A Comparison of Hydrothermal Reservoirs of the Western United States

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Prepared by
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A COMPARISON OF HYDROTHERMAL RESERVOIRS OF THE WESTERN UNITED STATES

**EPRI ER-364
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December 1976

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ABSTRACT

This report presents a portion of the results from a one-year feasibility study sponsored by the Electric Power Research Institute to assess the feasibility of constructing a 25 to 50 MWe geothermal power plant using low salinity hydrothermal fluids as the energy source.

It contains the results of a comparative study of sixteen hydrothermal reservoirs in the United States. The reservoirs were selected for comparison on the basis of available data, development potential, and representativeness of known hydrothermal reservoirs in the United States. Six reservoir and fluid criteria were considered the most important in determining the development and power conversion potential: depth and lithology, reservoir temperature, tested flow rate per well, fluid chemistry, magnitude of the reserve and reinjection potential. These criteria were evaluated for each of the selected reservoirs.

Geothermal reservoirs are classified by origin and occurrence into three types: those associated with unusual artesian or thermo-artesian conditions, the volcano-tectonic type, and the volcanic type. Two conceptual models for hydrothermal reservoirs are discussed: sedimentary and volcanic. An imaginary or hypothetical reservoir representative of the mean of the majority of commonly occurring hydrothermal reservoirs in the United States was defined as an aid in assessing the representativeness of the actual reservoirs. The properties of the hypothetical reservoir were derived by comparative study of reservoirs, statistical data and reservoir engineering calculations from which performance was estimated. The hypothetical reservoir appears to have a reasonable prospect for economic development using current technology. Ranking of the reservoirs according to development potential was not possible because of incomplete information; the Valles Caldera, Heber, and hypothetical reservoirs were ranked according to temperature only. Nine minimum criteria to determine whether a hydrothermal reservoir has development potential are proposed.

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INTRODUCTION AND SUMMARY

This Special Report is a part of a one-year study sponsored by the Electric Power Research Institute to (A) assess the feasibility of constructing a 25 to 50 MWe geothermal power plant using low salinity hydrothermal fluids as the energy source, and (B) to prepare a preliminary design of the plant.

Part A of the study consisted of the assessment of the technical, economic and environmental feasibility of a 50 MWe conversion plant. The study investigated the binary, the flashed steam and the hybrid conversion processes at three different sites: Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho. The economic analysis resulting from this work provides insight into the relative merits of flashed steam and binary cycles with varying reservoir temperatures and provides useful information relating power generation costs to reservoir temperature.

The reservoir engineering studies have been carried out under the Tasks A-1 (Technical Feasibility of Reservoir Development) and A-6 (Reservoir Selection). Task A-1 consists of the following aspects of this study:

1. Selection of Reservoirs for Study
2. Quantification of Reservoir Characteristics
3. Definition of a Hypothetical Reservoir
4. Ranking of Selected Reservoirs According to their Potential
5. Detailed Evaluation of the Heber and Valles Caldera Reservoirs

Task A-6 consists of:

1. Establishing Minimum Reservoir Characteristics
2. Defining Reservoir Selection Criteria
3. Selection of the Demonstration Site

For convenience, the reservoir engineering study has been divided into two overlapping phases. The following items of Tasks A-1 and A-6 were covered under Phase I:

1. Select for study a number of important low salinity hydrothermal reservoirs in the United States.

2. Identify the most important reservoir characteristics for assessing power generation potential, and quantify these characteristics for selected reservoirs.
3. Define a hypothetical reservoir that best represents the average conditions for hydrothermal reservoirs in the United States.
4. Rank selected reservoirs and the hypothetical reservoir for their power generation potential.
5. Establish the minimum criteria for a reservoir in order to be considered as a possible power plant site.

This report presents the results of the first phase of our study. The remainder of the Tasks A-1 and A-6 will be included in the second phase report.

Phase Definition

The project is defined as a "Feasibility Study for a Low Salinity Hydrothermal Demonstration Plant". A hydrothermal reservoir is defined here as a volume of rocks containing a reasonably continuous body of water, naturally heated by various geological processes, which can be economically extracted. Economically paramarginal fluid deposits are not included in this definition. This definition, like that of 'mineral deposit', implicitly assumes that the definition of a given heated fluid deposit as a hydrothermal 'reservoir' or as a 'warm-water body' is dependent upon prevailing technology and comparative economics in the area. Thus, for example, the geothermal water body at Pauzetska, Siberia, would be considered a 'warm-water body' in the United States (being at 196°F (91°C) only), but is a 'geothermal reservoir' in Siberia, because it generates electrical power at a competitive price at that location.

Thus this study does not consider other forms of geothermal resources, specifically: vapor-dominated reservoirs (e.g., The Geysers, California), hydrothermal reservoirs with salinity greater than 35,000 ppm (e.g., Salton Sea KGRA, California), geopressured geothermal resources, hot dry rocks, and magmatic bodies at shallow depth. This study gives special attention to 'moderate' temperature hydrothermal reservoirs, namely, those in the range of 280°-480°F (135°-250°C). This emphasis is justified for several reasons:

1. Feasibility of electrical power generation from very hot (greater than 480°F (250°C)) hydrothermal systems has been demonstrated in some parts of the world, for example, Cerro Prieto, Mexico; Wairakei, New Zealand; and Otake, Japan. Hence, the need

for a feasibility study for power generation from such hot reservoirs in the United States is not critical, while a study of moderate temperature reservoirs is. Reservoirs below 280°F (135°C), although a potentially vast source of energy for space heating and other types of direct heating needs, do not have sufficient potential for power generation under current economics, with the exception of some special cases in such remote locations as Pauzetska, U.S.S.R. or in locations where multipurpose use of the resource is possible.

2. Moderate temperature reservoirs are far more common than hot ones.

3. Moderate temperature reservoirs are more likely to have low salinity water.

Definition of a Reservoir

It should be noted that the meaning of the word 'reservoir' in the geothermal industry is somewhat different from that in oil and natural gas industries. A hydrothermal reservoir, as defined in the previous section, may be comprised of many different reservoirs (in the conventional sense) at various depths, with impermeable barriers in-between. This usage is justified for the purposes of this study because most KGRA's have not been developed sufficiently to define each individual reservoir, and most wells will produce from large sections of formations with fluids commingled from several reservoirs.

Units Used:

For convenience, the report uses a set of commonly used 'working units.' Table 1 lists these units and conversion factors required for other units. Figure 1 gives the conversion factor required to convert water flow rate at a given temperature from pounds/hour to gallons/minute. This chart was derived by using density of pure water at a temperature level averaged over a pressure range of 100 to 3,000 psia (7 to 210 bars). This pressure range includes conditions for all known hydrothermal reservoirs in the United States. The variation of density of water with pressure is small over the range of temperature (up to 500°F (260°C) encountered in such reservoirs; hence, this chart is accurate enough for engineering purposes. The use of pure water density is justified considering the low salinity of the reservoir included in this study.

1 lb per hour = $C \times 10^{-3}$ gallons per minute

1 kg per hour = $C \times (2.205 \times 10^{-3})$ gallons per minute

C = Conversion factor from figure

APPROXIMATION: (1) Pure water is assumed

(2) Density at each temperature level
averaged over the pressure range
100-3000 lbs/in²

Figure 1. Conversion chart from pounds/hour to gallons/minute for low salinity brine from hydrothermal systems.

TABLE 1
UNIT CONVERSION TABLE

PARAMETER	UNITS USED	CONVERSION TO OTHER UNITS	
		Multiply by:	To Obtain:
Length	foot	0.3048	meters
	mile	1.609	kilometers
	inch	2.540	centimeters
Area	square mile	2.590	sq.kilometers
Volume	cubic mile	4.168	cu.kilometers
		0.8107×10^6	acre-ft.
	barrel	42.0	gallons
		5.615	cu. feet
		0.1590	cu. meters
	gallons	0.1336	cu. feet
		0.238	barrels
		0.3785×10^{-2}	cu. meters
Mass	pound	453.5	grams
Density	pound per ft. ³	0.1602×10^{-1}	gms/cm ³
Volumetric Flow Rate	barrel per day	0.2917×10^{-1}	gals./min.
		0.159	cu.m./day
	gallon per minute	34.29	barrels/day
		63.08	cu.cm./sec.
		5.45	cu.m./day
Mass Flow Rate	pound per hour	0.1260×10^{-3}	kg./sec.
Temperature	degree Fahrenheit	$\frac{(^{\circ}\text{F} - 32)}{1.8}$	$^{\circ}\text{C}$
Pressure*	pound per sq.in.	0.6896×10^{-1}	bars
		0.6806×10^{-1}	atmospheres
		0.7034×10^{-1}	kg/sq.cm
		0.6896×10^{-3}	dynes/cm ²
Heat/power	calorie	4.186	joules
		0.3969×10^{-2}	BTU
		0.1160×10^{-2}	watt-hours
	megawatt century	0.7530×10^{15}	calories

* All pressures absolute, with 1.01 bar added to gauge pressure at sea level and at low altitudes.

Sources of Data

Gathering relevant data from the following sources was a major effort of this study:

1. Published articles or reports from technical journals and newspapers.
2. Publicly available reports from Federal, State and local agencies, universities and various private organizations.
3. Telephone conversation or visits with knowledgeable persons in various governmental and private organizations.
4. Raw (uninterpreted) data from organizations engaged in exploration and drilling for geothermal reservoirs.

Because of their proprietary nature, data from some areas were unavailable from the operators. In such cases this study may not reflect the total extent of knowledge about those areas. We acknowledge total cooperation from Chevron Oil Company, Minerals Division, who provided us with a considerable amount of data about the Heber reservoir; without Chevron's help this report would have been less complete. Some reported data are confidential and cannot be presented in this report; however, the conclusions based upon those data are included herein.

For convenience the References and Bibliography section of this report has been divided into three geographical groups (Imperial Valley, Valles Caldera, and Other Areas) and a General References group. Under the General References category we have listed the references which are not related to a specific geographical area, for example, reservoir engineering references.

SELECTION OF RESERVOIRS

The following criteria were considered in selecting a group of reservoirs for a comparative study:

1. Development potential under current technology
2. Amount of data available
3. How representative the reservoir is of the hydrothermal reservoirs in the United States

Besides the Heber and the Valles Caldera reservoirs, which were to be studied in detail under the second phase, we selected six other reservoirs for which a significant amount of data were available. We also included eight more reservoirs in this study even though the data available for these reservoirs were sketchy. This was done to ensure a broad sample of hydrothermal reservoirs in the United States that considered reservoir and fluid characteristics. Table 2 (page 20) presents the name, geographical location, areal extent and the approximate depth of the deepest well drilled for each selected reservoir. The first eight reservoirs in Table 2 are the ones for which a significant amount of data were available.

Most of the geothermal prospect areas in the United States occur in four broad geological provinces:

1. The Imperial Rift Valley of California
2. The Basin and Range Province
3. The Northwest Volcanic Province
4. The Rio Grande Rift and Colorado Plateau borderland

Figure 2 shows these provinces and the location of reservoirs selected for this study. Reservoirs were selected such that all these physiographic provinces were represented in the sample. A general description that includes the geographic and geological settings of each selected reservoir is included in Appendix A.

Figure 2. Major geothermal geologic provinces of the United States (modified from TRW Systems and Energy, 1975).

QUANTIFICATION OF RESERVOIR CHARACTERISTICS

The first step in this task was to identify those reservoir and fluid characteristics that are considered the primary criteria in determining reservoir development and power conversion potential from hydrothermal reservoirs. Our study showed that the following reservoir and fluid characteristics may be considered to be the required primary criteria:

1. Depth and lithology.
2. Reservoir temperature.
3. Tested flow rate per well.
4. Fluid chemistry.
5. Magnitude of the reserve.
6. Reinjection potential.

In the following pages we describe the basis for selecting and the usual means of estimating these criteria. We have ignored those economic and environmental criteria that are not directly related to reservoir or fluid characteristics.

Depth and Lithology

The depth of the reservoir from surface and the lithology of the area determine the drilling rate and cost. If there were no economic depth limit for drilling or production, hot water could be recovered from great depths in practically any sedimentary basin. However, cost and the technical problems of drilling to and production from great depths prevent exploitation of such heat sources. Thus, the essential difference between a geothermal prospect and any ordinary sedimentary basin lies primarily in the depth to which one has to drill to recover water at a desired temperature. In general, the harder the rock formations to be penetrated, the slower is the drilling rate and higher the cost. Hence, depth and lithology may be considered the most important criteria that determine reservoir development cost. Until exploratory wells are drilled in an area, these criteria are estimated from geological or geophysical studies. Existing geothermal wells in the United States typically range in depth from 4,000 to 8,000 ft. (1200 to 2400 meters). Figure 3 represents approximate cost data for different depths and two main types of lithologies for geothermal wells compared to oil well data (after TRW Systems and Energy, 1975). These data must be appropriately escalated to account for the rise in drilling cost since 1975.

Figure 3. Cost of Drilling vs. Depth.
(Modified from TRW Systems and Energy, 1975)

Temperature

Figure 4 presents pressure versus specific enthalpy data for pure water. It can be seen from this figure that specific enthalpy is practically independent of reservoir pressure for low salinity, moderate temperature waters, for which pure water data will be valid. Thus, reservoir temperature alone indicates the specific enthalpy and consequently the gross power conversion potential per unit mass of water for such hydrothermal systems. The hydrothermal reservoirs under development in the United States exhibit temperatures in the range of 300°-700°F (150°-370°C). Reservoirs with temperatures near the upper limit of this range may contain very saline brine, e.g., Salton Sea, California, which was not considered in this report. An estimate of the subsurface temperature can often be made from geochemical studies of water from surface discharge such as hot springs and geysers. This approach is known as geothermometry. Sometimes formation temperatures are estimated from heat flow data obtained from shallow bore holes. However, the only reliable way to establish reservoir temperature is by drilling. No geotechnical techniques are available yet to establish the depth at which a certain temperature may be encountered.

Flow Rate Per Well

By knowing the temperature and water production rate per well, one can estimate the gross power generation potential per well. Then, for any desired power conversion process and power plant size, the number of wells required can be estimated. An accurate estimate of the flow rate required per megawatt net electricity depends on: the temperature and pressure of the water at the bottomhole conditions in the well bore (which determine the well-head conditions of the brine), the amount and chemical composition of the dissolved solids and gases at the well head, the design of the fluid handling facilities at the surface, and the design of the power conversion system. However, some broad generalizations are available in the literature. For example, Figure 5 shows average values of MWe generated per 1,000 gallons per minute (5450 cubic meters per day) flow rate under both binary and flash processes (after TRW Systems and Energy, 1975). The figure also gives data for a two-stage flash process derived from information provided to us by Chevron Oil Company and the data for flash and binary processes developed by the Ben Holt Company. The figure shows that the higher the temperature, the lower the required flow rate needs to be in order to obtain a certain amount of power. For a water with a specific temperature, the lower the flow rate the lower will be the number of wells required for a particular conversion process

Figure 4

Pressure-enthalpy diagram for pure water and vapor, showing contours of equal temperature, density and mass proportions of steam to water. (Shaded area shows the range of thermodynamic conditions of the reservoirs considered in this report. The solid circle indicates the conditions of the hypothetical hydrothermal reservoir of this study and the open dot indicates the same for vapor dominated systems.) Modified from Witherspoon et al, 1975.

Figure 5. Net energy derived under different power conversion processes (modified from TRW Systems and Energy, 1975).

and a specific power plant size. The cost of development and operation of a reservoir will be approximately proportional to the number of wells required. Thus, the flow rate per well is a criterion that determines the development as well as the operation costs of a reservoir. Existing hydrothermal wells in the United States show flow rates in the range of 500-3,000 gallons per minute (2,725 - 16,350 cubic meters per day).

Flow rate is a routinely measured quantity in any newly drilled well. There are various types of flow tests. Drill stem test may be run to determine productivity at various depths in the reservoir. Flow rate versus pressure and versus temperature at the well head are measured in most exploratory and development wells. All such tests indicate the productivity of the well. A well's productivity index (defined as flow rate per unit pressure drawdown at the well bore) can be estimated from the relation

$$\text{Productivity Index} = \frac{2\pi kh\rho}{\mu} / \ln (0.472 r_e/r_w) \quad (1)$$

(in gms/sec/atmosphere)

where, h = thickness of the producing formation (cm)
 k = permeability (Darcys)
 ρ = density of brine (gms/cm³)
 μ = brine viscosity (centipoise)
 r_e = drainage radius of the well (cm)
 r_w = well bore radius (cm)

In terms of field units, equation (1) can be rewritten as:

$$\text{Productivity Index} = 3.977 \times 10^{-2} \frac{kh\rho}{\mu} / \ln (5.664 r_e/r_w) \quad (2)$$

(in lbs/day/psi)

Where k is in millidarcies, h in ft, ρ in lbs/ft³, μ in centipoises, r_e in ft, and r_w in inches.

From an estimate of the reservoir and fluid characteristics involved in equation (2) a well's productivity can be estimated. The value of permeability and thickness of the formation can be estimated from well logs and core data. Brine density and viscosity can be measured from fluid samples. The drainage radius can be estimated from a knowledge of the reservoir. However, the actual flow test in a newly drilled well may show lower productivity because of the permeability

damage around the well bore caused by invasion of drilling mud into the formation during drilling. Such formation damage is usually rectified by reservoir stimulation techniques -- by recourse to chemical, hydraulic and explosive fracturing. On the other hand, the initial flow test in an exploratory bore hole may show higher productivity than calculated from equation (2) because of the effect of pressure transients in the early life of a well. An accurate evaluation of a well's future productivity requires more involved reservoir engineering calculations. Equation (2) is based on intergranular flow. If the reservoir has significant permeability due to the presence of fractures, this equation will give a reasonable approximation if k is assumed to be the effective permeability.

Fluid Chemistry

Hydrothermal water normally contains dissolved solids and gases as well as suspended particles. During its travel from the reservoir to the power plant the water may undergo loss of temperature and pressure. In response to this change of thermodynamic state, a part of the dissolved and suspended solid content may precipitate out from water, while a part of the dissolved gas may evolve from solution. Precipitation of solids may cause plugging of the formation around the well bore, thereby reducing well productivity. Precipitation of solids in the pipes causes scaling which reduces flow rates and damages equipment and flow lines. Noncondensable gases evolved from water may cause problems in the power conversion process. Some of the dissolved solids and gases cause corrosion in the well bore, flow lines and equipment, thereby sharply reducing the life of expensive hardware. Highly corrosive geothermal fluids are rather uncommon. Wherever they occur, in such places as some parts of the Niland Field, California or Tatun, Taiwan, they have created severe exploitation problems.

The waste geothermal water from the power plant is reinjected into the formation. The injection rate in a well may decrease with time (or injection pressure required to maintain a steady injection rate increase with time) due to formation plugging around the well bore. Some gaseous (e.g., hydrogen sulfide) or dissolved (e.g., boron, fluoride, arsenic) constituents of a geothermal fluid can be hazardous to plants and human health if present in sufficient concentration. Thus, knowledge of the chemistry of the fluid is required to assess potential technical and economic problems due to corrosion and scaling of equipment, plugging of formation and adverse environmental impact.

The fluid chemistry is usually assessed from an analysis of water samples from a well or surface discharge. The chemistry of water from a surface discharge may have limited resemblance to that from the actual hydrothermal reservoir because of mixing with shallow ground water.

A typical water analysis determines parts per million (ppm) concentration of the total dissolved solids (TDS), concentration of various anions and cations, pH of the water, and the amount of noncondensable gases. Total dissolved solid content of liquid-dominated geothermal systems can vary from a few hundred ppm to several hundred thousand ppm. Usually, the degree of salinity increases with temperature, although not in a linear fashion. A typical value of salinity of some well known liquid-dominated geothermal systems is on the order of 1-2%. Some exceptions occur, such as the Niland Field in the Imperial Valley, where salinities as high as 30% solid content occur in the fluid. These important exceptions may create severe scaling, corrosion and disposal problems.

Magnitude of the Reserve

Even if a reservoir satisfies depth, temperature, flow rate and fluid chemistry criteria, reservoir development will not be economically feasible unless it is proved to have sufficient heat and fluid reserves. The gross heat reserve of a reservoir consists of the heat stored in the fluid, the rock matrix that houses the fluid, and the impermeable layers within the rock. While a large part of the heat in the fluid can be recovered, only a small fraction of the heat stored in the impermeable layers is recoverable with present technology. This is so because of the slow transport rate of heat from rock to water. A part of the stored heat in the rock can be 'scavenged' by reinjecting low temperature waste brine into the cooler parts of the reservoir. This reinjected water will slowly travel to the producing wells while gaining heat from the surrounding rock matrix.

An estimate of the heat reserve in a hydrothermal reservoir can be made from a combination of geophysical, geochemical and bore hole data. As a general rule, the heat reservoir in a geothermal system is much greater than the fluid reservoir. An estimate of the gross heat reserve in a hydrothermal reservoir can be made if one can estimate the bulk volume, porosity and temperature of the reservoir; here the effects of reservoir pressure, lithology and fluid chemistry are minor. Such an estimate is likely to be conservative because it does not take into account the possibility of recharge by hot fluid moving upward along deepseated faults

or flow channels. Calculation of the recoverable heat reserve is complex. Such a calculation will have to take into account not only the gross heat reserve but also the nature of rock permeability (fracture or intergranular), spatial variation of the reservoir properties, possibility of heat recharge, well location, and production and injection rates from wells. Estimates of the ultimate heat recovery vary from 10 to 50 percent of the gross heat reserve. Due to the low thermodynamic efficiency of most geothermal systems (when utilized for power production) the ultimate conversion of heat energy stored in the system to useful electrical energy is generally estimated to be in the range of 2 to 5 percent. The reservoir should be able to deliver the required amount of well head fluid at the minimum acceptable temperature given a desired power plant size for at least 30 years, the usual amortization period for such an investment. Otherwise reservoir development for the desired power capacity is not economically feasible.

Reinjection Potential

It is desirable, and may be essential in some cases, to reinject waste geothermal brine from the power plant into the reservoir for several reasons:

1. If waste brine is not reinjected into the reservoir, it has to be disposed into shallower ground water aquifers or surface water bodies. In either case, there is considerable possibility of adverse chemical and thermal pollution of the local ground water resource.
2. Failure to replace reservoir voidage by reinjection of fluid may cause ground subsidence. Considerable ground subsidence due to voidage of oil reservoirs has been experienced in some areas, for example, Wilmington, California or Houston, Texas. Geothermal fields at Cerro Prieto, Mexico and Wairakei, New Zealand, where fluid reinjection is not practiced, have experienced ground subsidence.
3. If reservoir voidage is not replaced by reinjection, reservoir pressure will decline. A decline in reservoir pressure causes decline in well productivity. If the reservoir pressure is allowed to decline, eventually steam will form in the reservoir. Although formation of steam in the reservoir extracts energy from the rock matrix, this is not an efficient mechanism in most cases (Nathenson and Muffler, 1975). This is in part due to the fact that the steam produced from the low pressure reservoir does not have

sufficient pressure and temperature for power production by the time it reaches the wellhead.

The main considerations in assessing reinjection potential are the selection of optimum sites for injection wells, the pressure required to inject at a certain rate and the decline in injectivity with time. The optimum reinjection scheme should involve such injection sites and rates that the travel path and time for the flow of water from injectors to producers is maximized. This prevents rapid cooling of the produced water. At the same time, injected water should be in close enough continuity with the producing reservoir such that the decline in reservoir pressure with time is minimized. The key factor which determines the optimum injection plan is the variation, both areal and vertical, of water temperature and permeability in the reservoir. Equation (2) can be used to estimate the pressure required for injection at a desired rate. Cooling and pressure decline around the injection wellbore can cause formation plugging due to the deposition of some of the dissolved and suspended solids present in the water. This reduces injectivity. In order to maintain the injection rate, pressure has to be increased. Increase in injection pressure increases operating cost and technical difficulties. If the injection system reaches its maximum pressure capacity, more injection wells may need to be drilled or the old wells stimulated to maintain the total injection rate. This escalates the field development cost. There is no simple way as yet to estimate such gradual loss of injectivity with time. The only sure means of assessing reinjection potential is to inject continuously in a reservoir for an extended period, at least for a few months, and monitor wellhead injection pressure versus flow rate.

It may be possible to reduce plugging of formation bore space through a partial cleaning of the fluid to be injected by passing it through settlement ponds first. However, accumulation of salt at the settlement ponds creates other disposal problems. In some special cases, it is conceivable that the process of purification of the waste geothermal fluid might be linked with economic mineral extraction.

Data for Reservoirs Studied

Available quantitative data on the selected reservoirs are sketchy. In the following few pages we have pieced together data from numerous sources, published and unpublished. For convenience we have not provided reference for the quantitative data except where the data appear unusual.

Table 2 lists the location, depth and areal extent for the reservoirs selected for this study. Depth in Table 2 represents approximately the deepest occurrence of hydrothermal water as discovered by drilling so far. The shallowest depth to economically attractive hydrothermal water varies from a few hundred feet in the case of Yellowstone to almost 10,000 ft (3,050 meters) in Mountain Home. The downward limit of this resource has not been satisfactorily defined for any of the reservoirs. There is a definite possibility of occurrence of hotter reservoirs beneath the reservoirs currently being considered for development. The limiting factors to the downward extension of hydrothermal reservoirs at present are the escalated cost of drilling, limitations of wellbore technology and decline of rock permeability with depth. Areal extent in Table 2 presents an estimate from the available geological, geophysical, geochemical and borehole data of the areal extent of the reservoirs included in this study. Further drilling and exploration may well increase these estimates. The most striking estimate of areal extent is that for Bruneau-Grand View, which may actually be comprised of several independent reservoirs. Future drilling and exploration will substantially modify the estimates on depth and areal extent presented in Table 2.

