$ =	0.0069	0.0061	0.0053	0.0046

Note: See note for Table 8.

Table 10 Design parameters for two-stage systems:
flash fraction = 75%

Wellhead quality		=	10%	20%	30%	40%
Wellhead temperature						
150°C(302°F)	ψ	=	15.23	10.22	7.50	5.79
	$\dot{m}_1$	=	0.857	0.762	0.667	0.571
	$\dot{m}_2$	=	0.165	0.147	0.128	0.110
200°C(392°F)	ψ	=	7.71	5.92	4.82	4.07
	$\dot{m}_1$	=	0.576	0.512	0.448	0.384
	$\dot{m}_2$	=	0.066	0.058	0.051	0.044
250°C(482°F)	ψ	=	4.76	4.06	3.59	3.24
	$\dot{m}_1$	=	0.417	0.371	0.325	0.278
	$\dot{m}_2$	=	0.0049	0.0044	0.0038	0.0033

Note: See note for Table 8.

Table 11 Design parameters for two-stage systems:
flash fraction = 100%

Wellhead quality =		10%	20%	30%	40%
Wellhead temperature					
150°C (302°F)	ψ =	13.86	9.37	6.92	5.39
	$\dot{m}_1$ =	0.769	0.684	0.598	0.513
	$\dot{m}_{2'}$ =	0.148	0.131	0.115	0.099
200°C (392°F)	ψ =	6.17	4.88	4.08	3.53
	$\dot{m}_1$ =	0.527	0.380	0.332	0.285
	$\dot{m}_{2'}$ =	0.049	0.043	0.038	0.032
250°C (482°F)	ψ =	3.48	3.14	2.90	2.73
	$\dot{m}_1$ =	0.251	0.223	0.195	0.167
	$\dot{m}_{2'}$ =	0.0030	0.0026	0.0023	0.0020

Note: See note for Table 8.

Table 12 Fuel conservation factors for two-stage systems:
flash fraction = 25%

Wellhead quality =		10%	20%	30%	40%
Wellhead temperature					
150°C (302°F)	F_o =	1.035*	1.051*	1.050	1.049
	ϕ_h =	9.07	14.29	17.94	23.28
	ϕ_d =	3.30	4.76	5.48	6.78
200°C (392°F)	F_o =	1.068	1.065	1.063	1.061
	ϕ_h =	16.24	21.39	26.84	32.61
	ϕ_d =	6.27	7.68	9.00	10.18
250°C (482°F)	F_o =	1.063	1.062	1.061	1.061
	ϕ_h =	23.13	28.36	33.70	39.13
	ϕ_d =	8.02	9.28	10.38	11.28

*In these two cases, $\Delta < 1$; otherwise, $\Delta > 1$.

Table 13 Fuel conservation factors for two-stage systems:
flash fraction = 50%

Wellhead quality =		10%	20%	30%	40%
Wellhead temperature					
150°C (302°F)	F_o =	1.039*	1.053	1.050	1.049
	ϕ_h =	9.85	14.29	19.25	24.82
	ϕ_d =	3.58	4.76	5.96	7.14
200°C (392°F)	F_o =	1.065	1.063	1.061	1.060
	ϕ_h =	18.56	24.26	30.09	36.11
	ϕ_d =	6.84	8.33	9.62	10.72
250°C (482°F)	F_o =	1.057	1.057	1.058	1.058
	ϕ_h =	26.87	32.62	38.22	43.69
	ϕ_d =	8.39	9.70	10.75	11.54

*In this case, $\Delta < 1$; otherwise, $\Delta > 1$.

Table 14 Fuel conservation factors for two-stage systems:
flash fraction = 75%

Wellhead quality =		10%	20%	30%	40%
Wellhead temperature					
150°C(302°F)	F_o =	1.043*	1.052	1.051	1.049
	ϕ_h =	10.78	15.53	20.77	26.58
	ϕ_d =	3.92	5.15	6.36	7.54
200°C(392°F)	F_o =	1.062	1.060	1.060	1.059
	ϕ_h =	21.82	28.12	34.36	40.50
	ϕ_d =	7.59	9.09	10.33	11.28
250°C(482°F)	F_o =	1.050	1.053	1.054	1.055
	ϕ_h =	32.63	38.81	44.48	49.69
	ϕ_d =	8.84	10.13	11.05	11.65

*In this case, $\Delta < 1$; otherwise, $\Delta > 1$.

Table 15 Fuel conservation factors for two-stage systems:

flash fraction = 100%

Wellhead quality	=	10%	20%	30%	40%
Wellhead temperature					
150°C(302°F)	F_o	= 1.048*	1.054	1.051	1.049
	ϕ_h	= 11.89	16.99	22.54	28.60
	ϕ_d	= 4.32	5.59	6.82	7.89
200°C(392°F)	F_o	= 1.059	1.058	1.058	1.058
	ϕ_h	= 26.71	33.66	40.18	46.29
	ϕ_d	= 8.60	10.05	11.10	11.79
250°C(482°F)	F_o	= 1.044	1.048	1.051	1.053
	ϕ_h	= 42.61	48.66	53.69	57.93
	ϕ_d	= 9.25	10.36	11.02	11.38

*In this case, $\Delta < 1$; otherwise, $\Delta > 1$.

