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AN ESTIMATE OF THE GEOTHERMAL ENERGY RESOURCE IN THE SALTON TROUGH, CALIFORNIA

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Contents

AN ESTIMATE OF THE GEOTHERMAL ENERGY RESOURCE IN THE SALTON TROUGH, CALIFORNIA

Abstract

The geothermal energy resource in the Salton Trough is estimated based on measured geologic parameters, extrapolation of data from geophysical surveys, and current research in energy conversion systems. The total resource is estimated at 2×10^{19} J contained in 15×10^{12} kg of water, the quality of which varies from fresh to over 25% dissolved solids. More than one-half of the resource is in the high-saline deposit at the Salton Sea. It is estimated that 5×10^{8} MW of electric energy equivalent to 5000 MW for 20 yr could be generated. This is a substantial part of the present electric power requirements of Southern California and is the energy equivalent of 1.3 billion barrels of oil.

Introduction

This report estimates the potentially recoverable geothermal energy and the potential electric power generation from development of the U.S. part of the Salton Trough. The Salton Trough is a sediment-filled depression including, northwest to southeast, the Coachella Valley, the Salton Sea, and the Imperial Valley in California, the Mexicali Valley in Mexico, and extending into the Gulf of California. (See Fig. 1, from Ref. 1.)

The estimates developed here are intended as a guide to resource development and to research on production and energy conversion methods. From them, some important observations can be made on operating, production, and environmental considerations, such as, maximum plant size, operating rates, and land use. The results are summarized in Table 1.

This report is based on the best data available through August, 1974. Sources used for the data include exploration developments, well logs, and production results. This report is not detailed enough for major financial and engineering decisions but is adequate to guide further studies. Results are rounded to one or two significant figures as indicated by the basic data. The estimates herein must be used with caution and with recognition of the purposes for which the were made. There is very little hard data. Only 5% of the area of the Trough is believed to be underlain by the Resource (see the following section), and only 5% of this has been explored by the drill. In most of the drilled area, no more than 600 m of reservoir have been penetrated by drilling, and in many cases, only 300 m or so have been tested.

Following a section on definitions, the data for and method of calculating the volume of producible water are presented.

Consideration of estimates of in place enthalpy and electric energy potential led to a calculation of in place enthalpy based on pure water and of electric potential based on the Total Flow system[2] and assumed well conditions. The effect on the estimates of several different assumptions of enthalpy and electric generating systems is shown.

The final sections summarize ecomonic and operating consequences of the estimate and some unresolved technical issues that bear on the estimate. The results are summarized and compared to other published estimates.