Table 3 provides temperature data on these reservoirs. Figure 6 shows typical temperature profiles from the hydrothermal reservoirs of the Salton Trough, which is a regional tectonic basin extending from Baja California (Mexico) to the north of Salton Sea (California) which includes the Imperial Valley. For comparison, temperature profiles from two hotter reservoirs, Cerro Prieto (Mexico) and Salton Sea (California) are included in this figure. The main feature of the profiles from East Mesa, Heber and Dunes reservoirs is the flattening of the temperature gradient between 1,000-3,000 ft (300-900 meters depth). The temperature gradient above this depth is steep because of the poor thermal conductivity of the insulating cap rock. The extremely small temperature gradient below the cap rock depth is a result of thermal convection in the reservoir water. Figure 7 presents the temperature profiles and other temperature data for the reservoirs outside the Salton Trough. (The separation of reservoirs in these two groups was done merely for convenience in displaying data.) Also shown in Figure 7 is a boiling point curve for pure water. By definition, hydrothermal reservoirs should fall below this curve.

Table 3 and Figures 6 and 7 indicate that the hydrothermal reservoirs considered may be broadly grouped into four

TABLE 2
HYDROTHERMAL RESERVOIRS INCLUDED IN THE STUDY

RESERVOIR	COUNTY, STATE	MAXIMUM DEPTH (meters)*	AREAL EXTENT (sq.km)**
Heber	Imperial, California	1950	50-95
East Mesa	Imperial, California	2450	28-77
Raft River	Cassia, Idaho	1800	20
Long Valley ***	Mono, California	325	225
Bruneau-Grand View	Owyhee, Idaho	2150	2072-2850
Brady's Hot Springs	Lyon/Churchill, Nevada	1550	12
Roosevelt Hot Springs	Beaver, Utah	850	4
Valles Caldera	Sandoval, New Mexico	2925	65
North Brawley	Imperial, California	--	18-26
Dunes	Imperial, California	--	6-13
Surprise Valley	Modoc, California	2150	125
Beowawe	Lander/Eureka, Nevada	2900	21
Steamboat Springs	Washoe, Nevada	>600	6
Coso Hot Springs ***	Inyo, California	>150	168
Mountain Home	Elmore, Idaho	3050	39
Yellowstone ***	Park, Wyoming	335	375

* As determined by drilling to date. Data from published sources.

** The lower estimate from White and Williams (1975) and the higher estimate from published sources.

*** Limited drilling to date. Considerable extension to greater depth is expected from geological inference.

TABLE 3

TEMPERATURE DATA ON SELECTED HYDROTHERMAL RESERVOIRS *

RESERVOIR	TEMPERATURE OF SURFACE DISCHARGE (°C)	TEMPERATURE FROM GEOTHERMOMETRY (°C)	BOTTOMHOLE TEMPERATURE (°C)
Heber	---	---	149-190
East Mesa	---	---	149-204
Raft River	100	136-139	149
Long Valley	94	200-209	178-220
Bruneau-Grand View	40-84	149-179	145
Brady's Hot Springs	98	182-193	214
Roosevelt Hot Springs	85	213-283	216-230
Valles Caldera	87	---	204-218
North Brawley	---	---	200
Dunes	---	---	135
Surprise Valley	98	159-174	175
Beowawe	96	226-242	240
Steamboat Springs	97	207-226	210
Coso Hot Springs	93	161-238	220
Mountain Home	66	---	194
Yellowstone	96	250-270	250

* Data from various publications.

Figure 6. Temperature profiles from various geothermal fields in the Salton Trough, California and Mexico (well name in parentheses).

Figure 7. Temperature data (profiles and point data) from various hydrothermal systems outside the Salton Trough, California (well names in parentheses). Modified from TRW Systems and Energy, 1975.

classes (extrapolating temperature data to an average depth of 6,000 ft. (1,830 meters)):

1. Low temperature (280°-325°F (138°-163°C)) - e.g., Dunes, Bruneau-Grand View, Raft River.
2. Moderate temperature (325°-400°F (163°-204°C)) - e.g., Heber, East Mesa.
3. Higher temperature (above 400°F (204°C)) - e.g., Brady's Hot Springs.
4. Very high temperature (above 400°F (204°C) and with a temperature profile close to the boiling curve) - e.g., Yellowstone, Salton Sea.

Table 4 summarizes the well test data from the selected reservoirs. Considerable flow testing has been conducted in Valles Caldera, Roosevelt Hot Springs, Heber, East Mesa and Raft River areas. Figure 8 shows results of one such test at East Mesa. Most of the flow rates in Table 4 should be considered minimum values. The highest reported flow rate is 3,300 gallons/min. (18,000 cubic meters/day) from Beowawe. A value of 1,000 gallons/min. (5,450 cubic meters/day) is considered a good average.

Table 5 presents a summary of the data available on brine chemistry from these reservoirs. Most of the reservoirs are of low salinity (less than 15,000 ppm total dissolved solids) type. The Mountain Home reservoir shows the least salinity and contains potable water.

Table 6 presents data on bulk volume, stored heat and net electrical potential for the selected reservoirs. The bulk volume was calculated as the product of the areal extent (from Table 2) and the gross thickness. When no estimate of gross thickness was available an arbitrary value of 1.5 km (4,921 ft) was assumed following Nathenson and Muffler (1975). The stored heat was calculated as:

$$\text{Stored Heat} = V_B \times C \times \Delta T$$

(Calories)

where V_B is the bulk volume in cubic miles, C is the average volumetric specific heat of the rock-fluid system in calories/mile³/°F and ΔT is the difference between the average reservoir temperature in degrees F and a reference temperature of 60°F (16°C). An average volumetric specific heat of 0.6 calories/cm³/°C

TABLE 4
SUMMARY OF WELL TEST DATA

<u>Reservoir</u>	<u>Well Test Data *</u>
Heber ⁴	Flowed 50-150 m ³ /hr. Projected production rate $\approx$ 340 m ³ /hr/well. No temperature drop in wellbore at projected rate.
East Mesa ¹⁵	Up to 105 m ³ /hr in USBR wells, with WHT from 105-165 C and WHP from 0.5-6.5 bars. 0.265 m ³ /hr at WHT 105-110 C in RGI Well 38-30 (Bureau of Reclamation).
Raft River ¹	180-230 m ³ /hr.
Long Valley ¹⁴	230 m ³ /hr.
Bruneau-Grand View ⁸	160-340 m ³ /hr from pumped wells (probably irrigation wells).
Brady's Hot Springs ⁹	27 m ³ /hr, 214 C BHT, hot water with 5% steam flashover, problem of scaling.
Roosevelt Hot Springs ¹⁰	320 m ³ /hr at 29 bars WHP with 90,000 kg steam/hr ($\approx$ 90 m ³ /hr).
Valles Caldera ⁷	134-267 m ³ /hr. Hot water with 5-10% steam flashover.
Beowawe ⁷	756 m ³ /hr in three wells at 7-9 bars WHP, 165-170 C WHT and 2-3% steam.
Steamboat Springs ³	Natural discharge estimated at 250 m ³ /hr. 45 m ³ /hr in shallow holes. Hot water present with 5-10% steam flashover.
Coso Hot Springs ²	9 m ³ /hr (natural discharge?)
Mountain Home ¹³	230 m ³ /hr.
Yellowstone ¹⁴	Dry steam and hot water with steam flash-over.

ABBREVIATIONS

BHT = bottomhole temperature
gpm = gallons per minute
WHP = wellhead pressure
WHT = wellhead temperature

* Unless otherwise mentioned, data are from unpumped wells.

TABLE 4 (CON'T)

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TEMPERATURE, PRESSURE AND FLOW RATES MESA 6-1 AND MESA 6-2 IMPERIAL VALLEY, CALIFORNIA

Figure 8. Well data from East Mesa Reservoir, California (after U.S. Bureau of Reclamation, 1974).

TABLE 5

WATER SALINITY AND CHEMISTRY OF HYDROTHERMAL RESERVOIRS *

Heber ⁴	12,000-20,000 ppm TDS, mostly NaCl, acidic (pH: 4.5-7.4).
East Mesa ¹⁵	14,000-28,000 ppm TDS, mostly NaCl and HCO ₃ , slightly acidic to alkaline (2,200 ppm TDS with almost no Ca, Mg in well 38-30 of RGI, Bureau of Reclamation).
Raft River ¹	2,000 ppm TDS. NaCl and CaCO ₃ are being deposited.
Long Valley ¹⁴	1,000-2,000 ppm TDS, Cl with significant amount of As and B.
Bruneau-Grand View ¹⁸	18,000-110,000 ppm TDS, primarily NaHCO ₃ . Dissolved gases mostly atmospheric O ₂ , N; no mineral deposits near spring.
Brady's Hot Springs ⁹	2,400-2,600 ppm TDS. Chiefly NaCl.
Roosevelt Hot Springs ¹³	7,000-7,800 ppm TDS.
Valles Caldera	5,000 ppm TDS.
Dunes ⁵	3,000 ppm TDS. Alkaline sodium chloride brines.
Surprise Valley ¹⁷	1,500 ppm TDS (in Spring). Na, SO ₄ , B, F, As (in some cases).
Beowawe ⁷	1,200 ppm TDS Ca-rich water.
Steamboat Springs ³	2,500 ppm, TDS (in Spring), Cl -- HCO ₃ water, alkaline (pH - 7.9).
Coso Hot Springs ⁶	2,000-5,800 ppm TDS, highly acidic and very low in Cl. 2,300 ppm sulfate.
Mountain Home ¹¹	300-800 ppm TDS.
Yellowstone ¹²	2,000 ppm TDS, Cl -- HCO ₃ to acid SO ₄ , pH: 2 to 7.5, B, As, F, CO ₂ .

ABBREVIATIONS

TDS = Total Dissolved Solids
ppm = parts per million

* Appendix C gives detailed chemical analysis. References in Table 4.

TABLE 6
MAGNITUDE OF RESOURCE IN VARIOUS HYDROTHERMAL RESERVOIRS

RESERVOIR	VOLUME (km ³)*	STORED HEAT (10 ¹⁸ cal)	ELECTRICAL POTENTIAL (MWe. Cent)
Heber	100.0	11.0	292
East Mesa	55.9	5.5	146
Raft River	30.0	2.3	61
Long Valley	450.1	55.0	1830
Bruneau-Grand View	3380.2	263.0	6990
Brady's Hot Springs	30.0	3.6	119
Roosevelt Hot Springs	7.9	1.0	33
Valles Caldera	129.2	18.0	598
North Brawley	27.1	3.0	100
Dunes	9.2	0.6	16
Surprise Valley	250.1	24.0	637
Beowawe	41.7	5.7	189
Steamboat Springs	15.8	1.9	63
Coso Hot Springs	337.6	41.0	1360
Mountain Home	11.7	1.3	35
Yellowstone	942.0	133.0	5300

*Thickness assumed to be 1,000 ft (300 meters).

or 1.39×10^{15} calories/mile³ /°F was assumed. Considering the uncertainties involved in estimating areal extent and thickness, assumption of an average volumetric specific heat is justified. The net electrical potential in megawatt-centuries was calculated as the product of the stored heat times a recovery factor. Recovery factors were taken from the estimates given by Nathenson and Muffler, 1975. They suggested net recovery factors of 0.020, 0.025, and 0.030 for hydrothermal reservoirs in the temperature ranges of 300°-392°F (150°-200°C), 392°-482°F (200°-250°C), 482°-572°F (250°-300°C), respectively. We feel that these estimates are at best very approximate and are conservative. Yet, it is apparent that most of the reservoirs in Table 6 can provide several hundred megawatts of power for 30 years, which is considered the minimum required reservoir life for power plant development.

Injection data are available only from the Heber and East Mesa reservoirs. About one year of continuous injection has been successful in one Heber well.

DEFINITION OF A HYPOTHETICAL RESERVOIR

No two geothermal reservoirs are alike, but broad similarities exist between reservoirs. In the following section we have attempted to group hydrothermal reservoirs into various types based on their origin and occurrence. In essence a liquid-dominated geothermal reservoir is a body of water located in a porous and permeable rock at an economically attractive temperature. It is usually associated with a heating mechanism which imparts to it a temperature higher than the normal temperature encountered at that depth elsewhere. The term 'reservoir' implies fluid producibility. A geothermal reservoir may be associated at times with a much greater heat reservoir nearby, in the earth's crust or upper mantle. In some cases, the heat source may be relatively distant, but tectonic factors, such as regional faults, may cause the occurrence of a hydrothermal anomaly locally.

Types of Hydrothermal Reservoirs

Generally, geothermal systems may be divided into three types: (a) those related to some special artesian or thermo-artesian conditions in an area of normal geothermal gradient, (b) volcano-tectonic type, and (c) volcanic type.

The artesian or thermoartesian cases refer to those situations where warm or hot water will flow upward in a drilled hole because of a positive pressure on the water-bearing layer. A classical example of the utilization of thermal water because of unique artesian conditions is provided by that of the Paris Basin in France. The deeper aquifers in part of that basin are under artesian pressure. The temperature gradient in the basin is quite normal, about 28°F/1000 ft. (30°C/km). Wells drilled to a depth of 6,600 ft. (2,000 meters) produce thermal water at about 126°F (52°C) without pumping. They are used for comfort heating of a housing project in Melun, near Paris.

Thermoartesian systems are those where water that has traveled deeply into the crust, rises back to the surface because of a positive buoyancy pressure that the colder, and therefore denser, water imparts to the lighter, warmer water. The warm springs at Hot Springs, Arkansas or Thermopylae, Greece, are believed to fall into that category. Drilling into those systems is likely to detect a less-than-normal temperature gradient up to the base of the flow system, and

a normal gradient thereafter. Geopressure geothermal resources, such as those occurring in Texas, Louisiana and elsewhere, may be considered as a special case of artesian systems. There, wellhead pressures as high as 11,000 psig (760 bars) are encountered in wells drilled to a depth of 10,000-20,000 ft (3,000-6,000 meters). Geopressured resources are not discussed in this study.

The volcano-tectonic geothermal system is a system where hot water occurs at a relatively shallow depth due to a combination of factors, volcanic as well as tectonic. Such a system will occur in areas where relatively young volcanism, in general less than 10 million years, has taken place. It is generally associated with a crustal thickness less than normal. Whereas the normal crustal thickness is of the order of 25-30 miles (40-48 kilometers), volcano-tectonic provinces, such as the entire area west of the Rockies in the United States, are characterized by crustal thickness which is smaller than the average. In the Imperial Valley, for example, crustal thickness is estimated by different investigators to be in the range of 8-14 miles (13-23 kilometers) only.

Faulting in areas of young volcanism or thin crust creates channelways for thermal water to ascend to the surface or to a shallow depth below the surface. In time, all hot spring systems seal themselves up through deposition of silica, calcite, and other minerals, as the hydrothermal solutions cool down and decompress. However, in areas of active tectonism, the fault systems are kept open through the continued movement along the faults. This is the case in the Imperial Valley of California where the west side of the valley is moving away from the east side at a rate of about 3 inches/ year (7 cm/year) (Whitten, 1955). This movement is distributed across many faults which are kept thereby open and permeable.

The Basin and Range province of Nevada also falls into the category of volcano-tectonism. Here, through the spasmodic compression and dilatation caused by movement in the upper mantle (due to subduction of the oceanic Farrallon Plate under the American Plate), a combination of rift valleys and separating ridges have formed. Recent volcanism is associated with some of these. The rift valleys are sediment-filled, typically to a depth of about 3,000-10,000 ft (900-3,000 meters).

Geothermal reservoirs occur in the volcano-tectonic systems where a recent heat source is nearby or where faulting has created means for hot water to flow upwards to a shallower

depth, or a combination of the two conditions. The rocks can be either sedimentary or a complex combination of sedimentary strata intruded by volcanic flows. Most of the Imperial Valley geothermal fields, the Basin and Range, Raft River and the Rio Grande Rift Valley fall into this category. The water usually comes from rainfall on the ridges bordering the valley. Water percolates down the faults on the mountain ridges, is heated up at depth, and rises along the basin faults, usually the bounding faults. In the Imperial Valley the source of the geothermal fluid is believed to be the Colorado River, based upon electrical resistivity and isotope chemistry studies.

The volcanic geothermal system occurs in areas of shallow, recent volcanism. Heat conduction to a shallow aquifer system is important, although local faults will provide some added efficiency in heat transfer to shallower aquifers through convection. A volcanic geothermal system may be associated with a large extruding lava field, such as many of the lava fields of the northwest, volcanic calderas such as Long Valley, Valles Caldera and others, or intrusives such as the Salton Sea (Niland) field. In the latter case, a semi-molten rock mass at a depth of a few miles is believed to be the primary source for the elliptical thermal anomaly surrounding it.

Conceptual Model

Based on the above discussion and a comparative examination of the data on the selected reservoirs, we propose two conceptual models which represent essentially two broad classes of hydrothermal reservoirs being considered for development in the United States. Figure 9 presents the first model. It is a volcano-tectonic type reservoir located in a sedimentary basin in a regional structural depression. The reservoir is a porous, clastic, sedimentary rock with occasional layers of volcanic flows containing brine confined between a cap rock (low-permeability overburden) and an impervious basement rock. The lateral limits of such a reservoir could be defined by faults or low permeability zones. There is a convecting magma at a relatively shallow crustal depth supplying heat to the reservoir by conduction through the basement rock. This heat creates large hydrothermal convection cells within the reservoir. These cells may be partially controlled by structural features within the reservoir. The cap rock has poor thermal conductivity and hence higher thermal gradients. There may be some mass recharge from meteoric water percolating down boundary faults. Heat recharge may take place from deep faults or intrusives extending into a locally fractured basement.

LOW SALINITY, MODERATE TEMPERATURE
HYDROTHERMAL RESERVOIR - TYPE I
SEDIMENTARY BASIN (STRUCTURAL DEPRESSION)

Figure 9

Surface manifestations such as hot springs, fumaroles or geysers are limited. Some shallow, normal temperature aquifers may occur close to the surface. Typical examples of this model are reservoirs in the Imperial Valley of California, namely, Heber, East Mesa, etc.

Figure 10 presents the second model. The reservoir is of volcanic type and occurs underneath a volcanic caldera, which may have collapsed. The collapse structure is filled with lava flows mixed with sediments. The crystalline rocks (igneous or metamorphic) underlying the caldera are fractured and faulted. The main geothermal reservoir is located in the crystalline rocks. A convecting magma emplaced at a relatively shallow crustal depth supplies heat to the reservoir by conduction. Hot brine is present within the fractures. Large scale thermal convection cells, modified by fracture and fault locations, occur in the reservoir. Some hot brine escapes to the surface through faults. This gives rise to hot springs, geysers, etc. Cold meteoric water percolates down faults near the cooler parts of the reservoir. There may be hot aquifers present at shallow depths in the caldera. These shallow, hot aquifers are recharged primarily from the larger reservoir underneath. Long Valley, California is an example of this model.

Table 7 presents a comparison of the two models pointing out the differences that have some bearing on exploration and exploitation of hydrothermal reservoirs. The second model requires higher drilling costs per well as noted from Figure 3. The fact that porosity and permeability are controlled by fractures makes the second model more difficult to evaluate. In a naturally fractured reservoir, the orientation, location or extent of fractures cannot be estimated with a high degree of certainty. Yet properly located fractures can make a reservoir far more permeable than is possible in intergranular type permeability, where flow takes place through pore spaces between rock grains. Core analysis and well log analysis may not readily identify fractures because these techniques essentially provide data on a few inches to a few feet from the well bore, while major fracture systems may occur farther away. Well test analysis or some geophysical surveys may identify a fractured system, but there is no technique yet for detailed delineation of fractures. Thus formation evaluation and prediction of performance for such reservoirs are difficult. Because of the non-uniform nature of fracture occurrence, a well may encounter very low permeability in close proximity to a high permeability well, or vice versa. This makes reservoir development more difficult to plan.

LOW SALINITY, MODERATE TEMPERATURE
 HYDROTHERMAL RESERVOIR – TYPE 2
 EXTINCT VOLCANIC CALDERA

Figure 10

TABLE 7

COMPARISON OF HYDROTHERMAL RESERVOIR MODELS

<u>Model 1 (Sedimentary)</u>	<u>Model 2 (Volcanic)</u>
1. Limited surface manifestation.	1. Some surface manifestations (hot springs, fumaroles, etc.)
2. Drilling cost relatively lower.	2. Drilling cost relatively higher.
3. Formation evaluation simple.	3. Formation evaluation more complex.
4. Porosity and permeability of largely intergranular type.	4. Porosity and permeability controlled by fractures.
5. Vertical permeability restricted due to interbedded shale layers.	5. Vertical permeability similar in magnitude to horizontal permeability in places.
6. Reservoir development relatively simple (storage and flow capacities distributed uniformly).	6. Reservoir development more difficult (storage and flow capacities distributed non-uniformly).
7. Reservoir performance prediction relatively easy.	7. Reservoir performance prediction may be difficult.
8. Subsidence likely unless waste brine is reinjected.	8. Subsidence less significant.

In the first model, because of the clastic, sedimentary lithology, impermeable shale or siltstone layers are likely to be interbedded with permeable layers. This may greatly restrict overall vertical permeability in the reservoir. This fact may be used to advantage when reinjecting waste brine from power plants. Waste brine may be reinjected in lower layers, while production may take place from upper layers. Limited vertical communication will retard breakthrough of cooler, waste water in the producing wells. This situation is less likely for the second model, where there may be no definite horizontal, impermeable layers. If reservoir voidage is not compensated by reinjection, land surface may subside due to compaction of granular sediments in the first model. Subsidence due to reservoir voidage is less significant for the second model because crystalline rocks will not undergo compaction as readily as do sediments. However, exceptions to both the above generalizations may exist.

Characteristics of a Hypothetical Reservoir

There is no obvious correlation between either of the proposed models and the primary reservoir criteria presented before, namely, depth, temperature, flow rate, fluid chemistry, reserves, and reinjection potential. It may then be possible, from the point of view of power conversion, to define a hypothetical reservoir, irrespective of its affinity to either model, by determining typical values of these primary criteria. While the two conceptual models were proposed considering the origin and occurrence of hydrothermal reservoirs, the hypothetical reservoir to be developed in this section will typify those reservoir characteristics that determine power conversion potential. The hypothetical reservoir discussed below typifies the majority of the commonly occurring hydrothermal reservoirs in the United States. It does not necessarily represent the limited number of hydrothermal reservoirs currently under development. In the next few pages we shall attempt to define the reservoir and fluid properties of the reservoir. A depth value of 6,000 ft. (1,800 meters) was chosen to be the most typical (see Table 2). Table 2 indicates that 10 square miles (25.9 square kilometers) is the approximate median for the subsurface area of hydrothermal reservoirs selected. To verify this, a histogram of the number of identified convection systems under various area classes (logarithmic scale) was prepared (Figure 11). Data were taken from U.S.G.S. Circular 726 (White and Williams, 1975). In that circular, all convection systems for which area was unknown were assigned a value of 1.5 square kilometers. All such convection systems were ignored in preparing Figure 11. The data

Subsurface Area (Sq.Km.)

Figure 11. Frequency of Areal Distribution of Hydrothermal Reservoirs in the United States.

seemed to appear in a log normal distribution with a mean of between 2.5 and 5 square km (0.97 to 1.93 square miles), which is much lower than the estimate of 10 square miles (2.6 km²). The discrepancy may be due to the fact that extensive geophysical surveys to delineate reservoir extent has been conducted only for a limited number of reservoirs. Those without the benefit of such surveys had been assigned an areal extent based on areally restrictive phenomena such as occurrences of hot springs, surface evidence of hydrothermal alteration of rocks, etc. This tends to bias the histogram in Figure 11 toward lower values. Hence, it was decided to accept 10 square miles as the subsurface area of the hypothetical reservoir. The net and gross thickness values of 1,000 and 4,000 ft (300 and 1,200 meters), respectively, were deemed most reasonable. Bulk volume was calculated from the assumed areal extent and gross thickness.

In order to determine the most typical temperature, the list of identified hydrothermal convection systems in the United States given in U.S.G.S. Circular 726 was divided into 14 temperature classes as shown in Figure 12. Then the number of such systems in each class was plotted in a histogram (Figure 12). Neglecting reservoirs at temperatures below 280°F (140°C), we find that by far the largest number of identified hydrothermal reservoirs fall in the 280°-325°F (140°-165°C) range. (It should be noted that the data in the U.S.G.S. Circular 726 cover only the identified hydrothermal convection systems, and do not include low temperature brine occurring in all normal temperature gradient areas. Otherwise, the histogram will show more bias toward low temperature classes.) Figures 13 and 14 show histograms of volume and gross heat content of hydrothermal reservoirs over the 14 temperature classes (data from U.S.G.S. Circular 726). From the last two figures, it is seen that the reserves display almost bimodal distribution with respect to temperature classes--a peak at the low temperature range of 280°-325°F (140°-165°C) and another at the high temperature range of 426°-500°F (220°-260°C). These two classes appear to agree with our temperature classification proposed in the section on Quantification of Reservoir Characteristics. We shall define in the following pages a hypothetical reservoir of the low temperature class--a reservoir with an average temperature of 300°F (150°C) and a range of 280°-325°F (140°-165°C) from the edge of the reservoir to the center. It should be emphasized that the hypothetical reservoir defined here is representative of the most commonly occurring hydrothermal systems and does not necessarily represent the reservoirs selected for this study. The gross stored heat and the electrical potential of the reservoir were calculated as discussed in the section on the Data for Reservoirs Studied.

Selection of representative values of porosity and permeability was difficult because of the unavailability of

Figure 12. U.S. Hydrothermal Resource Distribution Under Various Temperature Classes.

Figure 13. U.S. Hydrothermal Resource Distribution Under Various Temperature Classes

Temperature Classes (°F)

1	< 200	8	351 - 375
2	201 - 225	9	376 - 400
3	226 - 250	10	401 - 425
4	251 - 275	11	426 - 450
5	276 - 300	12	451 - 475
6	301 - 325	13	476 - 500
7	326 - 350	14	> 500

Figure 14. U.S. Hydrothermal Resource Distribution Under Various Temperature Classes

such data for most of the reservoirs. The values of porosity and permeability were chosen to be 0.15 and 100 millidarcy, respectively. A brine salinity of 5,000 ppm total dissolved solids was thought to be a reasonable assumption. The density and viscosity of brine were obtained from standard references for the assumed temperature, pressure and salinity conditions. The hydrostatic gradient value was chosen from a comparison of depth vs. pressure data from several hydrothermal reservoirs. The initial reservoir pressure was calculated from assumed values of depth and hydrostatic gradients. The maximum productivity index was calculated from equation (2), assuming a drainage radius of 500 ft. (150 meters) and a well bore radius of 6.875 inches (17.5 centimeters), 7-5/8 inch (19.4 cm) OD casing. Table 8 lists the reservoir and fluid properties of the hypothetical reservoir.