Table 16 Characteristics for site-specific case studies

	<u>Known Geothermal Resources Area (KGRA)</u>					
	<u>Salton Sea</u>	<u>Baca No. 1</u>	<u>Roosevelt</u>	<u>Brawley</u>	<u>Coso</u>	<u>East Mesa</u>
References ^(a)	[A, G, H]	[D, G, H]	[C, E - H]	[G, H]	[G, H]	[B, G, H]
Reservoir temp., °C	330	278	260	250	230	180
Wellhead temp., °C	235	182	187	180	167	150
Well flow, t/h	159	113	277	227	227	54
Wellhead quality, %	28	15 ^(b)	17	16	14	6
Dissolved solids, %	25	0.5	<0.8	10	0.2	<1
Hybrid plant type	2-stage	2-stage	2-stage	2-stage	2-stage	1-stage
Flash fraction, %	100	50	50	75	25	---
Objective	High F, F _f	High F _g	High F _g	Good F, F _f , F _g	High F _g , W	High W

(a) References for resource characteristics are listed on the next page.

(b) Some references quote values as high as 35%.

References for Table 16

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- [H] Williams, F., Cohen, A., Pfundstein, R., and Pond, S., 1977, "Site-Specific Analysis of Geothermal Development-Data Files for Prospective Sites", MITRE Tech. Rep. MTR-7586, Vol. III, DGE/4014-1, Metrek Div., The MITRE Corp, McLean, VA.

Table 17 Hybrid plant performance for six KGRA's

Known Geothermal Resources Area (KGRA)

<u>Characteristic</u>	<u>Salton Sea</u>	<u>Baca No. 1</u>	<u>Roosevelt</u>	<u>Brawley</u>	<u>Coso</u>	<u>East Mesa</u>
W_{net} , kJ/g, geofluid	0.623	1.099	1.080	0.951	1.262	1.458
(Btu/lbm)	(268)	(473)	(464)	(409)	(543)	(627)
$\dot{m}_a$, t/100 MW·h	578	328	333	379	285	247
(klbm/100 MW·h)	(1274)	(722)	(735)	(835)	(629)	(544)
$\dot{m}_1$, t/100 MW·h	140	249	240	243	267	289
(klbm/100 MW·h)	(310)	(548)	(530)	(537)	(589)	(636)
$\dot{m}_2$, t/100 MW·h	3.7	36.7	33.2	37.1	45.1	55.6
(klbm/100 MW·h)	(8.2)	(80.9)	(73.2)	(81.8)	(99.4)	(122.5)
No. wells/100 MW	3.6	2.9	1.2	1.7	1.3	4.5
$(W_g/W_{net}) \times 100$	47.1	11.7	15.7	15.5	8.9	3.5
$\eta_{eff,f}$, %	58	47	47	48	46	44
$\eta_{eff,g}$, %	79	83	84	82	83	82
ϕ_h , %	49	18	19	21	14	7

Figure Captions

- Fig. 1 Geothermal-Preheat System. Key: SG = Steam Generator; HPT, IPT, LPT = High, Intermediate, Low Pressure Turbines; RH = Reheater; C = Condenser; GHX = Geothermal Heat Exchanger; D = Deaerator; FWH = Feedwater Heater.
- Fig. 2(a) One-Stage Fossil-Superheat System. Key: S/F = Separator/Flasher; R = Regenerator; FSH = Fossil-Fired Superheater; ST/G = Steam Turbine/Generator; DSH/C = Desuperheater/Condenser; P = Pump.
- Fig. 2(b) Two-Stage Fossil-Superheat System. Key: F1, F2 = Flashers; R = Regenerator; FSH = Fossil-Fired Superheater; ST1, ST2 = Steam Turbines; C = Condenser.
- Fig. 3 One-Stage Compound Hybrid System. Key: PW = Production Well; S = Separator; SG, SH, RH, FSH = Steam Generator and Superheaters; FT1, FT2 = Fossil Turbines; FG = Fossil Generator; FC = Fossil Condenser; CP = Condensate Pump; BH = Brine Heat Exchanger; FWH = Feedwater Heater; BFP = Boiler Feed Pump; GT = Geothermal Turbine; GG = Geothermal Generator; GC = Geothermal Condenser; RP = Reinjection Pump; IW = Injection Well.
- Fig. 4 Two-Stage Compound Hybrid System. Key: PW = Production Well; S = Separator; R = Regenerator; SG, SH, RH, FSH = Steam Generator and Superheaters; FT1, FT2 = Fossil Turbines; FG = Fossil Generator; FC = Fossil Condenser; CP = Condensate Pump; BH1, BH2 = Brine Heat Exchangers; FWH = Feedwater Heater; BFP = Boiler Feed Pump; F = Flasher; GT1, GT2 = Geothermal Turbines; GG = Geothermal Generator; GC = Geothermal Condenser; RP = Reinjection Pump; IW = Injection Well.
- Fig. 5 Temperature-Entropy Cycle Diagram for One-Stage Compound System.
- Fig. 6 Temperature-Entropy Cycle Diagram for Two-Stage Compound System.
- Fig. 7 Detail View of Brine Heater Section in T-s Coordinates.
- Fig. 8 Figures of Merit Versus Hot Water Flash Fraction: $T_a = 150^\circ\text{C}$ and $x_a = 20\%$.
- Fig. 9 Figures of Merit Versus Hot Water Flash Fraction: $T_a = 200^\circ\text{C}$ and $x_a = 20\%$.
- Fig. 10 Figures of Merit Versus Hot Water Flash Fraction: $T_a = 250^\circ\text{C}$ and $x_a = 20\%$.
- Fig. 11 Figures of Merit Versus Wellhead Temperature: $r_f = 0.5$ and $x_a = 20\%$.
- Fig. 12 Net Work Output Versus Hot Water Flash Fraction: $T_a = 150^\circ\text{C}$.
- Fig. 13 Net Work Output Versus Hot Water Flash Fraction: $T_a = 200^\circ\text{C}$.
- Fig. 14 Net Work Output Versus Hot Water Flash Fraction: $T_a = 250^\circ\text{C}$.

- Fig. 15 Net Work Output Versus Wellhead Temperature: $x_a = 20\%$.
- Fig. 16 Figures of Merit and Net Work Output Versus Wellhead Quality:
 $T_a = 200^\circ\text{C}$ and $r_f = 0.5$.
- Fig. 17 Overall Figure of Merit and Relative Depletion Parameter Versus
Resource Ratio: $T_a = 200^\circ\text{C}$ and $x_a = 20\%$.
- Fig. 18 Overall Figure of Merit in the Neighborhood of the Optimum Value:
 $T_a = 200^\circ\text{C}$ and $x_a = 20\%$.
- Fig. 19 Optimal Resource Ratio and Overall Figure of Merit Versus Hot
Water Flash Fraction: $T_a = 200^\circ\text{C}$ and $x_a = 20\%$

Fig. 1

Fig. 2(a)

Fig. 2(b)

Fig. 3

Fig. 5

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

FIGURES OF MERIT, F and F_f
NET WORK OUTPUT, W /(kJ/g of geofluid)

Fig. 16

Fig. 17

Fig. 18

Fig. 19

APPENDIX A

[coded by H.E. Khalifa]

SUBROUTINE PROPS (P,T,H,S,V,IN)

```

C
C THE KEENAN AND KEYES FUNDAMENTAL EQUATION FOR STEAM AND WATER
C
COMMON/CYCLE/PC,TC,A(10,7),B(7),C(8),D(7),F(8),HC,SC
COMMON/XYZ/ XX,LUX
C
KUT=0
XX=1000.0
ERR=0.0001
SL=.0
HL=.0
VG=0.0
IF (IN,NE,0) GO TO 901
CALL PETE (P,T,H,S,V,HG,SG,VG,0)
IF (VG,LT,0.1E-6) GO TO 999
901 DT=100.
IF (P,GE,PC) GO TO 801
CALL BOILT (P,TS)
T=TS-273.15
CALL PETE (P,T,HL,SL,VL,HG,SG,VG,0)
GO TO 802
801 T=TC-273.0
IF (IN,EQ,1) GO TO 702
GO TO 602
802 IF (IN,GT,1) GO TO 601
IF ((S,GT,SG).OR.(S,LT,SL)) GO TO 702
X=(S-SL)/(SG-SL)
XX=X
H=HL+X*(HG-HL)
V=VL+X*(VG-VL)
GO TO 999
702 DT=DT/10
IF (DT,LT,0.0001) ERR=0.001
IF (DT,LT,0.1E-5) GO TO 706
SEX=0.0
KILL=1
IF ((P,LT,PC).AND.(S,GT,SG)) T=T+0.01
703 CALL PETE (P,T,H,SE,V,HG,SG,VG,0)
IF (KILL,EQ,1) SEX=SE
DELS=ABS((SE-S)/S)
IF (DELS,LE,ERR) GO TO 999
DIF=S-SE
IF ((P,LT,PC).AND.(S,LT,SL)) GO TO 707
IF ((P,GE,PC).AND.(S,LE,SEX)) GO TO 707
IF (DIF) 704,999,705
704 T=T-DT
IF (T,LE,0.0) GO TO 706
GO TO 702
705 T=T+DT
IF (T,GT,1000.0) GO TO 706
KILL=KILL+1
GO TO 703
707 IF (DIF) 714,999,715
714 T=T-DT