Table 9 presents the exploitation characteristics of the hypothetical reservoir. It was assumed that the fluid will be produced by downhole pumping through standard size (7-5/8 inch OD) casing. As indicated before, a flow rate of 1,000 gallons per minute (5,450 cubic meters per day) per well appears most representative (Table 4) and was chosen as the flow rate per well for the hypothetical reservoir. For this amount of flow, the minimum pressure drawdown required at the well bore can be calculated from the maximum productivity index given in Table 8. This approach gives a minimum drawdown of 57 psi (3.93 bars). However, the actual drawdown at the well bore will be higher because of poor completion efficiency and pressure interference between wells. Wells do not have a 100 percent completion efficiency because of formation damage around the well bore, incomplete penetration and the presence of a perforated casing; the lower the completion efficiency, the higher the required drawdown at the well bore. Wells producing from the same reservoir will interfere with each other's pressure drawdown characteristics; the closer the well spacing, the higher the interference. Interference between producing wells results in higher drawdown requirements in each producer. This point will be elaborated on later in this section.

It is assumed that all of the produced brine will be reinjected into the reservoir. Usually the thermal anomaly over a hydrothermal reservoir consists of the highest temperature at the center, with temperature declining toward the edges of the anomaly (for example, see Figure A-1 in Appendix A). Therefore, a logical development program for such a reservoir would be to locate the production wells in the hottest part of the anomaly and the injection wells near the edges.

TABLE 8

CHARACTERISTICS OF THE HYPOTHETICAL RESERVOIR

Reservoir and Fluid Properties

Depth	6000 ft	(1800 meters)
Subsurface area	10 sq miles	(26 sq km)
Gross thickness	4000 ft	(1200 meters)
Net thickness (permeable zone)	1000 ft	(300 meters)
Bulk volume	7.6 mile ³	(31.7 km ³)
Reservoir temperature (highest near the center, cooler near the edges)	280°-325°F	(138°-163°C)
Gross stored heat	2.6 x 10 ¹⁸ cal	(1.03 x 10 ¹⁶ BTU)
Gross electrical potential	3440 MW·centuries	
Net electrical potential	69 MW·centuries	
Expected life of a 200 MWe plant	35 years	
Porosity	15 percent	
Permeability	100 millidarcies	
Brine salinity (total dissolved solids)	5000 parts per million	
Brine density	58 lbs/ft ³	(0.93 gms/cm ³)
Brine viscosity	0.2 centipoise	
Hydrostatic gradient	0.43 psi/ft	(0.009 bars/meter)
Reservoir pressure	2600 psia	(180 bars)
Maximum productivity index	7980 lbs/hr/psi 17.4 gallons/min/psi 588 barrels/day/psi 93.5 cubic meters/day/psi	

TABLE 9

CHARACTERISTICS OF THE HYPOTHETICAL RESERVOIR

Exploration Characteristics

PRODUCTION MECHANISM	DOWNHOLE PUMPING	
Well Diameter (7-5/8 inch OD casing)	6.875 inch ID	(17.5 cm)
Expected flow rate per well	1,000 gallons/min	(5,450 cu.m./day)
Number of producers (50 MWe plant)	36	
Number of injectors	18	
Injection rate per well	2,000 gallons/min	(10,900 m ³ /day)
Flowing bottomhole pressure at producing well	1,680 psia	(116 bars)
Flowing bottomhole pressure at injection well	2,890 psia	(200 bars)
Flowing wellhead pressure (under pumping)	75-100 psia	(5.2-6.9 bars)
Shut-in wellhead pressure	50 psia	(3.5 bars)
Wellhead temperature (average over 30 years)	300°F	(150°C)
Reinjection wellhead temperature	150°F	(66°C)
Reinjection wellhead pressure	100-200 psia	(6.9-13.8 bars)

Figure 15 shows an idealized version of such a development plan. Here the injectors and producers are located on circular arrays. The wells in each array are equally spaced. The upper figure in Figure 15 shows a typical streamline pattern for a case with 8 producers and 8 injectors, while the lower figure shows the essential symmetry of the system. A similar plan is being considered for the Heber area by the developers.

The desired capacity of the demonstration power plant is assumed to be 50 MWe net electricity. The average expected temperature of the brine from the hypothetical reservoir is around 300°F (150°C). For a system at this temperature level, the binary power conversion system is usually assumed to be more efficient (see Figure 5). From Figure 5, we observe that the two-stage flash process (data provided by Chevron Oil Company) may also be equally attractive for the hypothetical reservoir. Figure 5 indicates that for an average brine temperature of 300°F (150°C), approximately 1.4 MWe net electricity can be generated per 1,000 gallons per minute (gpm) (5,450 cubic meters per day) flow rate. Thus, the total flow rate of 300°F (150°C) water required for a 50 MWe binary demonstration plant will be approximately 36,000 gpm (196,000 cubic meters per day). If the figure of 1,000 gpm (5,450 cubic meters per day) is assumed to be the production rate per well, the demonstration plant will require 36 producing wells. The waste brine (36,000 gpm/196,000 cubic meters per day total) may be reinjected through 36 injecting wells if an injection rate per well of 1,000 gpm (5,450 cubic meters per day) is assumed. It is more likely, however, to inject at a higher rate per well. The injection rate per well for the hypothetical reservoir has been assumed to be 2,000 gpm (10,900 cubic meters per day), requiring 18 wells for the total injection load. The reason for using higher rates per well for injection than for production is as follows: the positive gravity head due to cooler (and hence, heavier) brine in the injection well, compared to that in the reservoir, facilitates injection. In order to increase the injection rate to 2,000 gpm (10,900 cubic meters per day) only 100-200 psia (6.9-13.8 bars) injection pressure at the well head is expected to be sufficient. Increasing injection rate per well reduces the number of wells required and reduces the development cost.

In Appendix B, we have explained the mathematical relations used in calculating the flowing bottomhole pressures for producers and injectors. If the hypothetical reservoir is assumed to be circular, it should have a radius of 9,420 ft (2,870 meters) as calculated from its areal extent of 10 square miles (26 km²). It is assumed that the injectors will be located on a circular array of 9,420 ft (2,870 meters). The producing wells are assumed to be located on an inner, circular array, whose radius is

Figure 15. Location of producing and injecting wells in the hypothetical reservoir.

determined by the desired spacing of the producers. If the spacing of producers is too large, the producer array will have too large a radius. This will reduce the distance between the producers and injectors and increase the change of premature breakthrough of cooler water in the producing wells. Too large a radius of the producer array may place the producers outside the hottest region of the anomaly. On the other hand, if the spacing between producers is too short, the wells will interfere with each other, thus increasing the drawdown requirement, and consequently the pumping cost. Figure 16 presents the calculated flowing bottomhole pressures, at the producers and injectors for various producer spacings and various production rates per well. If the production rate per well is increased fewer wells are required. The upper horizontal scale in Figure 16 shows the number of producing wells required corresponding to a given production rate per well (lower scale). It is seen from the figure that for a production rate of 1,000 gpm (5,450 cubic meters per day), and an equal injection rate per well, the flowing bottomhole pressure at the producer will vary from 1,660 to 2,220 psia (115 to 153 bars) for producer spacings of 200 to 1,000 ft (60 to 300 meters). The flowing bottomhole pressure for the injectors is insensitive to spacing of producers (over the spacing range considered) and equals 2,810 psia (194 bars) for all spacings for a production rate of 1,000 gpm (5,450 m³/day) per well. A spacing of less than 200 ft (60 meters) or greater than 1,000 ft (300 meters) would be unreasonable for this reservoir. It should be noted that Figure 16 considers the case where injection rate per well was kept the same as the production rate per well.

In Figure 17 are presented the flowing bottomhole pressures at producing and injecting wells for various producer spacings for the case where injection rate per well is twice the production rate per well. The figure shows that for a production rate of 1,000 gpm (5,450 m³/day) per well and a simultaneous injection rate of 2,000 gpm (10,900 m³/day), the flowing bottomhole pressure at the producer varies from 1,680 to 2,220 psia (116 to 153 bars) for producer spacings of 200 to 1,000 ft (60 to 300 meters). The corresponding pressure for the injectors (insensitive to producer spacing) is 2,890 psia (200 bars). It should be noted that flowing bottomhole pressure curves for producers in Figures 16 and 17 are practically identical. In other words, for the spacings considered, producers are close enough together and far enough from the injectors so that increasing the injection rate per well and decreasing the number of injectors within the considered limits do not affect pressure distribution around producers. It should be noted that the distribution of streamlines in the case of the injection rate per well being twice the production rate per well will be different from that shown in Figure 15. In the flowing bottomhole pressure values in Table 9 we have assumed a producer spacing of 200 ft (60 meters).

Figure 16. Flowing bottomhole pressures for the case of equal production and injection rates per well.

Figure 17. Flowing bottomhole pressures for the case where injection rate per well is twice the production rate per well.

The pressure and temperature of the produced brine at the wellhead are determined by the flowing bottomhole pressure and temperature, the length, inner diameter, and friction characteristics of the well bore and the presence of pumps, valves, etc. in the well. Our calculations show that for this hypothetical reservoir, assuming a flowing bottomhole pressure as given in Table 9, the brine will flash to steam in the well bore if pumping is not used. Considering a reasonable range of friction factors (0.01 to 0.05), we find that for the flow rates and the flowing bottomhole pressures considered in Figures 16 and 17, the brine will flash at a depth range of 1,000 to 2,000 ft. (300 to 600 meters). If brine is allowed to flash, the corresponding wellhead pressure and temperature can drop to as low as 20 psia (1.38 bars) and 250°F (121°C). These orders of wellhead temperatures and pressures are considered too low for economical energy extraction. Hence, it was assumed that the fluid will be produced by downhole pumping to avoid flashing in the well bore. Pumping capacity will be so designed to provide a 75 to 100 psia (5.1 to 6.9 bars) pressure at the wellhead. A similar production mechanism is being considered for the Heber reservoir by its developers. It is expected that if the liquid is not allowed to flash in the well bore, there will be very small temperature drop as the fluid travels from the bottom to the top of the well, at the flow rate expected of this hypothetical reservoir. This was the experience during the well test at Heber. Thus, the wellhead temperature was assumed to be only 0°F - 5°F (0°C to 3°C) lower than the flowing bottomhole temperature. As shown in Table 9, our estimate is an average wellhead temperature of 300°F (150°C) over a period of 30 years. At this temperature, the average enthalpy of wellhead brine is about 150 cal/gm (from standard charts). A shut-in wellhead pressure of 50 psia (3.5 bars) was assumed reasonable for this reservoir.

By comparison with the existing hydrothermal operations, it was assumed that a pressure drop of 25 to 50 psi (1.725 to 3.5 bars) should take place as the brine travels from the wellhead to the turbine. Again, by comparison with typical systems, it was estimated that by the time the waste brine reaches the injection wellhead, it will have a pressure and temperature of 50 psia (3.5 bars) and 150°F (66°C), respectively. In order to inject the waste brine into the reservoir, a higher wellhead injection pressure will be required. This value of 100-200 psia (6.9 to 13.8 bars) was estimated as the flowing bottomhole pressure in the injector (Table 9) minus the gravity head due to a water column of 6,000 ft. (1,800 meters) in length (well depth)

at 150°F (66°C) in the injection well. This indicates that the waste brine will have to be pumped from 50 psia to 200 psia (3.5 to 13.8 bars) at the wellhead.

The results shown in Figures 16 and 17 were based on steady state pressure drop. If all produced brine is reinjected after power generation, the reservoir fluid should eventually reach a steady state. However, during the first few years, pressure transients in the reservoir will modify the pressure behavior of wells to some degree. The effect of such transients is to reduce the pressure drawdown at the well bore. Thus, the flowing bottomhole pressure at the producers will be more for the same flow rate under transient conditions than under steady state (such as results in Figure 16 and 17). Figure 18 shows the theoretical bottomhole injection pressure build-up with time for East Mesa due to transient effects. Since the time axis has a logarithmic scale, it is apparent that the effect of transients dies away in a few months, after which steady state solutions are valid. Figure 19 shows similar calculations for East Mesa for pressure build-up at various radial distances from the borehole. Figure 20 shows theoretical liquid levels (directly proportional to the required injection pressure) at the injection wells at East Mesa for various injection rates. At 1,000 gpm (5,540 m³/day) this figure gives a liquid level of about 175 ft. (50 meters), which is equivalent to about 80 psia (5.5 bars). This estimate is close to the 100 to 200 psia (6.9 to 13.8 bars) estimated for the hypothetical reservoir.

Finally, a forecast of the future performance of this reservoir is in order. At first, the produced water will be at 325°F (163°C). As time passes, the water from the colder parts of the reservoir will be produced, reducing the temperature at the outlet. The injected cold water will slowly travel toward the producers, while picking up heat during its travel through the pores and fractures in the rock. As a result, although the injected water will eventually reach producers, it will have a temperature higher than the waste brine temperature. In other words, the fluid front will advance faster than the temperature front from the injectors toward the producers. The rates of advance of both the fluid front and the temperature front depend on the vertical and horizontal distribution of permeable layers, thickness, and permeability of such layers and locations of producers and injectors.

For the same net formation thickness, the thinner the individual permeable zones, the lower is the decline in outlet temperature. The hypothetical reservoir consists of net

**MESA 5-1
IMPERIAL VALLEY, CALIFORNIA
THEORETICAL BOTTOM HOLE PRESSURE BUILDUP
AT VARIOUS INJECTED FLOW RATES**

Figure 18. (After U.S. Bureau of Reclamation, 1974.)

**MESA 5-1
IMPERIAL VALLEY, CALIFORNIA
THEORETICAL PRESSURE BUILDUP AT RADIAL DISTANCES
FROM THE POINT OF INJECTION**

CHANGE IN BOTTOM HOLE PRESSURE (lb/in²/100 gal/min)

Figure 19. (After U.S. Bureau of Reclamation, 1974)

**MESA 5-1
IMPERIAL VALLEY CALIFORNIA
THEORETICAL LIQUID LEVEL DURING INJECTION**

Figure 20. (After U.S. Bureau of Reclamation, 1974)

permeable thickness of 1,000 ft. (300 meters) and impermeable layers of 3,000 ft. (900 meters) (difference between gross and net thickness) total thickness. If the entire net thickness exists as one layer, the fluid temperature at the producing wells will decline more rapidly than if the net thickness consisted of many thin permeable layers.

The injected water advances faster through more permeable layers. Hence, the colder, injected water may break through the higher permeability layers and prematurely cool the produced fluid. The more the heterogeneity in a vertical distribution of permeability, the faster will be the temperature decline of the produced fluid.

The time required for the injected water to break through at the producers is shown in Figure 21 for various producer spacings and numbers of injectors, total injection rate being 36,000 gpm (196,000 m³/day). The calculation method is explained in Appendix B. This figure shows that the breakthrough time becomes independent of the number of wells for a large number of injectors. For a case of 18 injection wells and 200 ft. (60 meters) producing spacing, the break through time is 11.5 years.

The decline in the bottomhole temperature of the produced fluid with time is shown in Figure 22. The calculation procedure for this figure is explained in Appendix B. It was assumed that the net thickness of 1,000 ft. (300 meters) was distributed as 10 layers, each 100 ft. (30 meters) thick. In order to introduce vertical permeability variations, nine of the layers were assumed to have permeabilities of 55.56 millidarcies, while one layer was assigned a permeability of 500 millidarcies. This gives an average permeability of 100 millidarcies for the hypothetical reservoir. The lower curve in Figure 22 should be considered conservative. This curve indicates that over a period of 30 years, the temperature of the produced fluid declines from 325°F (163°C) to 272°F (133°C), an average of about 295°F (146°C). But the upper curve (with no permeability variation) is too optimistic. Hence, an average wellhead temperature of 300°F (150°C) was assumed to be more realistic.

Figure 23 is a schematic diagram showing the basic features of the hypothetical reservoir and the associated demonstration binary power plant of 50 megawatt net electrical capacity. The hypothetical reservoir has potential for 50 MWe net electricity generation for over 30 years. The average wellhead temperature of the brine from this reservoir is lower than what is normally economi-

cally attractive. However, our definition of this reservoir is conservative. The average U.S. hydrothermal reservoir will be economically more attractive if after power conversion the brine is used for direct heating needs; e.g., space heating.

Total Injection Rate = 36,000 gpm (8,200 m³/hr)

36 Producers on a circular array

Production rate per well = 1000 gpm / well (230 m³/hr per well)

Injection wells on a circular array - 9,420' radius (2,870 meters)

Figure 21. Breakthrough times of injected water for various number of injection wells and producer spacings.

Figure 22. Reduction of temperature of produced brine with time.

Figure 23. Schematic diagram of a hypothetical reservoir with a 50 MWe binary power plant.

RANKING OF RESERVOIRS

It is difficult to rank the reservoirs which were selected for this study in a meaningful way, because considerable information which is not available to the public would alter the impression gained about them from publicly available documents. Hence, we chose to rank only the three reservoirs which were selected for detailed study.

Sufficient information was not available to rank the three reservoirs using the criteria developed in the Quantification of Reservoir Characteristics section of this report. Therefore, the reservoirs were ranked according to their reported temperatures. The resultant ranking is:

1. Valles Caldera
2. Heber
3. Hypothetical reservoir

The hypothetical reservoir was selected to represent the most representative set of temperature conditions prevailing in reservoirs in the U.S., based upon analysis of published data.

The rather low temperature range (150-180°C) which is assigned to the hypothetical reservoir is near the lower economic limit of present technology. It is based upon the data gathered by the U.S.G.S. (Circular 726). It should be emphasized, however, that the present assessment may be too conservative for a number of reasons: firstly, because the assumed base-temperatures are calculated from the geochemical thermometry, which often yields a conservative value. Secondly, chemical thermometry provides an insight into the temperature of the uppermost aquifer, but is not normally useful in predicting the possibility of the existence of a deeper, hotter reservoir, which might underlie the reservoir which leaks warm water to the surface. Thirdly, some of the most promising geothermal provinces in the U.S. fall in national forests and national parks. Exclusion of those from potential development causes a reduction in overall resource quality.

ESTABLISHING MINIMUM RESERVOIR CRITERIA

The objective of this section is to establish a set of minimum conditions that must be met in order for a reservoir to qualify as a demonstration site for a low salinity hydrothermal power plant. Based on our assessment of the reservoir engineering, power plant requirements, economic and environmental aspects of hydrothermal power development, we propose tentatively (subject to EPRI approval) the following minimum reservoir characteristics:

1. Depth of the reservoir should be less than 10,000 ft. (3,000 meters).
2. Temperature of the brine should be greater than 300°F (150°C) at the wellhead.
3. Salinity of the water should preferably be less than 15,000 ppm.
4. A minimum flow rate of 500 gpm (2,725 m³/day) per standard diameter (7-5/8 inch casing) well should be achieved and maintained without frequent need for stimulation.
5. The reservoir should be able to deliver to the power plant sufficient water at a temperature higher than 300°F (150°C) to produce 50 MWe for at least 30 years.
6. Reinjection of waste power plant water should be possible without undue formation plugging.
7. There should be no adverse overriding environmental impact.
8. Demand for power should exist in the region.
9. Assuming demonstration is successful, cost of power should be projected to be competitive.

The rationale for selecting these criteria follows. The depth limit of 10,000 ft. (3,000 meters) was chosen by considering the data in Figure 3, which indicate a very sharp rise in well drilling cost at depths greater than 10,000 ft. (3,000 meters). A minimum wellhead brine temperature of 300°F (150°C) was chosen because the current state of technology does not allow economic power production with brines cooler than 300°F (150°C). A brine salinity less than 15,000 parts per million

was considered reasonably safe from corrosion and scaling problems. Figure 24 shows the rationale behind our choice of the minimum flow rate. In this figure, the number of wells was derived from Figure 5 by considering the flow requirement for a binary power plant with 25 megawatt net electrical capacity. Assuming a 6,000 ft. (1,800 meters) well and using data from Figure 3, the drilling cost per megawatt net electrical capacity by binary conversion process is also shown in this figure. It can be seen from this figure that for a 300°F (150°C) reservoir, the drilling cost rises very sharply as flow rate falls below 500 gpm (2,725 m³/day). A minimum reservoir life of 30 years is required for capital amortization purposes. The rest of the requirements are obvious. Some economic parameters and environmental and institutional parameters were not included because we are considering only the reservoir related criteria.

Figure 24. Effect of flow rate per well on economics of power plant construction.

CONCLUSIONS

The conclusions from the first phase of the reservoir engineering study can be summarized as follows:

1. Hydrothermal reservoirs in the United States occur in four geological provinces: the Imperial Rift Valley of California, the Basin and Range province, the Northwest volcanic province and the Rio Grande Rift and Colorado Plateau borderland.
2. There are six reservoir and fluid criteria that primarily determine the development potential of a hydrothermal reservoir: depth and lithology, reservoir temperature, tested flow rate per well, fluid chemistry, magnitude of the reserve and reinjection potential. Those economic, environmental and institutional factors that are not directly related to reservoir or fluid characteristics have not been included in this report.
3. Data available on most of the hydrothermal reservoirs in the United States are insufficient for a detailed study. Tables 2 through 6 list important reservoir and fluid criteria for sixteen well known U.S. hydrothermal reservoirs.
4. Geothermal reservoirs can be classified into three types based on origin and occurrence: those related to some special artesian or thermoartesian conditions, the volcano-tectonic type and the volcanic type.
5. Two conceptual models, a sedimentary type and a volcanic type, represent a majority of the U.S. hydrothermal reservoir as regards exploration and exploitation.
6. A hypothetical reservoir has been defined to represent a majority of the U.S. hydrothermal reservoirs. Tables 8 and 9, Figures 15 through 17 and Figures 21 through 23 present the reservoir and fluid properties and exploitation characteristics of this reservoir.
7. The hypothetical reservoir can support a 50 MWe net electricity power plant for 30 years at the current state of technology and economy.

8. Because of the incomplete nature of the publicly available data, it is not possible to rank the selected reservoirs in a meaningful way. From the estimate of temperature alone, the three reservoirs most relevant to this study can be ranked as:

1. Valles Caldera
2. Heber
3. Hypothetical Reservoir

9. We have established a set of nine minimum criteria that determine the development potential of a hydrothermal reservoir.

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APPENDIX A

GENERAL DESCRIPTION OF SELECTED RESERVOIRS

The Imperial Valley, California

The Imperial Valley is a large desert valley in Imperial County, California's southernmost county. From the Salton Sea in the northern part of the valley to the Mexican border a number of KGRA's have been designated (Figure A-1). The valley is the landward extension of the Gulf of California rift and is aligned with the East Pacific Rise and the San Andreas fault system. To the north, it is terminated by the San Jacinto and Transverse Ranges. To the southeast, it becomes the Gulf of California. It is bounded by faults and diagonally cut by normal and strike-slip faults that are seismically active, which make this one of the earthquake-prone areas of the United States. The valley contains up to 7,000 m of Tertiary and Quaternary continental sediments. Paleontological evidence indicates that the Gulf of California has existed as a morphotectonic depression for at least 15 million years. It is an area of rapid tectonic deformation where patterns of high heat flow, seismicity, sedimentation and volcanicity reflect a transition from the divergent plate boundary of the East Pacific Rise to the transform boundary of the San Andreas fault system.

Figure A-1 shows the location of various KGRA's in the Imperial Valley with temperature gradient contours.

Figure A-1

Heber, California

The Heber geothermal anomaly is located in Imperial County in Southern California between the town of El Centro and the Mexican border.

The anomaly was discovered by a wildcat well drilled by Amerada Hess Corporation in 1945. The Chevron Oil Company confirmed this with a shallow test hole in 1963. Since then, various companies have drilled wells. The Chevron Oil Company and Magma Power Company wells have both produced thermal waters (Palmer et al, 1975). Heber is one of several water-dominated geothermal fields in the Salton Basin physiographic province. The Salton Basin forms the northern part of the Colorado River delta and is the surface expression of the Salton Trough, a deep sediment-filled, structural trough or rift valley (Palmer et al, 1975). This complex rift valley is bordered by mountains of Mesozoic and older granite and metamorphic rocks. Along its sides are steeply dipping faults. The Heber geothermal anomaly is in the moderate temperature range. Salinity is much lower in Heber than in the Salton Sea (Palmer et al, 1975). The lithology of the geothermal reservoir includes sands, silts and shales. A 18 m thick layer of gabbro at 1,340 m depth has been reported from one well in the area (Butler 1976, personal communication). The Salton Trough has been an area of crustal thinning (Biehler et al, 1964) and geothermal activity appears to be related to heat from the mantle moving through the thinner crust (Nichols and Hollenbaugh 1975).

East Mesa, California

The East Mesa KGRA is one of several geothermal fields in the Imperial Valley in Southern California. It is located east of the town of Holtville in Imperial County.

The East Mesa KGRA is on the east flank of the Salton structural trough. Wildcat wells in the area indicate deltaic sediments reach a depth greater than 6,000 m. Bedrock is probably as deep as 3,700 m (Bureau of Reclamation, 1974). Up to six km of water-saturated, poorly consolidated sand and silt of the Colorado River Delta and coarse detritus of local marginal origin have been collecting on the granitic basement since the earliest Pliocene time (Nichols and Hollenbaugh, 1975). These Colorado River Delta sediments are predominantly quartz and calcite, with some dolomite, plagioclase, potassium feldspars, mica and clay; gypsum occurs sporadically throughout the sediments (Muffler and Doe, 1968).