```



```

      IF (T,LE,0.0) GO TO 706
      KILL=KILL+1
      GO TO 703
715  T=T+DT
      IF (T,GT,1000.) GO TO 706
      GO TO 702
706  WRITE ( 5,700)T,DT,S,DIF,P
700  FORMAT(10X,'CHECK P+S SEGMENT IN PROPS      ',5(F10.4,2X))
      GO TO 999
601  IF((H,GT,HG),OR,(H,LT,HL)) GO TO 602
      X=(H-HL)/(HG-HL)
      XX=X
      S=SL+X*(SG-SL)
      V=VL+X*(VG-VL)
      GO TO 999
602  DT=DT/10
      IF(DT,LT,0.001) ERR=0.001
      IF(DT,LT,0.0001) ERR=0.002
      IF(DT,LT,0.00001) ERR=0.005
      KILL=1
      HEX=0.0
      IF((P,LT,PC),AND,(H,GT,HG)) T=T+.01
603  CALL PETE (P,T,HE,S,V,HG,SG,VG,0)
      IF(KUT,GT,80) GO TO 999
      KUT=KUT+1
      IF(KILL,EQ,1) HEX=HE
      DELH=ABS((HE-H)/H)
      IF (DELH,LE,ERR) GO TO 999
      DIF=H-HE
      IF((P,LT,PC),AND,(H,LT,HL)) GO TO 607
      IF((P,GE,PC),AND,(H,LE,HEX)) GO TO 607
      IF (DIF) 604,999,605
604  T=T-DT
      IF (T,LE,0.0) GO TO 606
      GO TO 602
605  T=T+DT
      IF (T,GT,1000.0) GO TO 606
      KILL=KILL+1
      GO TO 603
607  IF (DIF) 614,999,615
614  T=T-DT
      IF (T,LE,0.0) GO TO 606
      KILL=KILL+1
      GO TO 603
615  T=T+DT
      IF (T,GT,1000.0) GO TO 606
      GO TO 602
606  WRITE( 5,600)T,DT,H,DIF,P
600  FORMAT(10X,'CHECK P+H SEGMENT IN PROPS      ',5(F10.4,2X))
999  CONTINUE
      RETURN

```

C
C

END

APPENDIX B

[coded by H.E. Khalifa]

```

SUBROUTINE PETE (P,T,H,S,V,HG,SG,VG,KER)
C
COMMON/CYCLE/PC,TC,A(10,7),B(7),C(8),D(7),F(8),HC,SC
C
TOL=.1E-4
LIQ=0
TOLY=.001
IF(P.LT.10.) TOLY=.005
IF(P.LT.1.) TOLY=.01
IF(P.LT..2) TOLY=.2
NUT=0
C
T=T+273.15
TAU=1000/T
F01=(C(7)/T)+C(8)*(1+ALOG(T))/1000
FOT1=C(7)*(ALOG(T)-1)-(C(8)/TAU)
R=0.46151
DO 6 L=1,6
F01=F01+(L-1)*C(L)*(TAU**(2-L))/1000
FOT1=FOT1+(2-L)*C(L)/(TAU**(L-1))
6 CONTINUE
ROS=0.1E-6
IF((T.LT.TC).AND.(P.LT.PC)) GO TO 7777
IF((T.LT.TC).AND.(P.GT.PC)) GO TO 913
IF((T-TC).LE.50.0).AND.(P.GE.PC)) GO TO 913
71 RO=ROS
M=1
7 CALL TRUMP (TAU,RO,Y,Q,Q1T,Q1RO,Q2RO)
DEL=ABS((P-Y)/P)
IF (LIQ.NE.0) GO TO 706
IF (DEL.LE.TOL) GO TO 27
GO TO 708
706 IF (DEL.LE.TOLY) GO TO 27
708 YP=4.6151*T*(1+2*RO*Q+4*RO*RO*Q1RO+(RO**3)*Q2RO)
707 RO=RO+(P-Y)/YP
M=M+1
L=L+1
C
IF(M.GT.20) GO TO 27
GO TO 7
C
27 H=R*T*(RO*TAU*Q1T+1+RO*Q+RO*RO*Q1RO)+FOT1
S=-R*(ALOG(RO)+RO*Q-RO*TAU*Q1T)-F01
T=T-273.15
V=1/RO
IF(M.GT.20) GO TO 277
IF (NUT.NE.0) GO TO 914
GO TO 15
7777 IF (KER) 1312,1312,912
C
```

```

1312 CALL BOILT (P,TS)
      IF (ABS(T-TS),LE.,1E-3) GO TO 912
      IF(TS-T) 71,912,913
913  CT=T-273.15
      V1=0.95372+0.836E-3*CT-0.285E-5*CT*CT+0.120E-7*(CT**3)
      RO=1/V1
      M=1
      L=1
      LIQ=1
      GO TO 7
912  NUT=1
      GO TO 71
914  HG=H
      SQ=S
      VG=V
      T=T+273.15
      NUT=0
      GO TO 913
C
277  IF(DEL,LE,0.001) GO TO 15
      HER=P*DEL/H/10.0
      IF((LIQ,EQ,1),AND,(HER,LE,0.001)) GO TO 15
      WRITE ( 5,200)LIQ,P,T,DEL
200  FORMAT(///10X,'NO CONVERGENCE AFTER 20 TRIALS',5X,I5,2(5X,F8.3),5X
1,F8.5///)
15  CONTINUE
      RETURN
C
C
C
      END

```

APPENDIX C

[coded by H.E. Khalifa]

```

SUBROUTINE TRUMP (TAU,RO,Y,R,R1T,R1RO,Q2RO)
C
COMMON/CYCLE/PC,TC,A(10,7),B(7),C(8),D(7),F(8),HC,SC
C
E=4.8
TAUC=1.544912
IF (ABS(TAU-TAUC),LE,0.1E-6) GO TO 71
S0=0.0
S1=0.0
C
DO 12 J=1,7
S2=EXP(-E*RO)*(A(9,J)+A(10,J)*RO)+A(1,J)
DO 11 I=2,8
S2=S2+A(I,J)*(RO-D(J))**(I-1)
11 CONTINUE
IF(J,EQ,1) GO TO 4444
IF(J,EQ,2) GO TO 111
X1=((TAU-B(J))**(J-2))*S2
GO TO 112
4444 X1=S2/(TAU-B(J))
GO TO 112
111 X1=S2
112 S1=S1+X1
IF(J,EQ,1) GO TO 1234
IF(J,EQ,2) GO TO 1235
IF(J,EQ,3) GO TO 1236
X0=(J-2)*((TAU-B(J))**(J-3))*S2
GO TO 114
1234 X0=-S2/((TAU-B(J))**(TAU-B(J)))
GO TO 114
1235 X0=0.0
GO TO 114
1236 X0=S2
114 S0=S0+X0
12 CONTINUE
C
R=S1*(TAU-TAUC)
S3=0.0
S5=0.0
DO 14 J=1,7
S4=EXP(-E*RO)*(A(10,J)*(1-E*RO)-E*A(9,J))+A(2,J)
S6=-E*EXP(-E*RO)*(A(10,J)*(2-E*RO)-E*A(9,J))+2*A(3,J)
DO 13 I=3,8
S4=S4+(I-1)*A(I,J)*(RO-D(J))**(I-2)
IF(I,EQ,3) GO TO 515
ADD=(I-1)*(I-2)*A(I,J)*((RO-D(J))**(I-3))
GO TO 516
515 ADD=0.0
516 S6=S6+ADD
13 CONTINUE
IF(J,EQ,1) GO TO 2233
IF(J,EQ,2) GO TO 131
XY=(TAU-B(J))**(J-2)
GO TO 3322

```

```

2233 XY=1.0/(TAU-B(J))
3322 X3=XY*S4
      X5=XY*S6
      GO TO 132
131  X3=S4
      X5=S6
132  S3=S3+X3
      S5=S5+X5
14   CONTINUE
      Q1RO=(TAU-TAUC)*S3
      Q2RO=(TAU-TAUC)*S5
      AT=1000/TAU
      Y=4.6151*RO*AT*(1.+RO*Q+RO*RO*Q1RO)
      Q1T=S1+S0*(TAU-TAUC)
      GO TO 76

```

C

C CRITICAL ISOTHERM

C

```

71   Q=EXP(-E*RO)*(A(9,1)+A(10,1)*RO)+A(1,1)
      DO 72 I=2,8
      Q=Q+A(I,1)*(RO-D(1))**(I-1)
72   CONTINUE
      Q1RO=EXP(-E*RO)*(A(10,1)*(1-E*RO)-E*A(9,1))+A(2,1)
      Q2RO=2.*A(3,1)+E*EXP(-E*RO)*(A(10,1)*(E*RO-2)+A(9,1)*E)
      DO 73 I=3,8
      Q1RO=Q1RO+(I-1)*A(I,1)*(RO-D(1))**(I-2)
73   CONTINUE
      DO 77 I=4,8
      Q2RO=Q2RO+A(I,1)*(I-1)*(I-2)*(RO-.634)**(I-3)
77   CONTINUE
      Q1T=0.0
      DO 75 J=2,7
      S2=EXP(-E*RO)*(A(9,J)+A(10,J)*RO)+A(1,J)
      DO 74 I=2,8
      S2=S2+A(I,J)*(RO-D(J))**(I-1)
74   CONTINUE
      Q1T=Q1T+((TAU-B(J))**(J-2))*S2
75   CONTINUE
      Y=4.6151*RO*1000*(1+RO*Q+RO*RO*Q1RO)/TAUC
76   CONTINUE
      RETURN

```

C

END

APPENDIX D

[coded by H.E. Khalifa]

```
C      SUBROUTINE BOILT(P,TS)
C      COMMON/CYCLE/PC,TC,A(10,7),R(7),C(8),D(7),F(8),HC,SC
C      M=1
      TC=TC-273.15
      TS=TC
      YS=P/PC
1      FUN=0.0
      DO 8 I=1,8
      FUN=FUN+F(I)*((0.65-0.01*TS)**(I-1))
8      CONTINUE
      X=0.01*(TC-TS)*FUN/(TS+273.15)
      Y=EXP(X)
      DEL=ABS ((YS-Y)/YS)
      IF (DEL,LE,0.1E-4) GO TO 11
      FUN1=-0.01*F(2)
      DO 9 I=3,8
      FUN1=FUN1-0.01*(I-1)*F(I)*((0.65-0.01*TS)**(I-2))
9      CONTINUE
      X1=0.01*(((TC-TS)*FUN1/(TS+273.15))-FUN*(TC+273.15)/((TS+
1273.15)**2))
      YP=Y*X1
      TS=TS+(YS-Y)/YP
      M=M+1
      IF (M,GT,10) GO TO 11
      GO TO 1
11     TS=TS+273.15
      TC=TC+273.15
      RETURN
C
      END
```

APPENDIX E

[coded by H.E. Khalifa]

```
C      SUBROUTINE SATUR(P,T,H,IS)
C      CALL BOILT (P,T)
      T=T-273.15
      CALL PETE(P,T,H,S,V,HG,SG,VG,1)
      IF (IS,EQ,0) GO TO 11
      H=HG
      S=SG
      V=VG
11     CONTINUE
      RETURN
C
      END
```