The Bureau of Reclamation in cooperation with the U.S. Geological Survey, National Science Foundation and others are evaluating the East Mesa KGRA to determine the full extent of the field and its capability for production of desalted water from geothermal fluids. The Bureau of Reclamation has drilled five deep wells. All five wells were located on the basis of geophysical surveys. They are being tested for productivity and reservoir conditions. Temperature, pressure and chemical tests have been performed. Geothermal production well Mesa 6-1 was drilled to a total depth of 2,450 m. The well has been used to supply geothermal liquid for desalting equipment shake-down operations and tests, and for other purposes. Mesa 6-1 has produced primarily from the upper zone, to a lesser extent from the next two lower zones and probably not at all from the bottom zones. Test well Mesa 6-2 was drilled to a total depth of 1,830 m. Temperature at the bottom of the hole was measured at 187°C and maximum flow was 890 kg/min. A series of flow tests have been done since then. Test well Mesa 5-1 was drilled to a total depth of 1,834 m. Bottom hole temperature was 150°C and the final flow pressure was 8,584 kPa (1,245 lb/in²). Mesa 8-1 is an injection well. Mesa 31-1 was drilled to a total depth of 1,899 m. Bottom hole temperature was 157°C and final flow pressure was 16,380 kPa (2,376 lb/in²). Two desalting test units have been installed at the East Mesa test site. Operations have produced high quality water (U.S. Department of the Interior, Bureau of Reclamation, 1974).

North Brawley, California

The North Brawley geothermal anomaly is located southeast of the Salton sea near the town of Brawley in Imperial County in southern California.

North Brawley is one of several geothermal fields in the Salton Basin. The Brawley fault first appeared in the literature on maps by Rex (1970) based on unpublished work by E.A. Babcock. Later, gravity surveys confirmed the presence of large vertical displacements beneath the valley alluvium. However, they were inconclusive in demonstrating the continuity of major fault zones within the trough (Dutcher et al, 1972). Meidav (1972) has been able to clearly identify the North Brawley thermal anomaly by the very low resistivity of 0.35-0.76 ohm-m at depths greater than 180 m. This is a four-fold decrease in resistivity compared to surrounding rocks. It would require an eight-fold increase in temperature gradient were salinity and stratigraphic factors to be ignored. There is evidence of at least one and perhaps two hydrologic discontinuities from the Sand Hills to a few miles northwest of the town of Brawley which would signify faults and would account for salinity and/or stratigraphic changes along the line. These discontinuities are the North Brawley and the San Andreas faults.

The sedimentary section from 0-300 m in the North Brawley area contains a lower percent volume of sand bodies than some other fields in the Imperial Valley. In North Brawley, the Amerada Veysey 1 has 61% sand. In the Heber field, the Amerada Tompkin 1 has 76% . West of El Centro, the Texas Company Browne 1 has 83%. Northwest of Yuma, the LCRP 12 has 84% (Rex et al, 1971). The deposits of usable and recoverable water in storage have been estimated to be about 4,000 m thick in North Brawley (Dutcher et al, 1972). A study by the University of California at Riverside has estimated the depth to basement in this area to be about 6,000 m.

Additional Reference

Dutcher, L.C., Hardt, W.F., and Moyle, W.R., Jr., 1972.
Preliminary Appraisal of Ground Water in Storage with
Reference to Geothermal Resources in the Imperial Valley
Area, California, U.S. Geol. Survey Circ. 649, 57 p.

The Dunes, California

The Dunes Geothermal Anomaly is located in southeastern Imperial Valley, east of Holtville and adjacent to the Algodones sand dunes.

The Dunes Anomaly was initially defined by shallow thermal gradient wells (Combs, 1971). Biehler (1972) inferred that the anomaly is an oval-shaped feature, one square mile in area, with the hottest regions near the center. There is a two mgal positive closure shaped like the thermal anomaly, but centered almost 2 km to the northeast of the thermal anomaly (Biehler, 1971). This has been explained by the higher density silicified sand body found in wells in the area. Over the anomaly, resistivity drops by 50% to a depth of 180 m (Black et al, 1973). According to seismic refraction profiles, basement depths do not change greatly near the anomaly (Wilt, 1975). Telluric studies carried out by Wilt (1975) support the anomaly outlined by previous geophysical methods. He also found evidence of a strike-slip fault under the sand hills immediately to the east of the anomaly.

Major parts of the section are composed of up to 90% unconsolidated, highly porous sands with minor amounts of shale. These shales are very important in explaining why there is no surface expression of the hydrothermal system here. These impermeable shale layers have served as sites for silica deposition by the upward circulating hot waters. A mushroom shaped cap rock was formed which effectively seals off the hydrothermal system from the surface (Elders and Bird, 1974).

From east to west, depth to basement increases from 600 m to 3,400 m (Kovach et al, 1962; Biehler et al, 1964). The San Andreas fault system is believed to extend southeast and through the axis of the sand hills (Biehler et al, 1964, and Garfunkel, 1972). This and other faults may be partially responsible for the formation of the Dunes hydrothermal system (Biehler, 1972; Elders et al, 1974).

Local ground water has its origin in the Colorado River (Coplen, 1973). Being low in salts, it is very different from the ground water in northern Imperial Valley (Rex, 1972).

The Colorado River dominates the chemistry of ground water in the Imperial Valley. Water from three of the Bureau of Reclamation's East Mesa wells is of the sodium chloride type. There is less frequent occurrence of the sodium bicarbonate type, mostly at depths of 140 to 270 m. The presence of sulfate as a significant anion in some samples may indicate gypsum and anhydrite in the sediments. There is a general increase in concentration of major constituents with increase in temperature and increase in depth. However, the chemistry of the subsurface water is due to the solution of minerals in the upper part of the sedimentary section. Chemical temperature indicators suggest that the water had never been in equilibrium with the rock of a high temperature system (Nichols and Hollenbaugh, 1975).

Additional References

- Biehler, S., Combs, J., 1972. Abstract and Programs, Geological Society of America, 4, no.3, p.128.
- Combs, J., Rex, R.W., 1971. Geothermal Investigations in the Imperial Valley of California, Geological Society of America, Bulletin 3, no.2, p. 101-102.
- Garfunkel, Z., 1972. The Tectonics of the Salton Trough of California, Cooperative Investigations of Geothermal Resources in the Imperial Valley Area and their Potential Value for Desalting of Water and Other Purposes, R.W. Rex, ed., University of California, Riverside, p. H1-H3.

Raft River, Idaho

The Raft River or Frazier KGRA consists of 31 km² in Cassia County of south-central Idaho. The prospect lies about 64 km southeast of Burley, in the southern Raft River Valley, near the Utah border.

The Raft River Valley is similar to the Basin and Range province which lies to the south. The Snake River volcanic province lies to the northwest, and Tertiary silicic volcanics form the valley's western boundary. North-trending major faults probably control the locations of hot springs.

The Raft River constitutes the major drainage system for the area. There are many intermittent and permanent streams in the valley. Ground water is shallow and additional shallow drilling has been disallowed because of declining pressure.

Two shallow wells produce boiling water at 120 m in the valley's alluvium. One flowed at 27 m³/hr in the 1930's, which declined to 14 m³/hr by 1969, and the other flowed at 6 m³/hr in 1961. Dissolved solids concentrations from the two wells were 1,720 and 3,360 ppm, and halite (NaCl) and calcite (CaCO₂) are being deposited at the wellsites (Nichols and Hollenbaugh, 1975).

Two deep geothermal test wells were drilled recently in Sec. 23 in the valley by a coalition of ERDA, USGS, the State of Idaho and the Raft River Electrical Cooperative. These wells and their relations to faults in the area are shown in Figure A-2. The first well went through about 1,160 m of Tertiary sediments and tuffs, intercepted a fault zone, then passed through Pre-Cambrian shists (?) and quartzites before entering a quartz monzonite basement at 1,500 m. The hole bottomed at 1,526 m. Before casing was laid, the well flowed at 140-160 m³/hr and after casing to 1,100 m, it flowed 100-115 m³/hr at 150°C (TRW, 1975). The second well, located near the first, also passed through the Tertiary section and the fault before entering the Pre-Cambrian Elfa Quartzite at about 1,460 m. Basement was penetrated at about 1,490 m and the hole bottomed at 1,831 m. The 1,280-1,585 m zone produced 170-180 m³/hr of good quality water (TDS of less than 2,000 ppm) at 147°C. A chemical temperature of 181°C was obtained from well samples (TRW, 1975).

Figure A-2. Geologic structure and location of wells RRGE-1 and RRGE-2, Raft River Valley, Idaho (after Narasimhan and Witherspoon, 1975).

The Raft River Project is important because it is one of the first medium to low temperature geothermal reservoirs to be developed. Since these are the most abundant of our geothermal resources, its success would be highly significant.

An environmental analysis record with respect to geothermal leasing was prepared by the Bureau of Land Management in 1974. An environmental report concerning the geothermal test wells has also been made (Specer, 1975).

Additional Reference

Specer, S.G., 1975. Environmental Report--Deep Geothermal Test Wells in the Raft River Valley, Aerojet Nuclear Company.

Long Valley, California

Long Valley is located in Mono County in east-central California at the foot of the Sierra Nevada Mountains. It is 50 km northwest of the town of Bishop and 31 km south of Mono Lake. A KGRA has been established which includes Long Valley and a large area to the north of it.

Long Valley is a caldera in the early stages of collapse. It is an elliptical depression 19 by 29 kilometers formed by crustal collapse 680 thousand years ago following the explosive eruption of the Bishop Tuff. The tuff is a coarsely porphyritic biotite rhyolite whose eruption partially emptied the shallow magma chamber (see Figure A-3). This was followed by an accumulation of about 300 meters of aphanitic to sparsely porphyritic rhyolite on the floor of the caldera. At that time, the floor was arched into a structural dome about 15 kilometers in diameter and about 610 m high which includes a 5 kilometer wide northwest-trending keystone graben. Subsequently, coarsely porphyritic hornblende-biotite rhyolite erupted from three groups of vents peripheral to the resurgent dome and during this time, ring fracturing occurred. The fracturing was accompanied by extrusion of trachybasalt, trachyandesite and rhyodacite from north-south fissures in the western caldera moat and rim (Lachenbruch et al, 1973). Geophysical evidence indicates that 2,700-4,000 meters of lake, marsh and periglacial sediments and volcanics overlie granitic basement in the eastern half of the caldera (Nichols and Hollenbaugh, 1975). In the western portion, maximum depth to basement is probably 1,800-2,100 meters (Geothermal Overview of the Western United States, 1972).

There are several surficial indications of a geothermal reservoir. Hot springs occur along recently reactivated Sierra faults that transect the caldera. Springs exhibit about the same geochemical temperature and identical chloride-boron ratios, which indicate a single reservoir. The Bishop Tuff extends throughout the lower part of the caldera fill and gravity data indicate that it has a significant porosity. Although previous intense and widespread geothermal activity caused some of the near-surface rock to be hydrothermally altered, the rocks above the Bishop Tuff are relatively impermeable except along faults. Any significant reservoir in the Long Valley caldera is likely to be in the Bishop Tuff and the Glass Mountain rhyolites. The heat source may be a cooling magma chamber beneath the caldera (Muffler et al, 1976). Heat flow measurements show that the area of excess heat extends almost three kilometers west of the caldera (Lachenbruch et al, 1973).

Additional Reference

Bailey, R.A., Dalrymple, B.G., Lanphere, M.A., 1976. Volcanism, Structure, and Geochronology of Long Valley Caldera, Mono County, California, Journ. of Geophys. Research, v. 81, No. 5, p. 725-742, copyrighted by American Geophysical Union.

Figure A-3. Generalized geologic map of the Long Valley-Mono Basin area (after Bailey et al, 1976).

Bruneau-Grand View, Idaho

The Bruneau-Grand View geothermal anomaly is an area of about 2,800 square kms that is a part of a large artesian basin in northern Owyhee County in southwestern Idaho. Owyhee County may be divided into two physiographic provinces, the Owyhee uplift and the Snake River Valley. Bruneau-Grand View is mostly within the Snake River Valley, on the southern flank of a large depression containing the western Snake River Plain (Young and Whitehead, 1974).

The rocks of the Bruneau-Grand View area range in age from Late Cretaceous to Holocene. Igneous rocks include siliceous and basic intrusive and extrusive bodies and sedimentary rocks are compacted stream and lake sediments. The Cenozoic rocks have been subdivided into (1) unnamed rhyolitic and related rocks, (2) the Idavada Volcanics, (3) the Idaho Group and (4) the Snake River Group. These can be grouped again by their hydrologic properties into (1) the volcanic rock aquifers including the Idavada Volcanics, the Bandbury Basalt of the Idaho Group and undifferentiated silicic volcanics and (2) the sedimentary rock aquifers including sedimentary units of the Idaho and Snake River Groups (Young and Whitehead, 1974).

Precipitation in the higher altitudes to the south and southwest, where the aquifers crop out, is thought to provide recharge for the volcanic aquifers, except the Bandbury Basalt. In the igneous aquifers the groundwater is imperfectly confined beneath sediments of the Idaho formation and the Bandbury Basalt, forming a leaky artesian system. The Idavada Volcanics or underlying rock units probably constitute the thermal reservoir (Young and Whitehead, 1974). Figure A-4 shows the flow paths of recharge and ground waters.

Although the ground water contains a relatively moderate amount of dissolved solids, much of it is unsuitable for irrigation and domestic use because of high sodium and fluoride concentrations. The quality of water for irrigation ranges from excellent in the south to unsuitable in the north (Littleton and Crosthwaite, 1957). Thermal waters are the sodium bicarbonate type. TDS are usually less than 500 mg/l, but ranged from 181-1,100 mg/l in the volcanic aquifers (Young and Whitehead, 1974).

Figure A-4. Geological section of the Bruneau-Grand View area, Owyhee County, Idaho (after Young and Whitehead, 1975).

Well and spring temperature ranged from 9°-83°C. Water temperatures from volcanic rock aquifers ranged from 40°-83°C, while temperatures from the sedimentary rock aquifers were usually below 35°C. SiO₂ and Na-K-Ca geochemical thermometers show that reservoir temperatures probably do not exceed 150°C; however, a mixed-water method indicates that temperatures at depth may exceed 180°F. Thermal waters are thought to be heated by deep circulation in a zone of high geothermal gradient resulting from thinning of the earth's crust. An audio-magneto-telluric survey indicates that part of the area is underlain by a large conductive zone with resistivities approaching 2 ohm-meters at a shallow depth (Young and Whitehead, 1975).

Brady's Hot Springs, Nevada

Brady's Hot Springs KGRA consists of 398 km² in Churchill County in west-central Nevada. It is about 80 km east of Reno and 2 km from Interstate Highway 80. The KGRA is in the Basin and Range province at about 1,200 m elevation on a plain with alkali flats, dry washes and buttes. There are no permanent streams near the thermal area, but shallow groundwater is available.

Sedimentary rocks near the thermal area are mostly Tertiary age consisting of sandstone, shale, tuff, diatomite, limestone and Pleistocene Lake Lahontan lacustrine deposits of clay, silt and sand with tufa coatings (Figure A-5). Recent sediments are coarse alluvial-fan and pediment deposits. In the mountains east of the springs are volcanic rocks, chiefly basalt of Tertiary and possibly early Quaternary age. To the north are Jurassic basement rocks and younger sediments.

The Brady Thermal Fault controls the locations of the former hot springs, warm ground, hydrothermally altered deposits, steam vents, snow melt and hydrothermal alteration. The alteration includes deposition of tufa and sinter, silicification of rocks, oxidation of metallic elements and formation of kaolinite (Olmstead et al, 1975). The fault is a normal fault of unknown displacement, steeply dipping westward, and trending northward for about ten kilometers. Because the fault scarp is covered by alluvium, the type of movement cannot be determined; some evidence for recent activity exists. Hydrothermal deposits mark the fault trace for about 4 kms and are the major evidence for the fault; geothermal activity has been continuous for 10,000-11,000 years (Hose and Taylor, 1974; Garside, 1974).

Magma Power Company drilled several shallow wells from 1959-1961 which encountered hot water and steam from the fault zone at depths of about a hundred meters. A five km line of new steam vents opened along the fault trace, and mud pots were born with explosive force, while most of the original springs went dry. Numerous areas of hot moist ground developed, most with some steam escaping from cracks. Most of these phenomena, however, were dormant by mid-1961. The increased activity may have been caused by the progressive lowering of the water table by the blowing wells or simply by steam escaping through the uncased portions of the well bores into the adjacent fault zone (Osterling and Anctil, 1960). In 1964 Earth Energy, Inc. drilled a well in the

Figure A-5. Geological map showing test holes, Brady's Hot Springs, Lyon/Churchill Counties, Nevada (from United States Geological Survey).

Legend to Figure A-5

same area as Magma. It showed an approximately linear static temperature gradient from 134°C at 240 m to a bottom hole temperature of 212°C at 1,543 m. When tested, it produced 27 m³/hr of water and steam from a 70 m zone through 11.4 cm slotted liner set at 1,500 m. Other wells from 1,100-2,100 m deep have been drilled since then. Maximum well temperature was 214°C from a well producing hot water with 5% steam flash-over. A scaling problem has been reported from this well (Nichols and Hollenbaugh, 1975).

A steam well near the center of the thermal area produced thermal water having a dissolved-solids concentration of 2,600 mg/l, chiefly sodium chloride. Wells and ground water have high concentrations of dissolved solids about 2,600 mg/l, chiefly sodium chloride, which probably results from high rates of evaporation from a shallow water table (Olmstead et al, 1975).

There is good agreement between chemical estimates of maximum reservoir temperature from analysis of hot spring water and shallow ground water and geothermal well water. Temperatures are estimated to be 190°-200°C. That ground water, in communication with the local water table, affects the flow in the near-surface levels of the fault zone is suggested by the higher temperatures observed at 1,500 meters and the interactions between the shallow wells and springs (TRW Systems Group, 1975).

Using test well data from the early 1960's, estimates of 200°C have been made for the rising thermal water. Thermal gradients outside the thermal area are normal, so unless a local crustal heat source is present, the thermal water must circulate to depths of several km in order to reach the observed temperatures. Temperature profiles indicate that the hot water moves westward from the Hot Springs fault through shallow aquifers. This movement is more pronounced in the northern part of the area. Discharge of thermal water is small enough to be derived from local ground water recharge, but the high water temperatures suggest deep circulation. The fault seems to function as a long, narrow steeply-inclined aquifer, nearly perpendicular to the gently dipping aquifers in the alluvial and lacustrine deposits. Thermal water moves upward along the Hot Springs fault. Vertical potential gradients are believed to be small except near the Hot Springs fault and in the gap south of Hot Springs Flat, where sizable upward gradients are indicated (Olmstead et al, 1975).

The Bureau of Land Management in 1974 prepared an environmental analysis of the thermal area. There is a county

general plan which includes a partial environmental impact statement.

Roosevelt Hot Springs, Utah

The Roosevelt Hot Springs KGRA consists of 121 km². It is located in southwestern Utah in Beaver County, 19 km north-east of Milford and 32 km northwest of Beaver.

The KGRA is in the basin and range province on the western flank of the Mineral Mountains (Figure A-6). Tertiary and Quaternary alluvium covers most of the area, with Pre-Cambrian (?) metamorphics, Tertiary volcanics and other rocks cropping out to the east. The Dome fault, one of a set of north-south trending faults, is the most important structural feature and may be traced for 5.6 km (Ward, 1975). The fault probably controls the location of the hot springs.

There is one permanent stream in the southeastern part of the area but the rest are intermittent. Cooling water (for geothermal purposes) will probably not be available because the only potential source is shallow ground water and use of ground water for irrigation in the Milford area has already resulted in up to 2 meters of subsidence. (Mower and Cordova, 1973).

In 1908 the main spring flowed at about 2 m³/hr at 88°C but discharge decreased until it dried up in 1966. A 1957 analysis of the spring water gave a TDS of 7,800 ppm and a silica content of 313 ppm (Nichols and Hollenbaugh, 1975). Currently there is only a small seep with a temperature of 38°C (Ward, 1975).

A shallow well drilled in 1968 encountered steam at 18 m, blew out at 84 m and was controlled with difficulty. Water temperatures of 130°C were measured in the hole (Petersen, 1973). Phillips Petroleum Company has a deep geothermal test well nearby. They report substantial flows from the 820-850 meter zone in altered volcanics. Initially, 90,000 kg/hr of steam at 204°C was recovered. This is equivalent to a water flow of 90 m³/hr. After installation of a control valve, a sustained hot water flow was obtained, indicating that the reservoir is probably water dominated (TRW Systems Group, 1975). Two other wells have commercial potential. The first well is 831 m deep with a flow rate in excess of 90,000 kg/hr at a temperature above 204°C. The second well is 696 m deep, and during a 24-hour flow test registered 110,000 kg/hr of saturated steam. The reservoir is a liquid-dominated system containing hot water at higher than hydrostatic pressure and salinity less than sea water (Geothermal Resources Council, 1975).

Figure A-6. Geologic map showing earthquake epicenters, Roosevelt Hot Springs, Utah (after Ward, 1975).

Some geophysical work has been done in the Roosevelt area by the University of Utah and others. Simple Bouguer gravity positives occur along the Dome Fault and coincide with hot springs activity. This is also the area of highest thermal gradients, 40°C/100 m. The anomalous region appears to be a long, narrow, north-south trending feature. Two sources have been postulated for the hot water: 1) the deep meteoric ground water is heated at shallow depths by high geothermal gradients; 2) the water is heated by a hot mass such as a cooling still or magma complex occurring at shallow depths, and fractured by the faulting that extends to the surface (Ward, 1975).

There is a general plan for land use for Beaver County (Mountain Area Planners, 1972), and an Environmental Analysis Report has been prepared for the Roosevelt Area (United States Department of the Interior, 1975).

Additional Reference

Mower, R.W., and Cordova, R.M., 1973. Groundwater in the Millard Area, Utah, Utah Geological Association Publication 3.

Valles Caldera, New Mexico

The Valles Caldera KGRA comprises about 400 km² of the Jemez Mountains, north of Albuquerque (and west of Los Alamos) in north-central New Mexico.

The Caldera is one of the largest volcanic "craters" in the world. It is a subcircular volcanic depression 19-24 km in diameter, 150-600 m deep and surrounded by 3,000 m peaks. The Jemez Mountains volcanism probably began in early to middle Pliocene with basalt eruptions, and continued with successive eruption of andesite, dacite, quartz latite and associated rhyolite. It culminated in the Pleistocene with eruption of voluminous rhyolite ash flows and the formation of two collapse calderas. The older, unnamed caldera is truncated by the younger and larger Valles Caldera. Later activity was confined within the Valles Caldera and included structural adjustments of the caldera floor and the eruption of rhyolite domes and flows (Figure A-7, Ross et al, 1961). The Valles Caldera was formed by the collapse of the magma chamber roof following eruption of the Bandelier rhyolite tuff. The ring faulting around the subsided caldera block is a complex fracture zone three or four kilometers wide. Within this zone is a central block that is arched into a steep-sided, slightly elongated structural dome which is the result of post-collapse uplift of the caldera floor. At about the same time large quantities of viscous rhyolite were extruded from the peripheral ring-fracture zone forming the ring of volcanic domes surrounding Redondo (Ross, Smith and Bailey, 1961).

Geophysical studies indicate that the region is one of relatively high terrestrial heat flow, low crustal density, low crustal seismic velocities, low crustal resistivity and thin crust (West, 1973). A solid or semimolten intrusive at depth under the Valles Caldera has been postulated on the basis of a pronounced gravity low (Jiracek, 1974).

Figure A-7. Generalized geologic map of the Valles Caldera--Los Alamos areas, New Mexico (after Ross et al, 1961).

Surprise Valley, California

The Lake City-Surprise Valley KGRA comprises 292 km² in Modoc County of northeast California. The valley's major town is Cedarville with Alturas 40 km to the west.

The valley is a north-south trending graben about 89 km long and 13 km wide. It is flanked by the Warner Mountains on the west and the Hays Canyon Range on the east. Surprise Valley is part of a transition zone between the horst and graben structures typical of the Basin and Range province to the east and the Modoc Plateau sediments and volcanics to the west. At least 2,100 meters of sediments and volcanics have accumulated in the valley. These are separated from the Warner Mountains by the Surprise Valley fault. This fault lies on the western side of the valley and forms a major structural feature with a vertical displacement of about 3,700 m (Slosson, 1974). Recent major movement is suggested by the lack of erosion on the fault scarp and the presence of landslide scars; dams formed by landslides created some of the more prominent lakes. Radiometric ages suggest faulting began less than 15 million years ago. Quaternary rhyolite flows and obsidian bodies crop out in the Fandango Valley of the northern Warner Mountains and also near the south end of the range (Duffield and Fournier, 1974). These volcanics may indicate the presence of a shallow crustal magmatic heat source.

The Warner Mountains watershed provides most of the runoff, which is the main local source of both surface and ground waters. Streams, springs and artesian wells are numerous on the western side of the valley, but an alkali desert occupies most of the eastern side of the valley. Surprise Valley forms a closed basin which has been occupied by lakes since the late Tertiary (Nichols and Hollenbaugh, 1975). Three shallow, alkali lakes of poor water quality currently exist on the valley floor during most of the year.

The Surprise Valley fault zone provides structural control for many of the hot springs. Hot springs are also associated with the young rhyolite flows and plugs found in the northern half of the valley (Duffield and Fournier, 1974). The thermal water appears to rise along several faults which are subparallel to the sides of the valley (Nichols and Hollenbaugh, 1975). Flow rates vary but do not exceed 500 l/min (Nichols and Hollenbaugh, 1975). Springs waters are rich in sulfate, boron (0.61-7.6 ppm), fluoride, sodium and, some springs contain

arsenic. (Woods, 1974). All but one of the samples from Surprise Valley are sodium-sulfate type water. The chemical compositions and temperature indicators of the samples reflect that shallow aquifers have water up to 170°C, but deep waters may have temperatures up to 200°C (Duffield and Fournier, 1974).

Three deep test wells were drilled in Surprise Valley through lake sediments to depths of 2,085 m, 1,647 m, and 2,135 m. The bottom hole temperature of the deepest well was 160°C while the others reached only 116°C.

Beowawe, Nevada

The Beowawe KGRA consists of 134 km² in Eureka and Lander Counties in north-central Nevada. The area is about 30 km east of Battle Mountain, south of Interstate Highway 80. The major water sources are the Humboldt River and good quality, shallow ground water.