APPENDIX F

MAIN CALLING PROGRAM FOR TWO-STAGE ANALYSIS

[Coded by E. M. Avelar]

Cross-Reference Table for State Points*

<u>Figure 6</u>	<u>Program TWOSTA</u>
4	5
4s	5s
5	6
6	7
6s	7s
8	9
9	12
10	13
10s	13s
ls	l'
p	o
n	m'
t	q

*All other state points bear the same designation in the program as in Fig. 6.


```

COMMON/CYCLE/PC,TC,A(10,7),B(7),C(8),D(7),F(8),HC,SC
COMMON/XYZ/XX,LUX,VUX
OPEN(UNIT=33,FILE='CS')
OPEN(UNIT=34,FILE='FS')
OPEN(UNIT=35,FILE='AS')

```

```

C
C
C CRITICAL CONSTANTS
C

```

```

PC=220.88
TC=647.286
ROC=0.3155
HC=2099.3
SC=4.4298
KRON=0

```

```

C
C CONSTANTS OF THE KEENAN AND KEYES EQUATION
C

```

```

TAUC=1.544912
READ (33,10) (C(I),I=1,8)
READ (34,10) (F(I),I=1,8)
10 FORMAT (8F10.0)
READ (35,20) ((A(I,J),J=1,7),I=1,10)
20 FORMAT (7F11.0)
DO 3 J=1,7
IF (J.EQ.1) GO TO 1
B(J)=2.5
D(J)=1.0
GO TO 2
1 B(J)=TAUC
D(J)=0.634
2 CONTINUE
3 CONTINUE

```

```

C
C
WRITE(5,111)
111 FORMAT('1','STATE',5X,'PRESSURE',5X,'TEMPERATURE',5X,'ENTHALPY',5X
1,'ENTROPY',//)

```

```

C
C *** STATE 1 ***
C

```

```

ID=1
P1=165.0
T1=540.0
CALL PROPS(P1,T1,H1,S1,V1,0)
WRITE(5,222)ID,P1,T1,H1,S1

```

```

C
C *** STATE 2S ***
C

```

```

ID=22
P22=41.0
S22=S1
CALL PROPS(P22,T22,H22,S22,V22,1)
WRITE(5,222)ID,P22,T22,H22,S22

```

```

C
C *** STATE 2 ***
C

```

```

ID=2
P2=P22
H2=H1-(0.82*(H1-H22))
WRITE(5,223)ID,H2

```

C *** STATE 3 ***

C

ID=3
P3=P2*0.90
T3=540.0
CALL PROPS(P3,T3,H3,S3,V3,0)
WRITE(5,222)ID,P3,T3,H3,S3

C

C *** STATE 5S ***

C

ID=55
P55=.05628
S55=S3
CALL PROPS(P55,T55,H55,S55,V55,1)
WRITE(5,222)ID,P55,T55,H55,S55

C

C *** STATE 5 ***

C

ID=5
H5=H3-(0.85*(H3-H55))
P5=P55
WRITE(5,223)ID,H5

C

C *** STATE 6 ***

C

ID=6
P6=.05628
CALL SATUR(P6,T6,H6,0)
CALL PROPS(P6,T6,H6,S6,V6,0)
WRITE(5,222)ID,P6,T6,H6,S6

C

C *** STATE 7S ***

C

ID=77
P77=P2/0.81
S77=S6
CALL PROPS(P77,T77,H77,S77,V77,1)
WRITE(5,222)ID,P77,T77,H77,S77

C

C *** STATE 7 ***

C

ID=7
P7=P77
H7=H6+(H77-H6)/0.80
CALL PROPS(P7,T7,H7,S7,V7,2)
WRITE(5,222)ID,P7,T7,H7,S7

C

C *** STATE 12 ***

C

ID=12
P12=P2
CALL SATUR(P12,T12,H12,0)
CALL PROPS(P12,T12,H12,S12,V12,0)
WRITE(5,222)ID,P12,T12,H12,S12

C

C *** STATE 13S ***

C

ID=13
P133=P1/0.90
S133=S12
CALL PROPS(P133,T133,H133,S133,V133,1)
WRITE(5,222)ID,P133,T133,H133,S133

C *** STATE 13 ***

C

ID=13
H13=H12+(H133-H12)/0.80
P13=P133
WRITE(5,223)ID,H13

C

C *** DEAD STATE ***

C

P0=0.03567
CALL SATUR(P0,T0,H0,0)
CALL PROPS(P0,T0,H0,S0,V0,2)
WRITE(5,444)P0,T0,H0,S0
444 FORMAT(/,3X,'0',5X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE B ***

C

L=1
300 IF(L.EQ.1) GO TO 301
IF(L.EQ.2) GO TO 302
IF(L.EQ.3) GO TO 303
301 PB=39.73
GO TO 304
302 PB=15.538
GO TO 304
303 PB=4.758
304 CALL SATUR(PB,TB,HB,1)
CALL PROPS(PB,TB,HB,SB,VB,2)
WRITE(5,113)PB,TB,HB,SB
113 FORMAT('1',3X,'B',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE D ***

C

TD=510.0
PD=PB*0.81
GO TO 191
192 PD=PB*0.90
191 CALL PROPS(PD,TD,HD,SD,VD,0)
WRITE(5,114)PD,TD,HD,SD
114 FORMAT(/,3X,'D',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE ES ***

C

PES=2.0/0.90
SES=SD
CALL PROPS(PES,TES,HES,SES,VES,1)
WRITE(5,115)PES,TES,HES,SES
115 FORMAT(/,3X,'ES',5X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE E ***

C

PE=PES
HE=HD-(0.85*(HD-HES))
CALL PROPS(PE,TE,HE,SE,VE,2)
WRITE(5,116)PE,TE,HE,SE
116 FORMAT(/,3X,'E',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)
IF(KRON) 7117,7117,7771

C *** STATE G ***

C

7117 FG=PB

CALL SATUR(PG,TG,HG,0)

CALL PROPS(PG,TG,HG,SG,VG,2)

WRITE(5,117)PG,TG,HG,SG

117 FORMAT(/,3X,'G',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE H ***

C

HH=HG

TH=TG

PH=PG

SH=SG

VH=VG

WRITE(5,118)PH,TH,HH,SH

118 FORMAT(/,3X,'H',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE I ***

C

HI=HG

TI=TG

PI=PG

SI=SG

VI=VG

WRITE(5,119)PI,TI,HI,SI

119 FORMAT(/,3X,'I',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE I' ***

C

HIP=HI

PIP=2.0

CALL PROPS(PIP,TIP,HIP,SIP,VIP,2)

WRITE(5,121)PIP,TIP,HIP,SIP

121 FORMAT(/,3X,'IP',5X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE O ***

C

PO=PIP

CALL SATUR(PO,TO,H0,0)

CALL PROPS(PO,TO,H0,S0,V0,2)

WRITE(5,122)PO,TO,H0,S0

122 FORMAT(/,3X,'O',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE J ***

C

PJ=PIP

CALL SATUR(PJ,TJ,HJ,1)

CALL PROPS(PJ,TJ,HJ,SJ,VJ,2)

WRITE(5,123)PJ,TJ,HJ,SJ

123 FORMAT(/,3X,'J',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C *** STATE C' ***

C

IF(TE-TB) 8125,8125,8124

8125

HC1=HB

HF=HE

KRON=1

GO TO 192

GO TO 7771

8124

TCP=TE

PCP=PB*0.90

CALL PROPS(PCP,TCP,HCP,SCP,VCP,0)

WRITE(5,124)PCP,TCP,HCP,SCP

124 FORMAT(/,3X,'CP',5X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE C ***

C

HC1=HB+(0.80*(HCP-HB))

PC1=PCP

CALL PROPS(PC1,TC1,HC1,SC1,VC1,2)

WRITE(5,125)PC1,TC1,HC1,SC1

125

FORMAT(/,3X,'C',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C **** STATE FP ***

C

TFP=TB

PFP=2.0

CALL PROPS(PFP,TFP,HFP,SFP,VFP,0)

WRITE(5,126)PFP,TFP,HFP,SFP

126 FORMAT(/,3X,'FP',5X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE F ***

C

HF=HE-(0.80*(HE-HFP))

PF=PFP

CALL PROPS(PF,TF,HF,SF,VF,2)

WRITE(5,1266)PF,TF,HF,SF

1266

FORMAT(/,3X,'F',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE A ***

C

7771 PA=PB

KRON=0

K=1

XA=0.10

71 HA=(1.0-XA)*HG+XA*HB

CALL PROPS(PA,TA,HA,SA,VA,2)

112

FORMAT(/,3X,'A',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

C

C *** STATE K ***

C

M=1

RF=0.00

PK=PIP

XIP=(HIP-H0)/(HJ-H0)

81 AM=RF*XIP*(1.0-XA)

HK=((AM*HJ)+(XA*HF))/(AM+XA)

CALL PROPS(PK,TK,HK,SK,VK,2)