The Beowawe KGRA is located in the Basin and Range province at the boundary of the plateau of Miocene (?) volcanics to the south and the down faulted Whirlwind Valley to the north. The major surficial geothermal expression is a large sinter terrace deposited by geysers, fumaroles and boiling springs (Hose and Taylor, 1974). Hydrothermal activity occurs along faults at the top and bottom of the terrace and is controlled laterally by recent cross-faulting. Activity is shifting from the top to the bottom. The maximum spring temperature at the Beowawe Geysers is 96°C (Nichols and Hollenbaugh, 1975).

There has been much exploratory drilling in the Beowawe area (Garside, 1974). Magma Power Company drilled two wells in 1959 and encountered temperatures of 158°C at 585 m in one and 212°C at 218 m in the other. They apparently drilled through a fault zone in the second well. Vulcan Thermal Power Company in 1961 drilled four shallow (200-234 m) holes along the top of the terrace. Profiles of bottom hole temperature recorded during drilling were very close to the boiling point versus hydrostatic pressure curve at depth, leveling off at 207°-210°C below 200 m. After completion, shut-in temperatures of 190°-200°C were recorded. Flows of 0.68 million kg/hr (approximately 680 m³/hr) at wellhead temperatures of 165°-170°C and pressures of 620-790 kPa were observed in three of the wells. These wells flash 2-3% steam. Flow rate, temperature and pressure were much lower in the fourth. In 1963-64 Sierra Pacific Power Company drilled four unsuccessful wells in a north-south line crossing the line of Vulcan wells. The best bottom hole temperature was 192°C at 625 m with a very small flow of water and steam. In 1974 Chevron Oil Company and American Thermal Resources, Inc. drilled to 2,915 m about 2.4 km west of the earlier wells and about 1/2 km northwest of a projected normal fault line, on the downthrown side. Nichols and Hollenbaugh (1975) have reported a maximum well temperature of 212°C and hot water with a 5-10% steam flash-over. However, problems of scaling and cold water inflow were encountered.

In general, test history shows temperature and pressure declining as fluid is extracted. Indications are that the

wells along the top of the terrace have interacted with ground water and the water table. However, the consistently high geochemical estimates of maximum reservoir temperature are encouraging. Estimates from geothermometers give temperatures from 200°-250°C. Salinity is about 1,200 ppm total dissolved solids (TRW Systems Group, 1975).

Steamboat Springs, Nevada

Steamboat Springs KGRA consists of about 50 hot springs on 36 km² in Washoe County in west-central Nevada. It is 19 km south of Reno and 11 km northwest of the Virginia City mining area. In general, the area is Basin and Range topography. The thermal portion includes the northeastern part of Steamboat Hills. The permanent streams are the Truckee River and Galena Creek, and Washoe Lake lies to the south.

The hot springs emerge near the northeast end of Steamboat Hills, a northeast-trending basement uplift transverse to the dominante regional trends. The basin floor is composed of alluvium. Throughout the Late Tertiary and Quaternary time, the Steamboat Springs thermal area has been part of a zone of balance between structural uplift and erosion on one hand and inundation by volcanics and alluvium on the other. The thermal area lies approximately on a line connecting three, and possibly five, Pleistocene or Holocene rhyolite domes which may be contemporaneous with Mono Craters in the Long Valley/Mono area to the southeast. This is a part of the Virginia City mining district, an area of extensive hydrothermal ore deposition (White, Thompson and Sandberg, 1964).

The hot springs lie on a terrace consisting of siliceous sinter, very small amounts of calcium carbonate, mercury, antimony and other ore minerals. Most of the sinter deposits trend northward and are broken by long fissures and small crack networks. An underlying fault zone trending to the northeast controls the location of hot springs and sinter deposits. Sinter deposition began in middle or late Pleistocene.

Spring waters range in temperature from 29° to 97°C, with a total dissolved solid content of about 2,500 ppm (Brannock et al, 1948). Discharge is about 250 m³/hr in total and is affected by surface conditions of pressure and water saturation after rainfall. Most of the spring water has a meteoric origin.

Between 1954 and 1961, the Nevada Thermal Power Company drilled six geothermal wells ranging in depth from 160 to 560 meters. The U.S.G.S. has drilled eight diamond-drill holes less than 300 meters deep. Below 150 meters, the temperature profiles are relatively constant at 170°-180°C. The Steamboat Springs #4 well had a maximum temperature of about 185°C

at a total depth of 221 meters. It flowed more than 45 m³/hr for more than two weeks, then declined, probably because of a decline in pressure and deposition of calcite. Geochemical temperature estimates range from 180°-207°C (TRW, 1975). Nichols and Hollenbaugh (1975) report a maximum well temperature of 187°C and hot water with 5-10% steam flashover.

Numerous homes in the Reno area are heated from warm water wells (Nichols and Hollenbaugh, 1975).

An Environmental Analysis Record of the area has been written by the Bureau of Land Management.

Additional References

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Coso Hot Springs, California

The Coso Hot Springs KGRA consists of 209 km² containing hot springs and fumaroles. The area is located in east central California, about 480 km north of Los Angeles and 55 km north of China Lake in Inyo County. It is part of the China Lake Naval Weapons Center.

Coso Hot Springs is in the Mojave Desert east of the Sierra Nevada Range in the southern part of the Coso Range. The region consists of Pleistocene and Holocene volcanics, mainly cinder cones, domes and flows. Volcanism may have occurred as recently as 5,000 years ago. An arcuate fault system encloses most of the Coso Range and forms a rough oval about 40 by 45 km. A set of steeply dipping, northeast and northwest trending faults break this arcuate structure. The ring faulting and associated structural subsidence suggest a caldera in the early stages of collapse (Duffield, 1975).

Hydrothermal alteration is common near the series of fumaroles and hot springs that make up Coso Hot Springs. They occur along one of the northeast trending faults. The spring water is highly acidic and lacking in chloride. Recent analysis gives a TDS content of 1-2,000 ppm and a silica content of 2-300 ppm; the maximum temperature exceeds 90°C (TRW, 1975).

A shallow hole drilled by the Navy in 1967 penetrated hematite stained alluvium to 56 meters below which granitic basement was encountered. A bottom hole temperature of 142°C was recorded. Water from this well is neutral to alkaline and rich in chloride. Production rates up to 9 m³/hr have been observed and downhole pressure is estimated to be in excess of 240 kPa (Austin, 1970). Withdrawal of ground water has not caused subsidence.

The Coso Hot Springs area is characterized by high seismicity. Swarm type microearthquake activity indicates that tectonic forces are currently active in the area. P-wave and S-wave velocities indicate a very low Poisson's ratio in the shallow subsurface, indicating that a vapor-dominated reservoir may exist at depth. Recent geophysical work includes microearthquake monitoring, resistivity surveying and the drilling of deep and shallow test tubes. Photogeology and extensive geochemical evaluation of waters is also being done.

Local waters are either sodium bicarbonate or sodium chloride-bicarbonate type. Relatively high values for chloride indicate that the waters are probably a part of a hot water rather than a vapor-dominated geothermal system. Calculated dissolved solids generally range from 1,200-1,800 ppm and flow rates usually range from 100-400 l/min (Nichols and Hollenbaugh, 1975).

The agreement between several geochemical thermometers implies that the water reached equilibrium at 200°-250°C and moved rapidly to the surface without cooling (Nichols and Hollenbaugh, 1975). Hydrologic and isotopic data indicate that the gross circulation in the hydrothermal system is west to east, suggesting that the hot springs gain their heat in the western caldera. Thermal gradient evidence is consistent with the view that the springs ascend along local fractures fed by aquifers at a depth of 500-1,000 meters (Lachenbruch et al, 1974). This is supported by geophysical data. The faults related to the Sierran front probably have fractured any deep reservoir. Significant commercial production of geothermal energy is most likely to be found near these major fractures (Pakiser, 1961).

Mountain Home, Idaho

The 37 km² Mountain Home KGRA is located in Elmore County in south-central Idaho about 80 km southeast of Boise and about 16 km east of Mountain Home.

The KGRA is located between the central Idaho Tertiary and Cretaceous granitics, and the Tertiary and Quaternary rocks of the Snake River Plain to the west. Mountain Home lies on the northwest-southeast trending fault that marks the relatively abrupt transition zone northwest of the KGRA, near Boise. The major hot springs in the area are controlled by faulting.

Although there are many permanent streams, practically all of them have been diverted for agricultural use. Ground water reserves are unknown but are thought to be small. Geothermal development may have a positive effect because of the suitability of the subsurface water for drinking and wild life support. Thermal water is abundant in the area. Temperatures range from 57°C-68°C in springs and irrigation wells 150-300 m deep. The water is fresh with a TDS content of about 300 ppm.

A deep test well, reported to be in a fault zone, which was discovered by remote sensing techniques and near a shallow intrusive, was recently drilled by the Gulf Energy and Mineral Company. The upper part of the well is in Pleistocene with the first basalt encountered at 360 m. At 660 m a section of clays, shales and detrital volcanic sands were found below which was 180 m of basalt, followed by 722 m of acidic volcanoclastics. At 2,170 m andesite was found and at 2,890 m granite was encountered. The drilling was completed in granite at 2,931 m (TRW, 1975). At 1,980 m temperatures about 150°C were measured. The bottom hole temperature was 176°C but this may be low because it was measured immediately after circulation was stopped (TRW, 1975). Initially, this well flowed at about 230 m³/hr but flow stopped within two weeks. Because the water is drinkable (TDS content of less than 800 ppm), the state has given permission to reinject it into shallow aquifers. The low TDS concentration and high temperatures probably indicate that reservoir recharge is by meteoric water through an extensive circulation system (TRW, 1975).

An Environmental Analysis Report on geothermal leasing and development in the Boise region has been prepared by the Bureau of Land Management. No county use plan had been adopted in 1975.

Yellowstone National Park, Wyoming

Yellowstone National Park in northwestern Wyoming presents one of the most spectacular surficial geothermal displays in the world. The abundance of geysers, hot springs and other thermal manifestations at Yellowstone are products of a history of intense Pleistocene volcanic activity. This occurred in three cycles, each of which was climaxed by a devastating pyroclastic eruption that produced enormous ash flows and caused collapse of the volcanic source area and formation of a large caldera. Basalts and rhyolites were erupted during each cycle with rhyolites overwhelmingly predominating. Later, ring fracturing developed around the caldera as shown in Figure A-8 (Eaton et al, 1975). Mammoth hot springs in the northern part of the park flow from Mesozoic shales and sandstones. Abundant travertine deposits characterize Mammoth. Bicarbonate, sulfate, calcium and magnesium are present. Sodium is present in excess of chloride. Silica content is low and potassium relative to sodium is very high. The composition of the hot-spring water probably reflects reaction with the carbonate sediments at depth (Rowe, Fournier and Morey, 1973).

The springs at Norris Geyser Basin and Lower Geyser Basin, in the west central part of the park, originate in Cenozoic rhyolite ash-flow tuff. Hot spring water can be divided into two end-member types of chloride-rich water by their potassium-lithium and potassium-sodium ratios. This area has the highest silica and chloride contents and the lowest bicarbonate contents of any waters in Yellowstone. The water is essentially unbuffered so that mixing with a very small amount of acid sulfate water may lower the pH to 3 or 4, giving rise to an acid chloride water. Silica deposits readily from the neutral waters, but little deposition occurs from the acid chloride water (Rowe, Fournier and Morey, 1973).

Acid sulfate waters, formed where steam, rich in acid-forming gases, intersects near-surface ground water, occur throughout Yellowstone, particularly at higher elevations and at the Mud Volcano area north of Yellowstone Lake (White, Sandberg and Brannock, 1953). It has very low concentrations of sodium potassium, but the sodium-potassium ratio is very high. It is relatively rich in aluminum and iron and poor in chloride (Rowe, Fournier and Morey, 1973).

Figure A-8. Geologic map of Yellowstone plateau region showing upper Cenozoic structural features. Caldera rim is dashed where buried. Faults are shown by solid lines with bar and ball on down-thrown side (after Eaton et al, 1975).

Springs in the large caldera issue from Pleistocene rhyolite or glacial sediments derived from rhyolite. Water here is neutral to alkaline and contains comparatively low concentrations of chloride, potassium, silica, boron and high concentrations of fluoride, bicarbonate and carbonate compared to the Norris Geyser Basin. There are 0.2-0.3 ppm tungsten. In terms of atomic proportion, dissolved lithium commonly exceeds potassium (Rowe et al, 1973).

The two end member types of neutral to alkaline waters in Upper Geyser Basin, to the south of Lower Geyser Basin, may be distinguished by their Cl: ($\text{HCO}_3 + \text{CO}_2$). This ratio is greater in the southeast than the northwest. Waters from the southeast part have slightly higher Li:K, Li:Na and K:Na. Silica is deposited by both types. Water at the margins of Upper and Lower Geyser Basins are moderately dilute and relatively rich in calcium and magnesium and have low Cl: HCO_3 ratio. They deposit small to moderate amounts of travertine and magnesium oxides and very little silica (Rowe, et al, 1973).

The U.S. Geological Survey has made a study of the near-surface aspects of the Yellowstone National Park thermal phenomenon. They found that shallow drilling upset the local hydrologic regime by short-circuiting aquifers of differing temperatures and pressures. They also found that porosity has been reduced considerably by deposition of hydrothermal minerals. Progressive restriction of flow channels leads to concentration of flow into a few channels (White, Fournier, Muffler and Truesdell, 1975).

The Yellowstone thermal system is characterized by pressures much in excess of cold hydrostatic due to thermoartesian pressure, perhaps supplemented by normal artesian pressure (White et al, 1975).

Additional References

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White, D.E., Sandburg, C.H., and Brannock, W.W., 1953. Geochemical and Geophysical Approaches to the Problems of Utilization of Hot Spring Water and Heat, Pacific Science congress, 7th, New Zealand, 1949, Proceedings, v.2, p.490-499.

APPENDIX B
RESERVOIR PERFORMANCE CALCULATIONS

Calculation of Steady State Pressure Drop:

- Assumptions:
1. Steady state
 2. Unconfined reservoir
 3. Spatially uniform and isotropic reservoir
 4. Intergranular permeability
 5. Same diameter of injection and production well bores
 6. No skin effect

Symbols:

d_i = see Figure B-1
 D_i = see Figure B-1
 h = net reservoir thickness
 k = permeability
 N = number of producers
 p = pressure
 p_i = initial reservoir pressure
 p_w = flowing bottomhole pressure
 q = production rate per well
 r = radial distance
 r_w = well bore radius
 R_1 = radius of producer array
 R_2 = radius of injector array
 t = time
 ϕ = porosity
 μ = viscosity

Derivation of equations: From the solution to the Diffusivity Equation in porous media and the special case of steady state, we can derive the following relations applying the principle of superposition:

$$p_w \text{ (producers)} = p_i - \frac{q\mu}{2\pi kh} p_d \text{ (producer)} \quad (B-1)$$

$$p_w \text{ (injectors)} = p_i - \frac{q\mu}{2\pi kh} p_d \text{ (injector)} \quad (B-2)$$

$$\text{where,} \quad p_d \text{ (producers)} = \sum_{i=1}^N \ln D_i - \sum_{i=1}^{N-1} \ln d_i - \ln r_w \quad (B-3)$$

$$p_d \text{ (injectors)} = \sum_{i=1}^{N-1} \ln D_i + \ln r_w - \sum_{i=1}^N \ln d_i \quad (B-4)$$

where d_i and D_i are defined in the upper figure in Figure B-1.

Figure B-1. Explanation of symbols.

$$d_i = 2R_1 \sin\left(\frac{\pi i}{N}\right), i = 1, 2, \dots, N-1 \quad (B-5)$$

$$= r_w, i = N$$

$$\text{and } D_i = \sqrt{(R_2 - R_1)^2 + 4R_1 R_2 \sin^2\left(\frac{\pi i}{N}\right)} \quad (B-6)$$

Results presented in Figure 16 were calculated using these relations.

For the case when injection rate is twice the production rate, we can derive

$$p_{w(\text{prod})} = p_i - \frac{q\mu}{2\pi kh} p_d \quad (\text{producer}) \quad (B-7)$$

$$\text{where } p_d (\text{producer}) = 2 \sum_{i, \text{odd}}^N \ln D_i - \sum_{i=1}^{N-1} \ln d_i - \ln r_w \quad (B-8)$$

Where d_i and D_i are as shown in the lower figure in Figure B-1.

$$D_i = 2R_2 \sin\left(\frac{i\pi}{N}\right), i = 1, 2, \dots, N-1 \quad (B-9)$$

$$= r_w, i = N$$

$$d_i = \sqrt{(R_2 - R_1)^2 + 4R_1 R_2 \sin^2\left(\frac{i\pi}{N}\right)} \quad (B-10)$$

A similar relation can be derived for flowing bottomhole pressure in injectors. Figure 17 shows results obtained by using equations (B-7) and (B-8).

Calculation of Breakthrough Time

Assumptions: 1. R_1 much smaller than R_2
 2. 36 producing wells with 227 m³/hr-well
 Other assumptions same as above.

Symbols: t_b = breakthrough time
 N = number of injectors

Derivation of relations: it can be shown that the breakthrough time for such a system is (Lee, 1948):

$$t_b = \frac{\pi h (R_2 - R_1)^2 \phi}{q (N+2)} \quad (B-11)$$

If S is the spacing of the producers, since there are 36 producers,

$$R1 = \frac{36S}{2\pi} \quad (B-12)$$

Also,
$$N = \frac{36,000}{q},$$

where q is the injection rate in gpm per well.

$R2 = 9,420$ ft
and using S in ft and t_b in years, we get from (B-11) and (B-12),

$$t_b = 3.352 \times 10^{-3} \left[\frac{(9420 - 5.735)^2}{18000 + q} \right] \quad (B-13)$$

Calculation of Water Temperature With Time

Gringarten et al (1975) have presented a solution to the problem of calculating heat extraction from hot dry rocks by flowing cold water through fractures. Fractures are uniformly spaced and drain heat from blocks of homogeneous and isotropic impermeable rock. Cold water enters at the bottom of each fracture and solutions are given in terms of dimensionless parameters from which the exiting water temperatures at the top of the fracture can be determined.

Gringarten et al's results (1975) were modified for use in our problem. The vertical fracture in these authors' model was replaced by a horizontal porous medium. The value of the constant linear velocity in the original model was replaced by an average velocity along the fastest streamline between an injector and a producer in the hypothetical reservoir. The result shown in Figure 22 was calculated by superimposing temperature performance (with time) of ten layers. Each layer had 30 m thickness. The layers were separated from each other by impermeable rock layers 90 m thick. One of the layers was assumed to have 500 md permeability, while the other nine had 55.556 md. The average permeability was 100 md.

APPENDIX C: CHEMICAL ANALYSES OF WATER

IMPERIAL VALLEY

Parameter*	Nowlin #1	Holtz #1	Holtz #2	C. B. Jackson #1	J. D. Jackson #1
Total Dissolved Solids	14,100	13,168	16,330	15,430	15,275
SiO ₂	120	268	187	267	268
Li	6.6	4	4.1	2.8	3.4
Na	3,600	5,500	4,720	4,688	4,563
K	360	220	231	181	197
Ca	880	1,062	1,062	891	781
Mg	2.4	5.6	23	4.7	3.8
Cl	9,000	7,420	8,242	8,320	8,076
SO ₄	100	100	148	152	150
CO ₃	4	NA	NA	NA	NA
HCO ₃	20	NA	NA	NA	NA
F	1.6	1.7	1.5	0.9	0.6
B	4.8	4.1	8	4.8	5.2
Fe	0.9	15	5	20	10
Mn	NA	0.9	0.9	1.3	1.9
Pb	0.1	1.6	0.6	0.6	0.9
Zn	0.68	0.3	0.1	0.4	0.5
Cu	0.2	0.5	0.4	0.4	0.4
Ba	NA	6	3	3	3
Sr	NA	37	42	32	36
Al	0.04	15	12	0.5	18
Ag	NA	NA	NA	NA	NA
LI	4	NA	NA	NA	NA
pH	7.1	NA	7.4	5.8	6.5

* Except pH, all parameters are in parts per million.

Chemical Quality of Water, Heber Geothermal Reservoir, Imperial Valley, California

IMPERIAL VALLEY ARTESIAN WELLS

Sample Number	Location	Owner or Operator	Date Sampled	Producing Depth (m)	Altitude (m)	Water Temperature (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (1/min)	δH^{18} (0/00)	δH^2 (0/00)
1	NW/SW Sec. 23 T. 12S., R. 15E., S.B.	D. Brownell	12/15/70	6.9-99.1	-23.8	31.5	7.85	3.17			
2	SE/SE Sec. 27 T. 12S., R. 15E., S.B.	C. Brownell	12/15/70	125.0-131.1	-25.9	34.1	8.12	2.75		-7.3	-63
3	NE/WE Sec. 35 T. 12S., R. 15E., S.B.	Cowell	12/15/70	92.7-104.9	-19.8	33.0	8.13	2.61			
4	SW/SW Sec. 31 T. 12S., R. 16E., S.B.	P. Rebik	12/16/70	281.9	- 7.6	39.1	7.79	6.08	20		
5	SE/NE Sec. 1 T. 13S., R. 15E., S.B.	Taylor	12/15/70	325.2-331.9	-19.8	55.2	7.66	6.90	64	-9.3	
6	SW/SW Sec. 3 T. 13S., R. 15E., S.B. School	Mulberry	12/14/70	271.3	-34.4	40.3	8.12	2.70			
7	NW/NW Sec. 5 T. 13S., R. 15E., S.B.	J. Williams	12/14/70	259.4-264.0	-43.3	35.7	7.80	2.69	40		
8.	NW/NW Sec. 5 T. 13S., R. 15E., S.B.	Wiest Store	12/14/70	235.3-247.5	-42.1	37.7	7.88	2.55			
9	SW/SW Sec. 16 T. 13S., R. 15E., S.B.	M. Lunceford	12/14/70	231.6	-36.0	39.4	8.29	2.58	40		
10	SW/SE Sec. 23 T. 13S., R. 15E., S.B.	J. Ratliff	12/13/70	396.2	-25.0	55.7	7.74	6.15	160	-8.8	
11	SW/SW Sec. 24 T. 13S., R. 15E., S.B.	V. Butters	12/13/70	213.4	-22.6	42.8	8.36	2.84	60	-7.5	
12	NW/NW Sec. 32 T. 13S., R. 15E., S.B.	T. Shank	12/12/70	304.8	38.7	43.5	7.82	4.76			

Table extracted from Nichols and Hollenbaugh, 1975

IMPERIAL VALLEY ARTESIAN WELLS

Sample Number	Location	Owner or Operator	Date Sampled	Producing Depth (m)	Altitude (m)	Water Temperature (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (l/min)	δH^{18} (0/00)	δH^2 (0/00)
13	NE/NE Sec.33 T13S, R15E, S.B.	Magnolia School	12/12/70	386.8-423.4	-33.5	50.9	7.70	6.61	140		
14	NW/SW Sec.34 T13S, R15E, S.B.	M. Phegley	12/13/70	285.3-290.8	-31.4	44.3	8.17	3.14	40	-8.9	
15	SE/SE Sec.6 T13S, R16E, S.B.	F. Schoneman	12/16/70	187.7	-11.6	33.3	8.16	2.83			
16	SE/SW Sec.6 T13S, R16E, S.B.	T. Olesh	12/16/70	91.4	-15.2	32.0	8.12	3.14	20		
17	NW/NE Sec.6 T14S, R15E, S.B.	N. Fifield	12/12/70	364.2-393.2	-40/2	51.4	7.77	6.72			
18	SW/SW Sec.9 T14S, R15E, S.B.	J. Birger	12/11/70	117.3	-34.4	31.1	7.79	4.79	20		
19	NW/NW Sec.11 T14S, R15E, S.B.	Moiola Feed Lot	12/13/70	195.1	-26.8	42.0	8.20	2.80	28		
20	SW/SW Sec. 12 T14S, R15E, S.B.	Mendiburu Feed Lot	12/13/70	356.9-375.8	-21.9	51.7	7.68	5.71			
21	NW/NW Sec.15 T14S, R15E, S.B.	A. Gisler	12/11/70	355.1	-20.0	47.5	8.08	3.56	240	-9.9	-90
22	NW/SW Sec.23 T14S, R15E, S.B.	J. Birger	12/11/70	121.9	-26.8	31.8	7.87	2.51	16		

Table extracted from: Nichols and Hollenbaugh, 1975.

IMPERIAL VALLEY ARTESIAN WELLS

Sample Number	Location	Owner or Operator	Date Sampled	Producing Depth (m)	Altitude (m)	Water Temperature (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (l/min)	δH^{18} (0/00)	δH^2 (0/00)
23	NE/NE Sec.34 T14S, R15E, S.B.	J. Birger	12/11/70	121.9	-26.8	31.8	7.87	2.51	16		
24	NW/NE Sec.34 T14S, R15E, S.B.	Jenson	12/11/70	108.8	-26.8	29.5	8.01	2.83	120		
25	SW/SE Sec.34 T14S, R15E, S.B.	Gaddis	12/11/70	185.9	-24.4	35.5	7.95	3.07	60	-9.9	
26	SW/SE Sec.4 T14S, R16E, S.B.	F. Borchard	12/10/70	118.9-139.0	-4.6	37.3	8.35	1.99			
27	SW/SE Sec.4 T14S, R16E, S.B.	F. Borchard	12/10/70	139.3	-4.6	38.4	8.38	1.96	48		
28	SE/NE Sec. 11 T14S, R16E, S.B.	U.S.-B.L.M.	12/16/70	86.9	7.6	34.5	8.23	2.28		-7.2	-62
29	NW/SE Sec. 16 T14S, R16E, S.B.	M. Axler	12/12/70	121.9	-5.2	25.4	8.17	1.41	4	-7.2	
30	NW/NE Sec.21 T14S, R16E, S.B.	S. Stacey	12/10/70	133.2	-4.9	32.5	8.32	1.85	20		
31	NW/NW Sec.22 T14S, R16E, S.B.	C. Singh	12/10/70	212.8-216.1	-2.1	41.7	7.91	4.95	20	-9.8	
32	SW/NE Sec.10 T15S, R15E, S.B.	Shawner	12/31/70	263.3	-13.7	40.0 z	8.14	2.60	40	-9.1	
33	SE/NE Sec.14 T15S, R15E, S.B.	J. DePaoli	11/29/70	240.8-289.6	-7.6	40.1	7.97	2.58		-9.4	

Table extracted from: Nichols and Hollenbaugh, 1975.

IMPERIAL VALLEY ARTESIAN WELLS

Sample Number	Location	Owner or Operator	Date Sampled	Producing Depth (m)	Altitude (m)	Water Temperature (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (l/min)	δH^{18} (0/00)	δH^2 (0/00)
34	SW/NE Sec.26 T15S, R15E, S.B.	J. DePaoli	11/29/70	240.8-289.6	-7.6	40.1	7.97	2.58		-9.4	-90
35	NE/NE Sec.35 T15S, R15E, S.B.	Holtville Ice Co.	11/29/70	335.3	-5.5	44.6	7.96	4.33	116	-10.5	-94
36	NW/NW Sec.36 T15S, R15E, S.B.	City of Holtville	11/28/70	255.4-259.7	-4.6	29.0	7.77	1.71	12	-7.8	
37	SE/SE Sec.7 T15S, R16E, S.B.	Hooke	12/3/70	202.4-211.8	-11.3	35.6	8.25	2.20	12		
38	SW/NW Sec.8 T15S, R16E, S.B.	G. Hoyt	12/3/70	144.8-148.7	-10.4	30.8	8.12	2.27	4		
39	SE/SW Sec.15 T15S, R16E, S.B.	R. Garewal	12/2/70	243.8	0	32.0	8.39	1.92		-7.2	
40	SW/NW Sec.19 T15S, R16E, S.B.	F. Strahm	12/2/70	254.2	-8.2	35.6	9.36	1.53	40	-7.4	
41	NE/SW Sec.22 T15S, R16E, S.B.	D. Starr	12/2/70	228.6	0.3	34.7	8.15	2.88	12	-9.8	
42	SE/NW Sec.23 T15S, R16E, S.B.	L. Foster	12/2/70	137.8-165.2	4.6	34.1	8.38	1.75	100	-8.2	
43	SW/SE Sec.29 T15S, R16E, S.B.	A. Fusí	11/30/7	163.7-187.8	-3.0	30.6	8.26	1.19	8	-6.9	

Table extracted from: Nichols and Hollenbaugh, 1975.

IMPERIAL VALLEY ARTESIAN WELLS

Sample Number	Location	Owner or Operator	Date Sampled	Producing Depth (m)	Altitude (m)	Water Temperature (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (l/min)	δH^{18} (0/00)	δH^2 (0/00)
44	SW/SE Sec.30 T15S, R16E, S.B.	A. Fusi, Jr.	11/30/70	270.7-285.9	-3.0	39.7	8.17	2.26			
45	SE/NW Sec.4 T16S, R16E, S.B.	C. Ansel	11/30/70	268.2-285.9	0	34.5	8.22	2.96			
46	NE/NE Sec. 14 T16S, R16E, S.B.	Watton Labor Camp	12/1/70	343.8	5.2	43.0	8.09	3.29		-10.0	
47	NW/NE Sec.15 T16S, R16E, S.B.	Alamo School (abd.)	12/1/70	263.3-267.3	3.7	37.2	8.33	2.21	16	-9.0	
48	NE/NW Sec.9 T17S, R16E, S.B.	L. Bornt	12/9/70	184.1-216.4	9.4	37.2	8.13	2.35		-10.3	

Table extracted from: Nichols and Hollenbaugh, 1975.

CHEMICAL CONSTITUENTS (in mg/l)

Sample Number	Location	Cations								Anions				Other		Calculated Dissolved Solids
		Li	Na	K	Mg	Ca	Sr	Fe	F	Cl	HCO ₃	CO ₃	SO ₄	SiO ₂	B	
1	NW/SW Sec.23	0.50	670	5.5	23	32	1.0	0.24	1.9	620	360	2.3	450	32	2.6	2200
2	SE/SE Sec.27	0.24	530	3.7	9.7	19	0.4	0.09	1.5	510	290	3.4	300	36	2.7	1710
3	NE/NE Sec.35	0.28	510	3.8	11	19	0.57	0.05	1.6	520	290	3.5	280	33	2.7	1680
4	SW/SW Sec.31	0.68	1200	7.7	11	37	1.7	0.25	1.3	1700	290	2.0	60	27	8.9	3350
5	SE/NE Sec.1	0.63	1100	9.4	14	43	1.6	0.03	1.3	1200	400	2.5	620	33	9.7	3440
6	SW/SW Sec.3	0.17	500	3.0	4.2	9.7	0.25	0.19	2.0	450	480	6.0	120	38	2.4	1620
7	NW/NW Sec.5	0.32	620	5.4	11	11	0.25	0.20	1.4	230	1300	7.7	100	36	2.6	2330
8	NW/NW Sec.5	0.20	530	4.5	8	8.7	0.18	0.28	1.4	200	200	8.7	53	43	5.8	2010
9	SW/SE Sec.16	0.13	490	3.1	3.3	9.9	0.14	0.10	1.9	400	40	9.8	120	30	2.4	1610
10	SW/SE Sec.23	0.56	980	8.7	10	29	0.95	0.12	1.3	960	450	3.2	540	33	3.7	3820
11	SW/SW Sec.24	0.17	500	2.9	3.3	8.7	0.16	0.09	1.4	450	470	10	130	29	1.8	1610
12	NW/NW Sec.32	0.13	900	4.5	12	19	1.2	0.17	1.2	820	680	4.9	160	30	5.7	2840
13	NE/NE Sec.33	0.51	1100	8.9	14	29	1.4	0.19	1.0	1400	550	3.5	270	32	2.2	3410
14	NW/SW Sec.34	0.14	570	3.4	4.0	8.8	0.21	0.12	1.9	380	830	13	100	44	4.9	1560
15	SE/SE Sec.6	0.32	560	3.8	10	21	0.87	0.03	1.2	610	250	3.2	250	22	2.5	1730
16	SE/SW Sec.6	0.41	580	4.1	9.3	23	0.83	0.04	1.0	660	270	3.1	240	31	4.7	1830
17	NW/NE Sec.6	0.23	1200	6.9	15	40	1.2	0.32	1.0	1300	890	6.9	310	35	2.0	3810
18	SW/SW Sec.9	0.17	1000	5.9	45	52	1.3	0.19	1.2	1200	560	3.3	490	36	3.7	3400

Table extracted from: Nichols and Hollenbaugh, 1975.

CHEMICAL CONSTITUENTS (in mg/l)

Sample Number	Location	Li	Na	Cations				Sr	Fe	F	Cl	Anions			SO ₄	Other		Calculated Dissolved Solids
				K	Mg	Ca	HCO ₃					CO ₃	SiO ₂	B				
19	NW/NW Sec.11	0.12	520	3.1	4.2	10	0.13	0.20	2.0	340	810	12	81	31	5.5	1820		
20	SW/SW Sec.12	0.42	940	8.0	10	33	0.75	0.11	1.2	1000	380	2.3	550	33	6.3	2970		
21	NW/NE Sec.15	0.15	610	3.7	4.2	22	0.47	0.19	1.6	490	800	11	130	36	13	2120		
22	NW/SW Sec.23	0.11	500	3.0	3.9	8.7	0.07	0.12	2.3	350	740	10	87	37	2.6	1740		
23	NE/NE Sec.27	0.09	530	4.2	15	26	0.49	0.24	1.7	330	700	4.4	280	24	3.7	1920		
24	NW/NE Sec.34	0.11	590	4.2	13	29	0.59	0.60	1.3	530	740	6.3	190	33	2.8	2140		
25	SW/SE Sec.34	0.11	620	4.6	17	30	1.3	0.34	1.3	420	650	5.4	370	24	2.7	2150		
26	SW/SE Sec.4	0.12	390	2.0	2.1	6.2	0.20	0.05	2.9	200	610	12	120	23	1.1	1270		
27	SW/SE Sec.4	0.11	390	2.1	2.0	4.8	0.12	0.07	3.3	170	640	14	130	23	7.6	1890		
28	SE/NE Sec.11	0.25	420	3.0	5.2	12	0.36	0.03	1.3	500	200	2.9	130	30	9.0	1810		
29	NW/SE Sec.16	0.03	310	2.2	5.3	13	0.33	0.10	1.6	300	310	3.1	57	18	0.8	1020		
30	NW/NE Sec.21	0.08	380	2.0	3.0	7.6	0.31	0.06	2.6	300	440	7.4	100	28	2.8	1270		
31	NW/NW Sec.22	0.36	900	5.7	8.2	31	0.61	0.22	1.7	1200	270	2.4	130	28	2.7	2580		
32	SW/NE SEc.10	0.12	670	4.9	17	22	0.95	0.12	1.8	600	670	3.4	190	37	1.9	2220		
33	SE/NE Sec.14	0.11	490	2.9	4.0	11	0.50	0.16	2.0	320	790	10	84	33	2.5	1750		
34	SW/NE Sec.26	0.12	500	3.2	4.7	11	0.47	0.19	2.0	300	790	6.9	110	26	3.6	1760		
35	NE/NE Sec.35	0.21	790	4.6	6.1	20	0.72	0.08	1.4	950	370	3.6	150	29	3.6	2330		
36	NW/NW Sec.36	0.04	350	2.5	7.9	15	0.44	0.32	1.7	290	490	2.1	79	23	3.2	1270		

Table extracted from: Nichols and Hollenbaugh, 1975.

CHEMICAL CONSTITUENTS (in mg/l)

Sample Number	Location	Cations								Anions				Other		Calculated Dissolved Solids
		Li	Na	K	Hg	Ca	Sr	Fe	F	Cl	HCO ₃	CO ₃	SO ₄	SiO ₂	B	
37	SE/SW Sec. 7	0.11	460	2.5	3.5	9.1	0.15	0.12	2.8	260	710	11	110	38	4.4	1610
38	SW/NW Sec. 8	0.08	510	3.3	8.6	16	0.39	0.42	1.4	280	880	9.4	130	24	6.7	1870
39	SE/SW Sec. 15	0.12	420	2.2	2.7	7.6	0.10	0.10	3.9	220	600	12	160	25	2.7	1480
40	SW/NW Sec. 19	0.05	320	1.8	2.7	6.5	0.11	0.16	3.2	72	750	12	100	35	1.2	1200
41	NE/SW Sec. 22	0.16	570	3.7	5.5	15	0.44	0.14	2.2	600	430	5.4	170	22	2.9	1830
42	SE/NW Sec. 23	0.13	370	2.1	2.0	6.7	0.09	0.04	3.4	160	580	12	140	23	3.5	1300
43	SW/SE Sec. 29	0.04	260	2.0	2.5	7.1	0.25	0.40	2.9	40	580	7.6	110	21	1.9	1040
44	SW/SE Sec. 30	0.09	450	2.5	3.3	9.0	0.18	0.20	2.3	260	690	9.4	130	41	6.7	1600
45	SE/NW Sec. 4	0.12	610	3.5	5.2	11	0.31	0.24	1.6	490	850	13	74	11	3.2	2080
46	NE/NE Sec. 14	0.25	560	3.6	3.5	17	0.57	0.05	1.1	630	310	3.8	120	26	3.4	1680
47	NW/NE Sec. 15	0.10	420	2.4	2.7	10	0.41	0.05	2.3	310	510	9.3	130	25	2.2	1420
48	NE/NW Sec. 9	0.11	450	2.9	4.2	17	0.70	0.12	1.7	400	370	4.4	180	29	1.5	1460

Table extracted from Nichols and Hollenbaugh, 1975.

CHEMICAL COMPOSITION OF WATER SAMPLES FROM DWR DUNES #1*

Sample #	Perforation interval, in meters	Sampling comments depths in meters	T °C	Li	Na	K	Mg	Ca	Ba	Mn	Fe	Ni
1	572 - 584	Bailed from 570	83	0.12	176	13	2.7	203	0.3	0.00	0.17	0.00
2	572 - 584	Bailed from 270	82	0.23	334	18	6.9	62	0.4	0.00	0.11	0.00
3	572 - 584	Bailed from 270	82	0.25	465	30	0.1	35	0.2	0.00	0.10	0.00
4	572 - 584	Bailed from 575	88	0.13	206	23	6.1	201	0.3	0.00	0.16	0.00
5	259 - 271	Bailed from 276	90	0.44	609	72	3.0	17	0.3	0.00	0.03	0.00
6	259 - 271	Bailed from 276	92	0.32	686	94	3.0	23	0.2	0.00	0.05	0.00
7	104 - 116	Bailed from 117	92	0.53	800	84	9.4	37	0.2	0.00	0.12	0.00
8	104 - 116	Bailed from 117	86	0.86	852	108	0.6	58	0.3	0.00	0.07	0.00
9	104 - 116	Bailed from 117	92	0.85	962	115	10.0	50	0.2	0.00	0.19	0.00

* Analyses performed by California Department of Water Resources. Units in parts per million.

Table extracted from: Coplen et al, 1973.

CHEMICAL COMPOSITION OF WATER SAMPLES FROM DWR DUNES #1*

Sample #	Cu	Zn	Cd	Pb	As	F	Cl	Br	I	SO ₄	B	SiO ₂	pH(field)	TDS
1	0.08	1.1	0.00	0.11	0.00	0.7	169	0.53	0.027	372	0.5	9.4		1260
2	0.07	1.0	0.00	0.11	0.00	0.34	343	0.94	0.012	343	0.6	3.7		1300
3	0.06	1.0	0.00	0.16	0.00	4.3	405	0.92	0.015	376	0.7	2.0		1460
4	0.07	0.6	0.00	0.04	0.00	1.4	188	0.66	0.021	416	0.6	19.0	8.4	1410
5	0.12	0.15	0.00	0.05	0.00	8.9	583	1.4	0.010	497	1.5	1.5		1870
6	0.12	0.22	0.00	0.05	0.00	10.0	570	3.0	0.019	675	1.2	1.9		2190
7	0.15	0.09	0.00	0.11	0.01	8.0	854	2.0	0.023	605	1.9	29	8.5	2530
8	0.17	0.03	0.00	0.07	0.03	7.9	968	2.5	0.016	542	1.9	78		2780
9	0.19	0.22	0.00	0.17	0.01	3.6	1210	2.8	0.022	549	1.9	17		3040

* Analyses performed by California Department of Water Resources. Units in parts per million.

Table extracted from: Coplen et al, 1973.

RAFT RIVER

from: Environmental Report: Deep Geothermal Test Wells in the
Raft River Valley, by S.G. Spencer, Aerojet Nuclear Company,
INEL, January, 1975.

Chemical Analyses of Hot Wells in Raft River Valley
(Chemical Constituents in Milligrams per Liter)

	Schmitt	Crank
Reported Well Depth (ft.)	414	540
Discharge (gpm)-reported, and variable	58	60
Temperature (°C)	93	90*
Silica	90	97
Calcium	53	130
Magnesium	0.4	0.4
Sodium	560	1,110
Potassium	22	35
Bicarbonate	55	36
Carbonate	0	0
Sulfate	57	61
Phosphate	0	0.01
Chloride	900	1,900
Fluoride	5.7	14
Nitrate	0.54	0.57
Dissolved Solids (Calculated)	1,720	3,360
Dissolved Solids (tons per acre-ft.)	2.34	4.57
Hardness (as CaCO ₃)	130	330
Hardness (Non-carbonate)	89	300
Specific Conductance	3,050	6,090
pH (field)	7.4	7.7
Alkalinity (as CaCO ₃)	45	30
Percent Sodium	88	87
Sodium Absorption Ratio	21	27

* Measured temperature is probably lower than at point of discharge

Chemical Analyses of Hot Wells - Specific Elements
(in ppm except as indicated)

	Schmitt	Crank
Mercury (ppb)	<0.1	<0.1
Silver	<0.02	<0.02
Gold	<0.01	<0.01
Cadmium	<0.01	<0.01
Cobalt	<0.05	<0.05
Copper	0.02	0.02
Nickel	<0.05	<0.05
Lead	<0.06	<0.06
Zinc	0.02	0.02
Arsenic	0.003	0.001
Antimony	<0.2	0.2
Iron	<0.02	<0.02
Manganese	0.02	0.02
Strontium	1.4	2.8

Environmental Report: Deep Geothermal Test Wells in the
Raft River Valley, by S.G. Spencer, Aerojet Nuclear Company,
INEL, January, 1975.

LONG VALLEY

Long Valley Springs and Wells

Sample Number	Location	Name	Date Sampled	Altitude (m)	Water Temperature (°C)	pH	Conductivity (mmho/cm)	Dis-charge (l/min)	δH^{18} (0/00)	δH^2 (0/00)
1	NE/NE Sec. 25 T. 2S., R. 27#., M.D.	Big Springs	5/21/72	2220	11	6.83	0.182	380	-15.89	-115.4
2	SW/NW Sec. 13 T. 3S., R. 28#., M.D.	Little Hot Creek Hot Spring	5/13/72	2135	79	6.51	1.95	280	-15.34	-121.8
3	NE/NE Sec. 25 T. 3S., R. 28E., M.D.	Hot Creek Hot Spring	8/29/73	2145	90	7.89	1.77	400		
4	SW/NW Sec. 32 T. 3S., R. 28E., M.D.	"Endogenous" 5 Magma Power Co. (123.4m deep)	5/19/72	2231	94	9.25	1.92	3200 (kg/min) mixed steam & water	-14.16	-115.3
5	SW/NW Sec. 35 T. 3S., R. 28#., M.D.	Hot Pool	5/24/72	2165	60	7.15	1.80	0	-12.44	-111.0
6	NE/NW Sec. 13 T. 3S., R. 29#., M.D.	Artesian Well (24.4 m deep)	5/23/72	2075	10	8.82	0.191	25	-17.07	-129.5
7	SW/SW Sec. 21 T. 3S., R. 29E., M.D.	Hot Spring	5/22/72	2105	56	6.53	1.79	100	-16.17	-123.9
8	SE/NE Sec. 28 T. 3S., R. 29E., M.D.	Hot Spring	5/22/72	2095	49	6.60	1.90	200	-15.85	-123.4
9	NE/NE Sec. 31 T. 3S., R. 29E., M.D.	Hot Spring	5/20/72	2130	58	7.53	1.50	190	-15.23	-121.3
10	NW/SE Sec. 34 T. 3S., R. 29E., M.D.	Hot Spring	5/23/72	2090	41	6.64	1.63	150	-16.08	-124.9

Table extracted from Nichols and Hollenbaugh, 1975.

CHEMICAL CONSTITUENTS (In mg/l)

Sample Number	Location	Li	Na	K	Cations		Mg	Ca	Sr	F	Cl	Br	Anions		CO ₃	SO ₄	Other		H ₂ S
					Rb	Cs							I	HCO ₃			SiO ₂	B	
1	NE/NE Sec. 25	0.04	23	4.0	0.01	<0.05	5.9	5.1	0.07	0.5	5.7	0.20		90	0	8.1	58	0.37	<0.
2	SW/NW Sec. 13	2.3	410	30	0.26	0.30	0.6	50	0.60	8.4	200	0.80	0.8	735	0.3	96	110	10.9	2.
3	NE/NE Sec. 25	2.3	400	24	0.22	0.2	0.1	1.6		9.6	225			580	25.9	100	150	10.5	2.
4	SW/NW Sec. 32	2.8	390	45	0.48	0.60	0.1	0.9	0.14	12	280	1.10	0.4	450	29.6	130	340	15	10.
5	SW/NW Sec. 35	2.5	380	24	0.28	0.45	0.1	3.3	0.10	11	250	0.80	0.5	866	0.7	120	300	13	1.
6	NE/NW Sec. 13	0.14	38	1.3	<0.01	<0.05	0.2	5.3	0.04	0.6	3.0	0.03		111	2.8	3.7	64	0.18	3.
7	SW/SW Sec. 21	1.5	310	37	0.11	0.10	0.6	25	0.20	4.6	140	0.50	0.4	828	0.3	65	250	7.7	0.
8	SE/NE Sec. 28	1.7	400	43	0.14	0.05	0.6	22	0.14	4.8	170	0.60	0.4	845	0.3	69	240	8.8	0.
9	NE/NE Sec. 31	2.0	310	22	0.19	0.20	0.4	15	0.28	7.5	170	0.60	0.5	516	1.9	81	150	7.9	0.
10	NW/SE Sec. 34	1.6	320	28	0.08	0.10	1.2	23		4.6	150	0.50	0.4	695	0.3	59	205	3.1	0.

Table extracted from Nichols and Hollenbaugh, 1975.

TRACE CONSTITUENTS (in mg/l)

Sample Number	Location	Al	Mn	Fe	Ni	Cu	Zn	As	Se	Sb	Hg	N (NH ₃)	P (PO ₄)	Calculated Dissolved Solids
1	NE/NE Sec. 25	0.002	<0.02	< 0.05	< 0.05	<0.03	0.045	0.02		< 0.1	< 0.0001	0.13	1.0	202
2	SW/NW Sec. 13	0.006	0.24	0.15	0.10	0.07	0.44	0.74	0.0005	< 0.1	< 0.0001	0.40	0.15	1660
3	NE/NE Sec. 25	0.060	< 0.02	< 0.05	< 0.05	0.02	< 0.01				0.0013	0.50		1510
4	SW/NW Sec. 32		< 0.02	0.05	< 0.05	<0.03	0.19	2.2	0.001	0.2	0.0001	0.40	0.18	1710
5	SW/NW Sec. 35	0.057	< 0.02	< 0.05	< 0.05	0.02	0.045	0.34	0.004	0.3	0.0003	0.15	0.71	1570
6	NE/NW Sec. 13	0.003	< 0.02	< 0.05	< 0.05	<0.03	< 0.01	0.02	0.002	< 0.1	0.0001	0.35	0.15	235
7	SW/SW Sec. 21	0.002	0.10	0.23	< 0.05	0.04	0.18	0.46	0.005	< 0.1	< 0.0001	0.20	0.28	1590
8	SE/NE Sec. 23	0.003	0.08	< 0.05	< 0.05	0.03	0.12	0.34	0.004	< 0.1	0.0001	0.10	0.43	1290
9	NE/NE Sec. 31	0.006	< 0.02	< 0.05	< 0.05	<0.03	0.02	0.84		< 0.1	0.0001	0.09	0.43	1290
10	NW/SE Sec. 34	<0.002	0.085	0.45	< 0.05	<0.03	0.10	0.36		< 0.1	< 0.0001	0.15	0.18	1500

Other trace constituents measured but below limit of detection:

Cd <0.01, Co <0.06, Au <0.1, Pb <0.1, Ag < 0.04

Table extracted from Nichols and Hollenbaugh, 1975.

Calculated Temperatures, Long Valley (in °C)

Sample Number	Location	Quartz Solubility		Na/K	Na, K, Ca		Measured Temperature
		(regular)	(with steam loss)		(B = 1/3)	(B = 4/3)	
1	NE/NE Sec. 25	109		259	187	82	11
2	SW/NW Sec. 13	143		150	171	138	79
3	NE/NE Sec. 25	161	153	131	191	257	90 (boiling)
4	SW/NW Sec. 32	219	200	201	238	344	94 (boiling)
5	SW/NW Sec. 35	209	192	140	189	225	60 (evaporation)
6	NE/NW Sec. 13	114		86	117	52	10
7	SW/SW Sec. 21	196		205	200	166	56
8	SE/NE Sec. 28	193		192	200	183	49
9	NE/NE Sec. 31	161		147	175	157	58
10	NW/E Sec. 32	182		169	183	155	41

Table extracted from Nichols and Hollenbaugh, 1975.

ROOSEVELT HOT SPRINGS

Roosevelt Hot Springs Water Chemistry from Mundorf (1970)

Date: 9-11-57

Temperature: 131°F

	<u>ppm</u>	<u>molality</u>
SiO ₂	313	.00521
Ca ⁺⁺	22	.000549
Mg ⁺⁺	0	0
Na ⁺	2500	.1087
K ⁺	488	.0125
HCO ₃	156	
SO ₄	73	.000760
Cl-	4240	.1196
F-	7.5	
NO ₃ -	11	
B	38	
Li	.27	
Br	3.3	
I	.3	
pH	7.9	
Ionic Strength	.1230	
Na-Ca-K Temperature	283°C	
SiO ₂ Temperature	200°C	

VALLES CALDERA

CHEMICAL QUALITY OF WATER, VALLES CALDERA AREA

	<u>JF-1</u>	<u>GT-2</u>	<u>Soda Dam</u>
Analysis	3-29-74	3-18-74	3-29-74
Silica (mg/l)	40	115	42
Calcium (mg/l)	115	78	320
Magnesium (mg/l)	10	42	16
Sodium (mg/l)	210	550	850
Carbonate (mg/l)	0	0	0
Bicarbonate (mg/l)	464	1,230	1,220
Sulfate (mg/l)	30	200	38
Chloride (mg/l)	290	400	1,480
Fluoride (mg/l)	2.6	3.1	3.3
Nitrate (mg/l)	0	0	0
Hardness (mg/l)	330	370	860
Total Dissolved Solids (mg/l)	1,100	2,500	4,000
Conductance (μ mhos)	1,700	2,920	5,900
pH	6.9	7.4	6.6
Temperature ($^{\circ}$ C)	16	56	46

JF-1 - Spring Upper Madera Limestone, Jemez River

GT-2 - Lower Madera Limestone

Soda Dam - Thermal Spring on Jemez Fault (Zone of Saturation)

(from Purtymun et al, 1974).