WRITE(5,27)XA,TA,RF

WRITE(5,112)PA,TA,HA,SA

WRITE(5,127)PK,TK,HK,SK

127 FORMAT(/,3X,'K',6X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)

```

C *** STATE L' ***
C
  PLS=0.05628
  SLS=SK
  CALL PROPS(PLS, TLS, HLS, SLS, VLS, 1)
  WRITE(5, 128) PLS, TLS, HLS, SLS
128 FORMAT(/, 3X, 'LS', 5X, F7.3, 7X, F6.2, 8X, F9.4, 5X, F6.4)
C
C *** STATE L ***
C
  PL=PLS
  HL=HK-(0.85*(HK-HLS))
  CALL PROPS(PL, TL, HL, SL, VL, 2)
  WRITE(5, 129) PL, TL, HL, SL
129 FORMAT(/, 3X, 'L', 6X, F7.3, 7X, F6.2, 8X, F9.4, 5X, F6.4)
C
C *** STATE M ***
C
  PM=PL
  CALL SATUR(PM, TM, HM, 0)
  CALL PROPS(PM, TM, HM, SM, VM, 2)
  WRITE(5, 130) PM, TM, HM, SM
130 FORMAT(/, 3X, 'M', 6X, F7.3, 7X, F6.2, 8X, F9.4, 5X, F6.4)
C
C *** STATE M' ***
C
  PMP=PD*0.90
  SMP=SM
  CALL PROPS(PMP, TMP, HMP, SMP, VMP, 1)
  WRITE(5, 131) PMP, TMP, HMP, SMP
131 FORMAT(/, 3X, 'MP', 5X, F7.3, 7X, F6.2, 8X, F9.4, 5X, F6.4)
C
C *** STATE 9 ***
C
  ID=9
  P9=P12/0.90
  T9=TH-3.0
  CALL PROPS(P9, T9, H9, S9, V9, 0)
  WRITE(5, 222) ID, P9, T9, H9, S9
C
C *** STATE Q ***
C
  PQ=PD*0.90
  TQ=T7+3.0
  CALL PROPS(PQ, TQ, HQ, SQ, VQ, 0)
  WRITE(5, 132) PQ, TQ, HQ, SQ
132 FORMAT(/, 3X, 'Q', 6X, F7.3, 7X, F6.2, 8X, F9.4, 5X, F6.4)
C
C MASS FLOW RATE CALCULATIONS
C
  OM=RF*(1.0-XIP)*(1.0-XA)
  HM1=(1.0-RF)*(1.0-XA)
  QM=OM+HM1
  SM=((HM1*HH)-(QM*HQ)+(OM*HO))/(H9-H7)
  TM=((SM*H9)-(SM*H12))/(H12-H2)
  TWM=SM+TM
  EM=SM

```

C WORK CALCULATIONS

C

```

WFT1=TWM*(H1-H2)
WFT2=SM*(H3-H5)
WGT1=XA*(HD-HE)
WGT2=(AM+XA)*(HK-HL)
WCP=SM*(H7-H6)
WBFP=TWM*(H13-H12)
WIP=(AM+XA)*(HMP-HM)/0.80
WNET=WFT1+WFT2+WGT1+WGT2-WCP-WBFP-WIP

```

C

C HEAT TRANSFER TERMS

C

```

QSG=TWM*(H1-H13)
QRH=SM*(H3-H2)
QFSH=XA*(HD-HC1)
QCG=(AM+XA)*(HL-HM)
QCF=SM*(H5-H6)
QRG=XA*(HC1-HB)
QBH=SM*(H9-H7)

```

C

C FOSSIL AND GEOTHERMAL WORK

C

```

WF=.43*(QSG+QRH+QFSH)
EA=HA-HO-(T0+273.15)*(SA-SO)
WG=.50*EA

```

C

C UTILIZATION EFFICIENCY

C

```

FT=WNET/(WF+WG)
FF=(WNET-WG)/WF
FG=(WNET-WF)/WG
PSI=WNET/WG
RBIG=0.10
RLIT=1.0/(PSI-FG)
DELTA=RLIT/RBIG

```

C

C

```

222 FORMAT(/,3X,I2,5X,F7.3,7X,F6.2,8X,F9.4,5X,F6.4)
223 FORMAT(/,3X,I2,33X,F9.4)

```

C

C

```

27 FORMAT('1',10X,'SYSTEM PERFORMANCE FOR A WELLHEAD QUALITY OF ',F6.
0000015,1X,'AND TEMPERATURE OF',F7.2,1X,'AND A HOT WATER SPLIT OF',F7.5)

```

C

C

```

WRITE(5,99)
99 FORMAT(/,4X,'MO',8X,'MH',8X,'MQ',8X,'M7',8X,'M2',8X,'M12',7X,'M9'
1,8X,'MJ')
WRITE(5,100)OM, HM1, QM, SM, TM, TWM, EM, AM
100 FORMAT(/,2X,8(F6.4,4X))
WRITE(5,98)
98 FORMAT(/,4X,'WFT1',7X,'WFT2',7X,'WGT1',7X,'WGT2',7X,'WCP',7X,'WBF
1P',7X,'WIP',7X,'WNET')
WRITE(5,91)WFT1,WFT2,WGT1,WGT2,WCP,WBFP,WIP,WNET
91 FORMAT(/,8(F10.2))
WRITE(5,92)
92 FORMAT(/,4X,'QRH',7X,'QSG',7X,'QFSH',6X,'QCG',7X,'QCF',7X,'QRG',7
1X,'QBH')

```

```

WRITE(5,666)QRH,QSG,QFSH,QCG,QCF,QRG,QBH
666 FORMAT(/,7(F10.2))
WRITE(5,787)
787 FORMAT(/,4X,'WF*',7X,'WG*')
WRITE(5,999)WF,WG
999 FORMAT(/,2(F10.2))
WRITE(5,900) FT,FF,FG,PSI,RBIG,RLIT,DELTA
900 FORMAT(/,4X,'F=',F6.4,8X,'FF=',F6.4,7X,'FG=',F6.4,7X,'PSI=',F7.4,
13X,'RBIG=',F7.4,3X,'RLIT=',F7.4,3X,'DELTA=',F8.3,///)

```

C
C

```

CLOSE(UNIT=33,FILE='CS')
CLOSE(UNIT=34,FILE='FS')
CLOSE(UNIT=35,FILE='AS')
M=M+1
RF=RF+0.25
IF(M-5) 81,81,82
82 K=K+1
XA=XA+0.10
IF(K-4) 71,71,70
70 L=L+1
IF(L-3) 300,300,80
80 STOP
END

```