SURPRISE VALLEY

Surprise Valley Springs and Artesian Wells

Sample Number	Location	Owner or Operator	Date Sampled	Producing Depth (m)	Altitude (m)	Water Temperature (°C)	pH	Conduc- tivity (mmho/cm)	Dis- charge (l/min)	δH^{18} (0/00)	δH^2 (0/00)
1	NW/NE Sec. 17 T. 46N., R. 16E., M.D.	Fort Bidwell Reservation	7/26/73		1414	45.1	7.85	0.733	400		
2	SW/NE Sec. 24 T. 44N., R. 15E., M.D.	Lake City Mud Explosion	8/16/73	pool	1366	96.5	7.44	3.74	0		
3	NW/NW Sec. 12 T. 43N., R. 16E., M.D.	Seyfreth Hot Springs	7/26/73	spring	1417	85.4	7.66	3.28	500		
4	NE/NE Sec. 13 T. 43N., R. 16E., M.D.	Leonards Hot Springs	7/25/73	spring	1390	61.8	7.82	2.59	150		
5	NE/SW Sec. 6 T. 42N., R. 17E., M.D.	Hot Springs Motel	7/27/73	27	1372	98.1	8.40	2.66	300		
6	NE/NE Sec. 7 T. 39N., R. 17E., M.D.	Menlo Hot Springs	8/23/73	spring	1384	57.4	8.91	0.808	500		

Table extracted from Nichols and Hollenbaugh, 1975

CHEMICAL CONSTITUENTS (in mg/l)

Sample Number	Location	Li	Na	K	Cations		Ca	Mn	Zn	F	Cl	Anions				B	Calculated Dissolved Solids
					Rb	Mg						HCO ₃	CO ₃	SO ₄	SiO ₂		
1	NW/NE Sec. 17	0.03	110	9.5	0.01	0.1	4.2	< 0.01	< 0.0005	2.2	31	131	1	86	82	0.61	458
2	SW/NE Sec. 24	0.24	320	15	0.08	<0.1	7.7	< 0.01	< 0.005	7.6	220	121	0	320	200	6.3	1210
3	NW/NW Sec. 12	0.15	300	9.0	0.04	<0.1	28	0.01	< 0.0005	4.5	220	63	0	370	110	7.6	1110
4	NE/NE Sec. 13	0.13	330	8.5	0.03	0.6	26	0.09	0.005	5.2	220	82	1	390	110	7.6	1180
5	NE/SW Sec. 6	0.10	280	5.5	0.03	<0.1	16	< 0.01	< 0.014	5.1	200	57	2	320	100	5.7	991
6	NE/NE Sec. 7	< 0.02	100	1.4	<0.01	<0.1	5.1	< 0.01	< 0.05	3.8	25	27	34	120	53	0.93	370

Trace constituents below detection:

Cs < 0.1
 Fe < 0.06
 Cd < 0.01
 Co < 0.05
 Cu < 0.02
 Ni < 0.04
 Po < 0.1

Table extracted from Nichols and Hollenbaugh, 1975.

BEOVAWE

BEOVAWE HOT SPRINGS

CBB-747-4758

From: Wollenberg et al, 1975. Geothermal Energy Resource Assessment. Report UCID-3762, Lawrence Berkeley Laboratory, University of California.

STEAMBOAT SPRINGS

GEOHERMAL FLUID PROPERTIES AT STEAMBOAT SPRINGS

<u>PROPERTY</u>	<u>VALUE</u>
Temperature ($^{\circ}\text{C}$)	94
pH	7.19
Specific conductance	3,340
Silica (SiO_2)	270
Calcium (Ca)	16
Magnesium (Mg)	0.7
Sodium (Na)	680
Potassium (K)	66
Lithium (Li)	7.5
Bicarbonate (HCO_3)	364
Carbonate (CO_3)	2
Sulfate (SO_4)	73
Chloride (Cl)	837
Fluoride (F)	2.1
Boron (B)	47

COSO HOT SPRINGS

Analyses of Water from Coso Hot Springs, Inyo County, California

<u>Constituents</u>	<u>#1 By Weight</u>	<u>#2 By Weight</u>
Sodium (Na)	49	81
Potassium (K)	11	12
Lithium (Li)	Trace	--
Ammonium (NH ₄)	Trace	--
Calcium (Ca)	45	59
Magnesium (Mg)	2.4	34
Iron (Fe)	122	83
Aluminum (Al)	201	56
Hydrogen (H)	16	12
Sulphate (SO ₄)	2,308	1,400
Nitrate (NO ₃)	Trace	0
Chloride (Cl)	Trace	40
Carbonate (CO ₃)	0	0
Metaborate (BO ₂)	--	0
Phosphate (PO ₄)	Trace	Trace
Silica (SiO ₂)	--	411

From the Geyser, vol.2, Issue 23, January 23, 1976.

YELLOWSTONE

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park

[See table 2 for location of unnamed hot springs and geysers. Locality numbers were applied during this study. Tr., trace; Alk., alkaline]

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Mammoth Hot Springs area										
Blue Spring, main terrace -----	White and others, 1956 ..	Aug. 1954	70.5	----	6.88	---	56	----	----	209
Cupid Spring (YF132) -----	This study -----	Oct. 1962	73	----	-----	51	52	0.2	<0.1	310
East Jupiter Terrace (YF17) -----	D. E. White, unpub. data -----	Sept. 1960	75	----	-----	-----	-----	-----	-----	-----
Do -----	This study ¹ -----	do	72	6.25	6.70	52	52	<1	<1	339
Jupiter Spring, main terrace -----	Allen and Day, 1935 -----	ca. 1930	---	----	-----	---	46	Tr.	0	335
Mammoth Spring, main terrace, near west edge -----	White and others, 1963 -----	Sept. 1957	72	----	6.6	---	60	.2	.06	372
Opal Spring (YF18) -----	D. E. White, unpub. data -----	Oct. 1947	72	----	6.48	---	---	----	----	-----
Do -----	do -----	Sept. 1960	69	----	6.45	---	50	----	----	-----
Do -----	This study ¹ -----	do	69	----	6.45	51	51	<1	<1	315
Spring near Opal Spring (YF26) -----	This study -----	do	---	----	-----	53	55	<1	<1	---

Norris Geyser Basin										
Bathtub Spring (YF45)	Allen and Day, 1935	1928	---	---	---	---	503	---	Tr.	6
Do	do	ca. 1930	---	---	---	---	327	48	*37	11
Do	This study	Sept. 1961	91	---	4.40	400	426	1.5	.2	1.8
Do	do	May 1965	92	4.45	4.18	452	456	---	---	---
Big Alcove Geyser (YF57)	do	Sept. 1961	87.5	---	6.3	222	227	0.41	.1	2.4
Cinder Pool (YF 25)	D. E. White, unpub. data	Sept. 1947	90.5	---	4.17	---	---	---	---	---
Do	do	Sept. 1957	92	---	4.2	---	270	---	---	8.4
Do	do	Sept. 1960	86	---	3.83	---	---	---	---	---
Do	This study ¹	do	86	3.9	3.8	316	348	1.6	.1	6.4
Do	This study	Sept. 1961	84	---	4.05	317	321	1.8	.1	7.0
Constant Geyser (YF38)	Gooch and Whitfield, 1888	Sept. 1885	92	---	Acid	---	468	4.8	Tr.	14.6
Echinus Geyser (YF23)	This study	Sept. 1961	77	---	3.0	458	460	1.9	1.1	3.15
Do	Gooch and Whitfield, 1888	Aug. 1884	91	---	Acid	---	253	2.7	0	11.5
Do	D. E. White, unpub. data	Sept. 1947	---	---	3.35	---	---	---	---	---
Do	Scott, 1964	Sept. 1959	82	---	3.5	---	250	1.6	2.3	5.6
Do	D. E. White, unpub. data	Sept. 1960	82	---	3.49	---	---	---	---	---
Do	This study ¹	do	87	3.55	3.40	280	287	2.2	1.8	1.6
Do	do	Sept. 1961	87	---	3.50	273	279	2.5	2.6	4.2
Do	do	Sept. 1962	83	---	3.4	294	294	2.3	1.2	4.3
Do	do	May 1965	86	3.50	3.42	---	273	---	---	---
Emerald Spring (YF47)	do	Sept. 1961	87.5	---	4.3	552	558	0.8	---	3.1
Do	do	Sept. 1962	86	---	3.93	---	570	0.6	---	3.1
Do	do	May 1965	86	4.60	4.40	---	596	---	---	---

Locality	Mg	Na	K	Li	NH ₄	HCO ₃	CO ₂	SO ₄	Cl	F	B	As
Mammoth Hot Springs area—Continued												
Blue Spring, main terrace	78	129	56	1.4	---	526	0	529	169	---	4.4	---
Cupid Spring (YF132)	68	122	42	1.5	---	---	---	578	161	1.6	4.0	---
East Jupiter Terrace (YF17)	---	124	52	1.6	---	---	---	---	163	---	3.8	---
Do	67	130	56	1.3	---	816	0	479	165	3.0	4.2	0.60
Jupiter Spring, main terrace	71	143	56	---	---	871	0	528	169	---	---	---
Mammoth Spring, main terrace, near west edge	68	129	69	2.3	1.0	667	0	501	170	2.4	4.3	.5
Opal Spring (YF18)	---	---	---	---	---	---	---	---	168	---	---	---
Do	---	---	---	---	---	---	---	---	165	---	---	---
Do	61	134	56	1.9	---	747	0	477	165	4.0	4.2	.63
Spring near Opal Spring (YF26)	62	141	55	1.8	---	---	---	---	---	---	4.0	---

Norris Geyser Basin—Continued												
Bathtub Spring (YF45)	1	517	52	---	19	19	---	97	810	---	5.8	---
Do	1	274	16	---	46	0	---	813	416	---	10.6	---
Do	.2	326	33	4.0	---	0	0	70	553	3.5	5.7	---
Do	---	---	39	---	---	---	---	---	---	---	---	---
Big Alcove Geyser (YF57)	.3	193	22	1.5	---	8	0	84	265	5.2	5.2	---
Cinder Pool (YF25)	---	---	---	---	---	---	---	---	---	---	---	---
Do	.2	518	72	5.9	---	0	0	---	790	---	12	---
Do	---	406	60	5.1	---	0	0	125	727	---	10	---
Do	.9	423	66	5.2	---	0	0	87	720	5.2	11.8	---
Do	.9	419	61	4.8	---	0	0	---	---	5.3	11.4	---
Do	---	319	74	3	1.0	0	0	---	---	---	---	---
Constant Geyser (YF38)	1.8	349	86	5.1	---	0	0	*111	574	---	9.9	1.3
Do	.5	349	86	5.1	---	0	0	134	584	2.7	10	---
Echinus Geyser (YF23)	0	126	40	Tr.	---	0	0	*232	121	---	5.4	1.2
Do	---	---	---	---	---	---	---	---	108	---	---	---
Do	4.9	164	54	1.2	---	0	0	310	105	6.0	1.0	.08
Do	---	151	49	1.5	---	0	0	286	108	---	1.7	---
Do	1.1	160	51	.9	---	0	0	284	108	6.0	2.2	---
Do	1.0	163	50	.7	---	0	0	280	115	6.0	2.0	---
Do	---	167	50	.7	---	0	0	270	107	---	---	---
Do	---	---	50	---	1.5	---	---	---	---	---	---	---
Emerald Spring (YF47)	.5	352	65	5.0	---	0	0	---	---	4.4	12.4	---
Do	---	360	68	5.2	---	0	0	85	618	---	9.7	---
Do	---	---	57	---	---	---	---	---	---	---	---	---

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park—Continued

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Norris Geyser Basin—Continued										
Green Dragon Spring (YF19)	White and others, 1963	Aug. 1954	87	----	2.47	----	369	1.5	.8	6.5
Do	D. E. White, unpub. data	Sept. 1957	-----	-----	3.0	-----	-----	-----	-----	5.2
Do	do	Sept. 1960	-----	-----	2.86	-----	-----	-----	-----	-----
Do	This study ¹	do	71	2.9	2.9	425	441	3.1	.4	4.3
Do	This study	Sept. 1961	85	-----	2.9	390	392	3.0	.6	4.8
Do	do	Sept. 1962	90	-----	2.87	-----	426	2.9	-----	-----
Do	This study	Sept. 1961	91	-----	3.2	406	420	2.1	1.0	2.5
Little Whirligig Geyser (YF37)	do	do	92	-----	6.1	432	444	.16	<.1	6.5
Minute Geyser (YF63)	do	May 1965	92	5.40	5.38	-----	404	-----	-----	-----
Opal Spring ⁴ (YF27)	Allen and Day, 1935	ca. 1930	-----	-----	3.08	500±30	717	0	Tr.	6
Do	White and others, 1956	Sept. 1947	Bolling	-----	7.63	-----	-----	-----	-----	1.1
Do	do	Aug. 1954	94	-----	-----	-----	-----	-----	-----	3.2
Do	D. E. White, unpub. data	Sept. 1957	93	-----	8.5	-----	-----	-----	-----	-----
Do	do	Sept. 1960	-----	-----	2.42	-----	-----	-----	-----	-----
Do	This study ¹	do	91	2.5	2.3	179	189	1.7	.5	0
Do	This study	Sept. 1961	87	-----	1.9	168	168	6.1	.7	.7
Do	do	do	77	-----	7.0	351	359	.1	<.1	7.2
Palpitator Geyser (YF66)	do	May 1965	80	6.70	6.85	-----	-----	-----	-----	-----
Pearl Geyser (YF64)	Gooch and Whitfield, 1883	Aug. 1884	84	-----	-----	-----	464	3.1	Tr.	5.4
Do	This study	Sept. 1961	82	-----	5.5	426	440	<.1	<.1	6.8
Do	do	May 1965	82	7.35	6.60	468	-----	-----	-----	-----
Perpetual Spouter (YF52)	do	Sept. 1961	93	-----	8.25	283	291	.1	<.1	7.7
Do	do	Sept. 1962	92.5	-----	8.54	-----	-----	.18	-----	-----
Do	do	May 1965	92	7.63	8.18	-----	291	-----	-----	-----
Pinwheel Geyser (YF29)	White and others, 1956	Sept. 1947	-----	-----	3.01	420±30	-----	-----	-----	-----
Do	This study ¹	Sept. 1960	95	2.75	2.90	456	460	1.8	1.1	-----
Do	This study	Sept. 1961	84	-----	3.1	444	444	1.9	1.1	2.1
Primrose Spring (YF41)	do	do	92	-----	3.15	400	410	1.6	1.7	2.7
Do	do	Sept. 1962	92	-----	3.45	414	416	1.0	1.0	2.7
Do	do	May 1965	93	3.25	3.45	-----	416	-----	-----	-----
Steamboat Geyser (YF22)	D. E. White, unpub. data	Sept. 1947	Bolling	-----	5.4	-----	-----	-----	-----	-----
Do	do	Sept. 1957	-----	-----	7.3	-----	-----	-----	-----	2.0
Do	do	Sept. 1960	-----	-----	7.2	-----	-----	-----	-----	-----
Do	This study	do	-----	7.0	7.7	550	570	<.1	<.1	-----
Do	do	Sept. 1962	-----	-----	7.87	-----	556	-----	<.1	2.4
Opalescent Pool (YF20)	This study	Sept. 1960	40	7.8	7.7	358	492	.1	.2	-----
Unnamed Spring (YF21)	D. E. White, unpub. data	Sept. 1947	90.5	-----	6.47	450±30	-----	-----	-----	-----
Do	White and others, 1963	Aug. 1961	84.5	-----	8.0	-----	529	-----	-----	5.8
Do	D. E. White, unpub. data	Sept. 1957	83	-----	7.8	-----	-----	-----	-----	7.3

Locality	Mg	Na	K	Li	NH ₄	HCO ₃	CO ₂	SO ₄	Cl	F	B	Az
Norris Geyser Basin—Continued												
Green Dragon Spring (YF19)	0	243	61	3.2	3.4	0	0	454	408	---	6.9	---
Do	1.0	---	---	---	---	0	0	---	550	---	---	---
Do	---	325	52	4.3	---	0	0	189	522	---	7.3	---
Do	.7	315	55	4.4	---	0	0	149	500	4.5	8.0	---
Do	.5	289	54	3.5	---	0	0	164	457	4.3	8.0	---
Do	0.5	285	55	3.5	---	0	0	185	456	---	---	---
Do	0.5	349	53	5.3	---	0	0	113	607	3.3	9.2	---
Little Whirligig Geyser (YF37)	---	---	---	---	---	---	---	---	---	---	---	---
Minute Geyser (YF63)	.4	352	44	4.9	---	0	0	53	623	5.4	9.4	---
Do	---	42	---	---	---	---	---	---	---	---	---	---
Opal Spring ⁴ (YF27)	Tr.	437	107	---	3	56	0	41	742	---	9.0	---
Do	---	---	---	---	---	---	---	---	748	---	---	---
Do	0	400	92	5.8	---	47	0	25	708	---	11	---
Do	1.0	---	---	---	---	30	7.9	---	740	---	---	---
Do	---	10	5.2	.1	---	---	---	---	6.0	---	.4	---
Do	1.1	9	4.2	.2	---	0	0	325	8.0	2.4	.4	6.43
Do	<.1	4.5	2.2	.05	---	0	0	760	5	4	.6	---
Do	.4	334	40	4.2	---	31	0	59	563	6.2	8.6	---
Do	---	34	---	---	---	---	---	---	---	---	---	---
Pearl Geyser (YF 64)	.9	404	54	2.2	---	10.5	---	272	652	---	8.5	2.9
Do	.4	400	54	5.8	.21	---	---	113	702	6.8	10.6	---
Do	---	---	54	---	---	---	---	---	---	---	---	---
Perpetual Spouter (YF52)	.7	349	46	5.3	---	---	---	69	599	6.7	13.8	---
Do	---	350	---	---	---	28	0	---	536	---	---	---
Do	---	46	---	---	---	---	---	---	---	---	---	---
Pinwheel Geyser (YF29)	---	---	---	---	---	---	---	---	---	---	---	---
Do	<.1	356	91	5.0	---	0	0	55	600	---	10.0	2.5
Do	---	352	86	5.1	---	0	0	---	603	---	---	---
Do	.5	286	74	3.9	---	0	0	---	122	2.6	8.4	---
Primrose Spring (YF41)	.8	283	53	3.9	---	0	0	93	469	2.6	7.8	---
Do	---	---	53	---	---	---	---	---	436	2.7	7.8	---
Steamboat Geyser (YF22)	---	---	---	---	---	---	---	---	---	---	---	---
Do	.7	431	80	5.5	---	24	0	100	395	---	---	---
Do	---	373	54	4.6	---	---	---	---	700	---	12	---
Do	---	352	65	4.6	---	---	---	---	566	---	9.5	---
Do	<.1	352	65	4.6	---	---	---	---	584	---	9.4	---
Do	---	377	60	5.2	---	---	---	75	601	15	---	---
Opalescent Pool (YF20)	.3	467	77	6.6	---	---	---	---	---	---	13.4	---
Unnamed Spring (YF21)	---	---	---	---	---	---	---	---	752	---	---	---
Do	.2	439	74	8.4	.1	27	0	33	744	4.9	12	2.1
Do	1.27	---	---	---	---	23	---	---	780	---	---	---

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park—Continued

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Norris Geyser Basin—Continued										
Unnamed Spring (YF21)	D. E. White, unpub. data	Sept. 1960	72	---	7.5	---	---	---	---	---
Do	This study ¹	Sept. 1961	71	7.10	7.45	428	435	<1	<1	6.4
Do	This study	Sept. 1962	72	---	7.45	420	430	<1	<1	10.4
Do	do	Sept. 1962	68	---	7.68	432	450	.2	---	8.6
Unnamed Spring (YF24)	D. E. White, unpub. data	Aug. 1954	70	---	2.20	---	259	---	---	2.6
Do	do	Sept. 1957	64.5	---	2.40	---	184	---	---	2.4
Do	do	Sept. 1960	54	---	2.29	---	---	---	---	---
Do	This study ¹	do	54	2.20	2.29	204	205	20	1.3	2.4
Do	This study	Sept. 1961	91	7.20	7.65	573	608	<1	<1	<1
Do	do	do	92	---	6.4	400	434	<1	<1	2.8
Unnamed Spring (YF40)	do	do	89	---	3.25	343	371	7.0	.7	2.8
Unnamed Spring (YF42)	do	do	89	---	3.65	474	494	1.2	.9	1.8
Unnamed Spring (YF43)	do	do	89	---	3.2	409	430	1.4	1.4	2.5
Unnamed Spring (YF44)	This study	Sept. 1961	90	---	5.45	426	444	0.1	<1	2.4
Do	do	May 1965	89	5.95	6.25	489	490	---	---	---
Do	do	Sept. 1961	78	---	5.75	494	496	.08	<1	2.5
Do	do	Sept. 1962	82.5	---	5.35	670	670	.2	---	1.8
Do	do	May 1965	86	5.65	6.4	491	---	---	---	---
Do	do	Sept. 1961	53	---	2.8	229	234	7.7	2.1	7.4
Do	do	do	88	---	3.0	276	311	2.7	1.4	3.4
Do	do	do	75	---	3.05	267	267	3.0	1.3	2.6
Do	do	do	92	---	3.6	350	347	3.2	1.0	3.7
Do	do	do	87	---	4.0	381	389	.6	1.1	2.6
Do	do	Sept. 1962	92	---	7.27	---	448	.2	<1	3.2
Do	do	May 1965	92	6.80	7.15	---	456	---	---	---
Do	do	Sept. 1961	92	---	2.0	290	290	25.9	1.6	.2
Do	do	Sept. 1962	92	---	2.17	---	207	12.0	1.1	.3
Do	do	Sept. 1961	79	---	5.4	484	504	.21	<1	3.0
Do	do	Sept. 1962	94	---	8.04	636	692	.17	<1	3.1
Do	do	May 1965	91	7.20	7.82	---	538	---	---	---
Do	do	Sept. 1961	82	---	2.6	332	338	6.0	1.6	3.1
Do	do	Sept. 1962	85	---	3.21	374	383	3.8	.5	2.4
Do	do	Sept. 1961	91	---	7.4	550	560	<1	<1	2.9
Do	do	Sept. 1962	85.5	---	3.45	496	496	2.2	.5	2.5
Do	do	Oct. 1962	85.5	---	---	---	432	1.7	.4	2.5
Do	do	May 1963	93	3.50	3.35	---	450	---	---	---
Do	do	Sept. 1961	82	---	2.7	315	323	2.3	.3	2.5
Do	do	do	69	---	2.3	262	258	4.9	1.1	2.5

Locality	Mg	Na	K	Li	NH ₄	HCO ₃	CO ₂	SO ₄	Cl	F	B	As
Norris Geyser Basin—Continued												
Unnamed Spring (YF21)	---	516	56	7.0	---	---	---	883	---	---	11	---
Do	.5	526	66	7.4	---	18	0	33	860	---	15.0	---
Do	.7	512	56	6.5	---	25	0	76	826	7.5	12.4	---
Do	---	502	56	6.5	---	---	0	26	780	7.0	---	---
Do	1.0	27	24	<1	---	0	0	482	6.0	---	1.5	---
Do	0	10	12	<1	---	0	0	471	7.0	---	.6	---
Do	---	15	15	.06	---	0	0	548	7.0	---	.66	---
Do	<1	15	13	<1	---	0	0	504	7.0	---	.8	0.2
Do	<1	400	91	6.2	---	34	0	24	700	6.0	11.2	3.0
Do	<1	308	66	5.3	---	11	0	95	543	4.5	8.2	---
Do	.5	304	79	4.6	---	0	0	183	504	3.0	4.5	---
Do	.7	329	87	5.1	---	0	0	86	536	3.5	4.9	---
Do	.9	282	77	4.1	---	0	0	121	485	2.8	4.5	---
Do	0.3	356	40	5.1	---	8	0	51	627	5.2	12.8	---
Do	---	---	41	---	---	---	---	---	---	---	---	---
Do	.3	404	50	5.6	---	20	0	195	687	5.7	13.8	---
Do	---	375	43	5.2	---	---	---	35	620	5.6	10.4	---
Do	---	---	40	---	---	---	---	---	---	---	---	---
Do	1.0	297	63	3.6	---	0	0	230	471	2	9.8	---
Do	.7	282	60	3.4	---	0	0	155	438	2.4	9.2	---
Do	.5	260	42	2.7	---	0	0	140	411	1.6	9.0	---
Do	.5	229	23	2.9	---	0	0	36	438	3.6	7.2	---
Do	.4	390	31	3.9	---	0	0	60	642	4.3	11.6	---
Do	---	397	31	4.2	---	18	0	29	626	5.6	10.6	---
Do	---	---	32	---	---	---	---	---	---	---	---	---
Do	.8	15	18	0.4	---	0	0	925	224	6	.6	---
Do	---	4.8	8.2	0.1	---	0	0	560	6	1.1	.3	---
Do	.2	378	85	6.2	---	6	0	172	637	5	10.0	---
Do	---	420	73	6.3	---	29.5	0	41	668	5	10.8	---
Do	---	---	90	---	---	---	---	---	---	---	---	---
Do	.2	356	87	6.3	---	0	0	288	721	2.5	10.0	---
Do	---	455	81	6.5	---	0	0	150	732	5	12.0	---
Do	<1	390	87	6.0	---	28	0	58	593	5.4	11.0	---
Do	---	385	85	5.8	---	0	0	105	640	4.6	10.2	---
Do	---	372	76	6.2	---	---	---	84	650	4.0	---	---
Do	---	---	83	---	---	---	---	---	---	---	---	---
Do	.3	267	39	3.8	---	0	0	137	458	2.4	7.0	---
Do	1.3	141	21	1.3	---	0	0	353	170	1.0	3.0	---

See footnotes at end of table.

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park—Continued

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Between Norris and Lower Geyser Basins										
Chocolate Pots (YF136)	Allen and Day, 1935	ca. 1930	54	----	----	----	98	0	6	25
Do	This study	Oct. 1962	53	----	----	----	106	.2	<1	10.7
Unnamed Spring (YF137)	do	do	53	----	----	----	162	4.0	2.2	8.3
Beryl Spring (YF31)	Allen and Day, 1935	July 1928	91	----	----	----	----	----	----	----
Do	D. E. White, unpub. data.	Sept. 1960	93	----	6.8	----	----	----	----	----
Do	This study ¹	do	91	6.4	6.8	269	268	<1	<1	1.6
Do	This study	Sept. 1961	92	----	6.8	262	266	<1	<1	4.6
Do	do	Sept. 1962	92	----	7.01	269	----	.6	----	5.1
Do	do	May 1965	93	6.65	7.25	----	270	----	----	----
Lower Geyser Basin										
Black Warrior Lake	Scott, 1964	Sept. 1959	65	----	----	----	175	0	0	18
Black Warrior Lake (vent)	D. E. White, unpub. data.	Sept. 1960	93	----	7.3	----	199	----	----	14
Black Warrior Lake (Steady Geyser) (YF30)	This study ¹	do	92	6.9	8.1	209	211	<1	<1	11
Do	This study	Sept. 1961	94	----	7.0	196	198	<1	<1	12.1
Do	do	Sept. 1962	93	----	7.62	----	204	.17	.1	12.3
Clepsydra Geyser (YF75)	do	Sept. 1961	87	----	8.85	329	338	<1	<1	.3
Do	do	Sept. 1962	87	----	9.23	----	247	.16	----	----
Do	do	May 1965	87	----	8.45	9.10	----	----	----	----
Firehole Pool (YF164)	This study	May 1965	90	7.80	8.40	----	323	----	----	----
Great Fountain Geyser (YF35)	Gooch and Whitfield, 1888	Aug. 1884	93	----	Alk.	----	318	2.1	Tr.	1.7
Do	Allen and Day, 1935	ca. 1930	----	----	----	----	316	1	1	Tr.
Do	This study ¹	Sept. 1960	95	6.25	8.7	324	325	<1	<1	<1
Do	This study	Sept. 1961	95	----	8.6	317	315	<1	<1	.5
Narcissus Geyser (YF34)	D. E. White, unpub. data.	Oct. 1947	----	----	8.95	800±20	----	----	----	----
Do	do	Sept. 1960	----	----	7.4	----	----	----	----	----
Do	This study ¹	do	90	6.45	6.8	331	354	<1	<1	<1
Do	This study	Sept. 1961	92	----	7.9	338	332	<1	<1	.7
Do	do	Sept. 1962	92	----	7.71	----	323	.07	----	1.0
Do	do	May 1965	89	7.25	8.00	----	----	----	----	----
Ojo Caliente Spring (YF156)	Allen and Day, 1935	1929	----	----	----	----	218	0	1	4
Do	White and others, 1956	Sept. 1947	95.7	----	----	----	240±30	----	----	----
Do	This study	May 1965	95	7.40	7.75	----	253	----	----	----
Shelf Spring (YF81)	do	Sept. 1961	95	----	8.65	350	352	<1	<1	.7
Do	do	Sept. 1962	95	----	8.76	400	412	.02	----	----
Do	do	May 1965	95	8.00	8.70	----	350	----	----	----

Locality	Mg	Na	K	Li	NH ₄	HCO ₃	CO ₂	SO ₄	Cl	F	B	As
Between Norris and Lower Geyser Basins—Continued												
Chocolate Pots (YF136)	1	114	31	---	---	353	0	28	29	---	---	---
Do	---	118	21	0.7	---	---	---	30	27	4	0.4	---
Unnamed Spring (YF137)	---	35	11	.4	---	---	---	296	18	<1	.3	---
Beryl Spring (YF31)	---	---	---	---	---	146	0	66	549	---	---	---
Do	---	409	23	8.3	---	---	---	---	543	---	6.2	---
Do	.4	400	22	6.1	---	129	0	43	540	16	7.8	2.3
Do	.3	408	22	6.0	---	---	---	---	---	17	7.2	---
Do	---	410	22	6.9	---	140	0	53	534	---	---	---
Do	---	---	22	---	---	---	---	---	---	---	---	---
Lower Geyser Basin—Continued												
Black Warrior Lake	0	96	12	0.9	0.5	165	0	35	53	11	0.42	0
Black Warrior Lake (vent)	.7	89	13	.46	---	160	---	26	52	---	.65	---
Black Warrior Lake (Steady Geyser) (YF30)	.9	89	13	.5	---	145	0	22	52	10	.8	.01
Do	.7	93	14	.5	---	---	---	---	---	10	.6	---
Do	---	85	14	.5	---	136	0	37	53	10	.5	---
Clepsydra Geyser (YF75)	<1	341	14	2.5	---	178	85	49	346	21	1.05	---
Do	---	325	14	2.3	---	136	106	23	324	---	---	---
Do	---	---	14	---	---	---	---	---	---	---	---	---
Firehole Pool (YF164)	---	---	11.5	---	---	---	---	---	---	---	---	---
Great Fountain Geyser (YF35)	2.3	335	15	2.5	---	*292	---	*22	351	---	3.1	1.5
Do	0	366	14	---	---	182	83	18	343	16	4.0	---
Do	<1	334	14	3.4	---	223	42	19	340	20	4.0	3.5
Do	<1	338	13	3.4	---	---	---	---	---	21	3.6	---
Narcissus Geyser (YF34)	---	---	---	---	---	---	---	---	---	---	---	---
Do	<1	312	16	2.0	---	---	---	---	---	---	---	---
Do	<1	312	20	2.3	---	221	0	14	340	18	2.7	---
Do	<1	297	21	2.1	---	---	---	---	---	20	4.0	2.3
Do	---	310	17	2.3	---	236	0	15	336	---	---	---
Do	---	---	18	---	---	---	---	---	---	---	---	---
Ojo Caliente Spring (YF156)	0	335	12	---	---	208	29	29	324	24	5.1	---
Do	---	---	---	---	---	---	---	---	---	---	---	---
Do	---	---	9.5	---	---	---	---	---	---	---	---	---
Shelf Spring (YF81)	<1	325	16	2.4	---	200	35	65	370	18	4.0	---
Do	---	335	16	2.4	---	170	51	21	347	---	---	---
Do	---	---	17	---	---	---	---	---	---	---	---	---

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park—Continued

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Lower Geyser Basin—Continued										
Surprise Pool (YF83)	This study	Sept. 1961	95	----	8.55	286	292	<.1	.01	.7
Do	do	Sept. 1962	95	----	8.67	---	327	.17	----	----
Do	do	May 1965	95	7.80	8.40	---	294	----	----	----
Midway Geyser Basin										
Excelsior Geyser (YF10)	Gooch and Whitfield, 1888.	Aug. 1884	92	----	----	---	221	1.2	1.8	2.2
Do	Allen and Day, 1935	ca. 1930	91	----	----	---	237	1	1	3
Do	White and others, 1956	Oct. 1947	----	----	8.45	280±30	----	----	----	----
Do	Scott, 1964	Sept. 1959	63	----	8.4	---	255	.2	0	1.6
Do	D. E. White, unpub. data.	Sept. 1960	76	----	8.0	---	----	----	----	----
Do	This study ¹	do	76	8.0	8.35	283	303	<.1	<.1	<.1
Do	This study	Sept. 1961	88	----	7.5	280	282	<.1	<.1	2.5
Upper Geyser Basin										
Artemisia Geyser (YF2)	Gooch and Whitfield, 1888.	Sept. 1884	89	----	Alk.	---	274	7.9	Tr.	1.4
Do	Allen and Day, 1935	ca. 1930	91.5	----	----	---	268	0	0	Tr.
Do	This study ¹	Sept. 1960	89	8.20	8.95	267	275	.2	.2	0
Do	This study	Sept. 1961	90	----	8.8	271	272	<.1	.1	.9
Bonita Pool (YF70)	do	do	92	----	8.7	294	293	<.1	<.1	.3
Do	do	Sept. 1962	92	8.55	9.11	---	296	1.2	<.1	----
Do	do	May 1965	92	8.25	8.95	---	292	----	----	----
Chinaman Spring (YF129)	Allen and Day, 1935	ca. 1930	93.5	----	----	---	---	----	----	----
Do	D. E. White, unpub. data.	Sept. 1960	Boiling	----	7.7	---	1287	----	----	1.2
Do	This study	Sept. 1962	92.5	----	----	---	323	.3	<.1	.9
Do	do	May 1965	94	7.85	7.75	---	327	----	<.1	----
Daisy Geyser (YF5)	Allen and Day, 1935	ca. 1930	88.6	----	----	---	---	----	----	----
Do	White and others, 1956	Oct. 1947	----	----	7.64	280±20	---	----	----	----
Do	This study ¹	Sept. 1960	90.5	7.60	7.80	306	304	<.1	<.1	.8
Ear Spring (YF86)	This study	Sept. 1961	95	----	9.25	390	388	<.1	<.1	.7
Do	do	Sept. 1962	95	----	9.4	---	374	.09	<.1	----
Do	do	May 1965	95	8.35	9.25	---	392	----	----	----
Giantess Geyser (YF7)	Gooch and Whitfield, 1888.	Aug. 1884	----	----	Alk.	---	394	4.9	Tr.	0.7
Do	Allen and Day, 1935	ca. 1930	94	----	----	---	372	0	0	0
Do	This study	Sept. 1960	95	7.95	8.85	384	417	<.1	.1	----
Do	do	Sept. 1962	95	----	9.1	---	397	<.7	<.1	.4
Do	do	Oct. 1962	92	----	----	---	392	----	----	----
Do	do	May 1965	93	8.07	9.00	---	400	----	----	----

Locality	Mg	Na	K	Li	NH ₄	HCO ₃	CO ₂	SO ₄	Cl	F	B	As
Lower Geyser Basin—Continued												
Surprise Pool (YF83)	.2	334	14	3.8	----	310	26	55	301	25	3.4	----
Do	----	335	14	3.5	----	282	39	17	296	----	----	----
Do	----	----	13	----	----	----	----	----	----	----	----	----
Midway Geyser Basin—Continued												
Excelsior Geyser (YF10)	2.2	419	33	2.0	0.01	*530	----	*18	279	----	5.0	2.0
Do	0	410	14	----	----	562	0	21	271	20	2.5	----
Do	----	----	----	----	----	----	----	----	278	----	----	----
Do	.6	408	12	2.6	----	527	20	21	278	18	2.5	2.0
Do	----	400	12	2.2	----	----	----	----	280	----	2.8	----
Do	.1	385	15	2.8	----	546	0	34	270	24	3.4	2.8
Do	.2	382	14	2.7	----	----	----	----	----	24	3.0	----
Upper Geyser Basin—Continued												
Artemisia Geyser (YF2)	0	398	16	7.0	0.21	*361	----	*15	300	----	5.5	1.1
Do	----	422	16	----	----	411	75	18	289	----	3.1	----
Do	<.1	385	17	4.0	----	425	58	27	290	22	3.0	1.4
Do	<.1	390	16	3.8	----	----	----	----	----	26	3.2	----
Bonita Pool (YF70)	.2	441	19	4.3	----	452	83	19	240	30	3.2	----
Do	----	440	15	3.9	----	452	76	17	305	----	----	----
Do	----	----	19	----	----	----	----	----	----	----	----	----
Chinaman Spring (YF129)	----	----	----	----	----	174	0	49	385	----	----	----
Do	<.1	338	17	4.6	----	165	0	42	375	----	3.3	----
Do	----	325	18	4.9	----	----	----	25	371	23	4.4	----
Do	----	----	17	----	----	----	----	----	----	----	----	----
Daisy Geyser (YF5)	----	----	----	----	----	619	15	----	311	----	----	----
Do	----	----	----	----	----	----	----	8	302	----	----	----
Do	<.1	460	21	4.4	----	621	0	20	310	29	3.2	----
Ear Spring (YF86)	<.1	341	20	5.1	----	59	18	21	446	25	4.8	----
Do	----	347	20	5.6	----	0	47	17	420	----	----	----
Do	----	----	19.5	----	----	----	----	----	----	----	----	----
Giantess Geyser (YF7)	1.2	345	40	5.7	----	*105	----	*16.7	441	----	7.2	0.45
Do	0	362	20	----	----	113	51	23	429	20	4.6	----
Do	.1	349	21	5.8	----	----	----	----	----	----	5.0	----
Do	----	360	20.7	5.8	----	40	68	22	427	29	----	----
Do	----	364	20.7	5.4	----	----	----	22	418	----	----	----
Do	----	----	18.5	----	----	----	----	----	----	----	----	----

See footnotes at end of table.

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park—Continued

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Upper Geyser Basin—Continued										
Hillside Springs (YF6)	Allen and Day, 1935	ca. 1930	---	---	---	---	170	0	0	9
Do	D. E. White, unpub. data.	Aug. 1951	---	---	7.43	---	---	---	---	---
Do	do	Sept. 1960	86	---	6.6	---	175	---	---	5.4
Do	This study	do	86	6.55	7.0	---	190	<1	<1	---
Do	do	Sept. 1961	86	---	6.65	180	180	<1	<1	5.4
Ink Well Spring (YF130)	do	Sept. 1962	91	---	---	---	286	<12	<1	7
Iron Spring (YF3)	Allen and Day, 1935	ca. 1930	90.8	---	---	---	365	0	Tr.	2.2
Do	This study	Sept. 1960	95	3.65	3.45	455	456	0.6	1.2	1.5
Old Faithful Geyser (YF33)	Gooch and Whitfield, 1933.	Sept. 1884	84-83	---	Alk.	---	283	0	Tr.	4
Do	Allen and Day, 1935	ca. 1930	---	---	8.97	---	357	0	Tr.	7
Do	This study	Sept. 1960	90	---	9.3	356	381	<1	<1	---
Do	This study	Sept. 1961	85	---	9.15	374	390	<1	1	---
Do	Noguchi and Nix, 1963	1962	---	---	---	---	384-396	---	---	---
Punch Bowl Spring (YF144)	Allen and Day, 1935	ca. 1930	92.5	---	---	---	328	0	0	0
Do	This study	Sept. 1962	95	---	7.94	---	340	.03	<1	.4
Do	do	May 1965	95	7.45	8.05	---	348	---	---	---
Riverside Geyser (YF8)	Allen and Day, 1935	ca. 1930	92.5	---	---	---	242	0	0	0
Do	White and others, 1956	Oct. 1947	---	---	9.02	---	240±20	---	---	---
Do	This study	Sept. 1960	95	8.6	8.9	226	268	<1	<1	.1
Do	This study	Sept. 1961	93	---	8.7	256	248	<1	<1	.5
Do	do	May 1965	95	8.15	8.8	---	---	---	---	---
Sapphire Geyser (YF9)	Allen and Day, 1935	ca. 1930	94.5	---	8.69	---	321	0	Tr.	4
Do	White and others, 1956	Oct. 1947	95	---	9.15	---	320±20	---	---	---
Do	Scott, 1964	Sept. 1959	---	---	9.2	---	2447	.3	.3	1.6
Do	D. E. White, unpub. data.	Sept. 1960	---	---	9.1	---	---	---	---	---
Do	This study	do	92	8.3	9.2	348	352	<1	<1	---
Do	This study	Sept. 1961	90	---	9.0	326	355	<1	<1	.5
Do	do	Sept. 1962	94	---	9.0	---	322	.8	<1	.3
Do	do	May 1965	94	8.1	8.7	---	331	---	---	---
Sentinel Geyser (YF103)	Allen and Day, 1935	ca. 1930	93.5	---	---	---	---	---	---	---
Do	This study	Sept. 1962	94	---	9.02	---	262	.8	<1	.3
Solitary Geyser (YF99)	Allen and Day, 1935	ca. 1930	92.5	---	---	---	365	0	0	4
Do	Noguchi and Nix, 1963	1962	---	---	---	---	374-392	---	---	---
Do	This study	Sept. 1962	91	---	9.21	---	364	.9	<1	.3
Spouter Geyser (YF90)	Allen and Day, 1935	ca. 1930	92.5	---	---	---	---	---	---	---
Do	This study	Sept. 1961	92	8.5	8.8	313	308	<1	<1	.7
Do	do	Sept. 1962	92	---	9.0	---	309	.61	<1	---
Tortoise Shell Spring (YF102)	Allen and Day, 1935	ca. 1930	94.5	---	---	---	329	---	---	0
Do	Scott, 1964	Sept. 1959	95	---	9.2	---	2597	0.1	0	1.6
Do	D. E. White, unpub. data.	Sept. 1960	---	---	9.3	---	---	---	---	---
Do	This study	Sept. 1962	93.5	---	9.45	---	340	.9	<1	.5

Locality	Mg	Na	K	Li	NH ₄	HCO ₃	CO ₂	SO ₄	Cl	F	B	As
Upper Geyser Basin—Continued												
Hillside Springs (YF6) -----	0	124	10	-----	-----	249	0	12	55	-----	1.6	-----
Do -----	-----	-----	-----	-----	-----	-----	-----	-----	66	-----	-----	-----
Do -----	0	133	8.9	.7	-----	246	0	14	71	-----	1.0	-----
Do -----	.7	145	8.3	-----	-----	-----	-----	12	-----	-----	1.2	-----
Do -----	-----	123	7	-----	-----	252	0	17	72	10	1.2	-----
Ink Well Spring (YF130) -----	Tr.	375	30	3.7	-----	0	0	15	262	25	3.1	-----
Iron Spring (YF3) -----	1.4	77	23	-----	-----	0	0	231	1	1.2	2.2	-----
Do -----	-----	122	46	.3	-----	0	0	220	6	2.0	-----	-----
Old Faithful Geyser (YF33) -----	.6	367	27	5.6	0.01	124	-----	18	439	0	4.6	1.6
Do -----	-----	372	31	-----	-----	0	100	21	435	22	5.6	-----
Do -----	<1	349	21	5.7	-----	-----	-----	-----	-----	-----	5.0	-----
Do -----	<1	326	22	5.3	-----	-----	-----	45	434	23	5.0	-----
Do -----	-----	-----	-----	-----	-----	-----	-----	18.6-21	451-466	-----	-----	-----
Punch Bowl Spring (YF144) -----	0	450	20	-----	-----	897	10	19	297	20	5.9	-----
Do -----	-----	425	19.5	8.6	-----	568	0	18	294	34	3.3	-----
Do -----	-----	20	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Riverside Geyser (YF8) -----	-----	372	19	-----	-----	329	54	16	296	-----	3.1	-----
Do -----	-----	-----	-----	-----	-----	-----	-----	-----	288	-----	-----	-----
Do -----	<1	338	17	3.5	-----	334	41	12	300	24	3.2	-----
Do -----	<1	341	16	3.6	-----	-----	-----	-----	-----	25	3.2	-----
Do -----	-----	18	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Sapphire Geyser (YF9) -----	Tr.	453	17	-----	-----	465	66	15	307	21.5	2.7	-----
Do -----	-----	-----	-----	-----	-----	-----	-----	-----	308	-----	-----	-----
Do -----	0	420	18	2.2	-----	332	99	22	309	13	2.6	2.5
Do -----	-----	429	16	1.8	-----	-----	-----	-----	305	-----	2.9	-----
Do -----	<1	423	19	2.1	-----	-----	-----	14	2707	-----	3.4	-----
Do -----	<1	412	20	2.1	-----	866	103	55	308	28	3.4	-----
Do -----	-----	445	20	2.3	-----	406	82	14	296	32	-----	-----
Do -----	-----	18	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Sentinel Geyser (YF103) -----	-----	-----	-----	-----	-----	303	90	12	240	-----	-----	-----
Do -----	-----	355	17	3.3	-----	328	69	18	242	26	2.6	-----
Solitary Geyser (YF99) -----	0	317	23	-----	-----	58	47	21	377	21.5	-----	-----
Do -----	-----	-----	-----	-----	-----	-----	-----	27-28.9	401-416	-----	-----	-----
Do -----	-----	320	24	4.4	-----	0	76	23	373	32	4.5	-----
Spouter Geyser (YF90) -----	.5	415	15	-----	-----	463	87	29	313	-----	-----	-----
Do -----	-----	416	15	3.5	-----	462	81	43	326	27	3.6	-----
Do -----	-----	425	20	3.3	-----	454	74	18	312	35	-----	-----
Tortoise Shell Spring (YF102) -----	0	420	23	-----	-----	282	76	18	351	-----	4.7	-----
Do -----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Do -----	0	403	19	4.8	-----	174	102	27	352	18	2.2	2.5
Do -----	-----	396	17	4.4	-----	-----	-----	-----	365	-----	6.1	-----
Do -----	-----	405	22	5.0	-----	157	60	20	378	32	4.4	-----

Table extracted from: Rowe et al, 1973.

—Chemical composition, in parts per million, of thermal waters, Yellowstone National Park—Continued

Locality	References	Date of Collection	Temperature (°C)	pH		SiO ₂		Al	Fe	Ca
				Field	Laboratory	Field	Laboratory			
Upper Geyser Basin—Continued										
Turban Geyser (YF36)	Gooch and Whitfield, 1888	Sept. 1884	91	---	Alk.	---	304	3.2	Tr.	2.8
Do	This study ¹	Sept. 1960	89	8.15	8.50	315	318	<1	<1	<1
Do	do	Sept. 1961	91	---	9.0	322	---	<1	<1	.3
Do	do	Sept. 1962	92	---	9.45	---	318	.8	<1	---
Do	do	May 1965	92	8.72	9.25	---	---	---	---	---
Unnamed Spring (YF1)	D. E. White, unpub. data.	Oct. 1947	85	---	4.39	---	200±20	---	---	---
Do	do	Sept. 1960	71	---	4.40	---	---	---	---	---
Do	This study ¹	do	71	4.6	4.3	270	278	.2	.2	<1
Do	do	Sept. 1961	71	---	3.7	268	266	.1	.2	.5
Do	do	Sept. 1962	70	---	4.5	---	262	.2	.2	---
Do	do	do	94	---	9.6	---	363	.2	.06	.8
Unnamed Spring (YF4)	White and others, 1963	Oct. 1957	94	---	9.6	---	---	---	---	---
Do	D. E. White, unpub. data.	Sept. 1960	92.5	---	9.6	---	---	<1	<1	.1
Do	This study ¹	do	92.5	8.75	9.7	361	374	<1	<1	.5
Do	do	Sept. 1961	91	---	9.4	367	370	<1	<1	---
Do	do	Sept. 1962	92	---	9.78	---	358	1.2	.4	---
Do	do	May 1965	92	8.65	9.60	---	368	---	---	<1
Do	This study ¹	Sept. 1960	78	---	8.9	313	318	<1	<1	.8
Do	do	Oct. 1962	94	---	---	---	320	1.0	<1	.8
Do	do	Sept. 1962	82	---	---	---	256	.07	<1	2.1
Smoke Jumper Hot Springs										
Unnamed Spring (YF14)	This study ¹	Sept. 1960	91	---	6.9	246	256	<1	<0.1	<0.1
Unnamed Spring (YF15)	do	do	82	---	6.3	254	264	<1	<1	---
Unnamed Pool (YF16)	do	do	92	---	2.3	262	300	.38	5.2	---
West Thumb Pools										
Abyss Pool (YF11)	Scott, 1964	Sept. 1959	81	---	8.2	---	1977	0.2	0	1.6
Do	D. E. White, unpub. data.	Sept. 1960	92	---	8.4	---	---	---	---	---
Do	This study	do	91	7.58	8.5	282	297	<1	<1	---
Do	do	Sept. 1961	91	---	8.45	286	289	<1	<1	.7
Do	do	Sept. 1962	92	---	8.49	---	290	.9	---	.53
Occasional Geyser (YF12)	This study ¹	Sept. 1960	94	7.80	8.6	262	283	<1	<1	<1
Do	do	Sept. 1961	95	---	8.4	266	266	<1	<1	1.2
Do	do	Sept. 1962	92	---	8.85	---	262	.6	---	1.1
Potts Hot Spring Basin										
Unnamed Spring (YF79)	This study	Sept. 1961	89	---	9.1	310	303	<0.1	<0.1	0.5
Do	do	Sept. 1962	92	---	7.32	---	305	.7	<1	---
Unnamed Spring (YF106)	do	do	92	---	8.13	---	143	.6	<1	.6
Upper Geyser Basin—Continued										
Turban Geyser (YF36)	0	382	16.7	3.6	---	270	25	377	7.6	.8
Do	<1	371	18	4.7	---	185	83	25	28	1.7
Do	<1	371	19	4.7	---	---	---	---	27	4.0
Do	<1	364	18	4.4	---	145	54	20	366	---
Do	---	---	18	---	---	---	---	---	---	---
Unnamed Spring (YF1)	---	---	---	---	---	---	---	4	---	---
Do	<1	37	19	.18	---	0	0	122	1.2	.05
Do	<1	42	20	.3	---	0	0	121	2	.06
Do	<1	40	20	.2	---	---	---	---	---	.02
Do	---	37	18	.16	---	---	---	116	---	---
Do	0	352	24	5.2	---	0	70	23	405	4.4
Do	<1	355	20	4.5	---	---	---	---	406	4.4
Do	<1	356	26	5.0	---	---	---	21	400	4.6
Do	<1	341	23	5.1	---	---	---	---	24	4.2
Do	<1	334	23	4.8	---	0	60	21	400	---
Do	---	---	22.5	---	---	---	---	---	---	---
Do	<1	297	16	4.9	---	50	49	17	370	4.2
Do	<1	415	20	3.0	---	---	---	15	301	3.6
Do	<1	370	20	2.7	---	168	0	85	430	5.5
Smoke Jumper Hot Springs—Continued										
Unnamed Spring (YF14)	0.2	33	14	<0.1	---	34	0	48	0	0.32
Unnamed Spring (YF15)	<1	40	15	<1	---	---	---	---	---	.38
Unnamed Pool (YF16)	1.2	10	7.5	<1	---	---	---	---	---	4.4
West Thumb Pools—Continued										
Abyss Pool (YF11)	0	444	20	3.4	---	598	0	55	298	19
Do	<1	423	17	3.1	---	---	---	---	298	3.0
Do	<1	423	21	3.5	---	---	---	---	---	3.3
Do	<1	427	17	3.3	---	---	---	---	---	4.0
Do	<1	420	21	3.5	---	518	35	52	298	26
Occasional Geyser (YF12)	<1	337	17	2.4	---	415	18	27	230	22
Do	<1	352	15	2.4	---	406	28	85	254	23
Do	---	335	16	2.4	---	338	89	42	235	---
Potts Hot Spring Basin—Continued										
Unnamed Spring (YF79)	0.2	334	15	3.5	---	220	106	68	258	24
Do	---	385	17	4.0	---	490	0	53	254	---
Unnamed Spring (YF106)	---	367	18	3.4	---	466	0	38	243	25