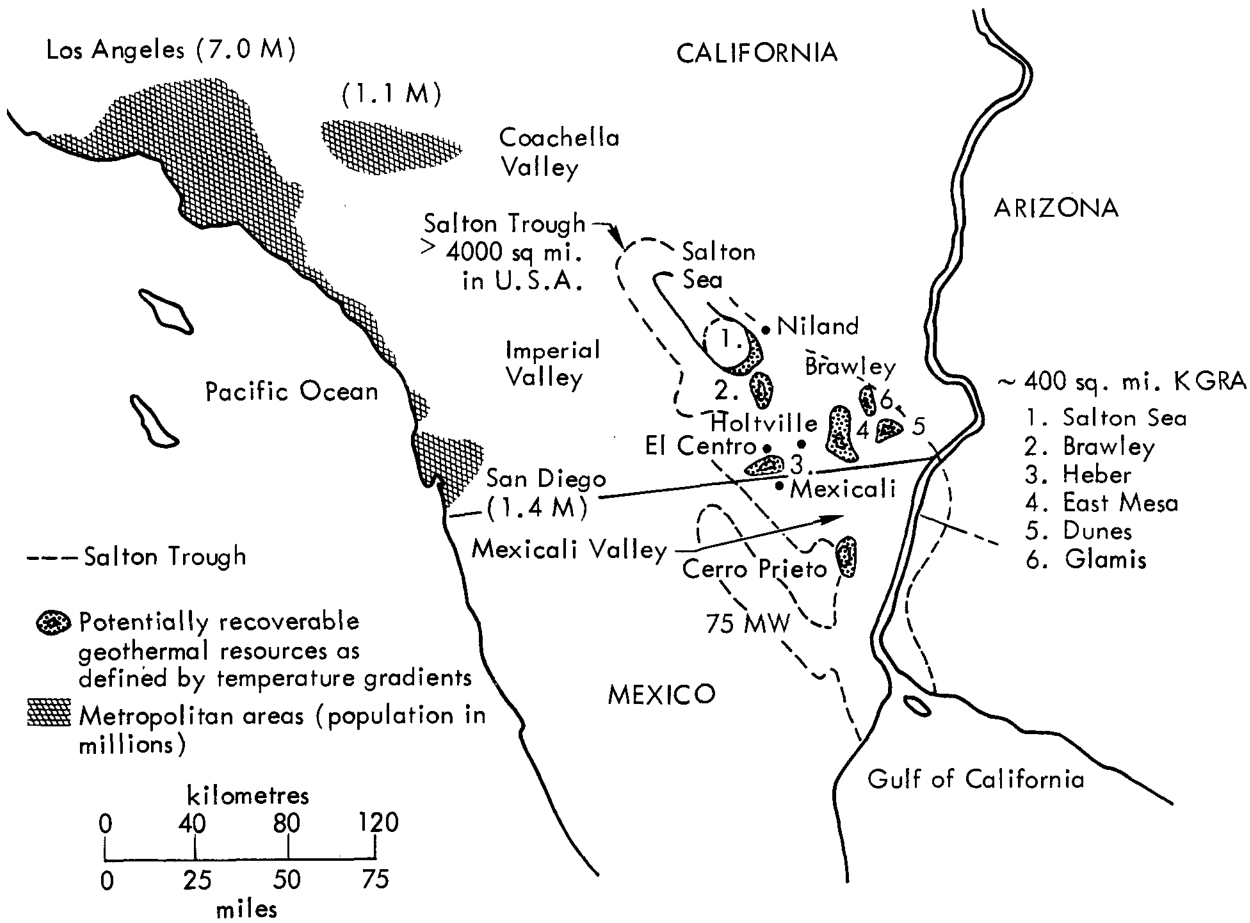

Fig. 1. Location of Salton Trough.[1]

Table 1.

Salton Trough geothermal energy estimate.

Thermal energy in place, 10^{18} J (10^{15} Btu) for:		Brine mass, 10^{12}kg	Expected electric energy production: 10^8 MWh	20-yr equivalent, MW
Salton Trough (U.S. portion)				
Identified	1(1)	0.8	0.42	250
Undiscovered	19(19)	14.2	7.6	4750
Total	20(20)	15	8	5000
Salton Sea KGRA[a]				
Identified	1(1)	0.8	0.42	250
Undiscovered	10(10)	8.2	0.46	2750
Total	11(11)	9	5	3000
Salton Sea Geothermal Field[b]				
Identified	1(1)	0.8	0.42	250
Undiscovered	1(1)	0.5	0.30	150
Total	2(2)	1.3	0.72	400

[a]KGRA: A tract of land designated a "Known Geothermal Resource Area" by the U.S. Department of Interior.

[b]The part of the Salton Sea KGRA designated as a geothermal field by the California Division of Oil and Gas.

Resource Definitions

California law[3] defines geothermal resources as "the natural heat of the earth, the energy in whatever form, below the surface of the earth present in, resulting from, created by, or which may be extracted from, such natural heat, and all minerals in solution or other products obtained from naturally heated fluids, brines, associated gas and steam ---." Only heat contained in naturally occurring fluid that can be brought to the surface through wells is considered in this report. Various temperature and depth limits are considered.

The Resource estimated here is defined as water with a minimum in situ temperature of 230°C (450°F) that is contained in and recoverable from Salton Trough geothermal reservoirs. Reservoirs are porous and permeable rocks at depths less than 2134 m (7000 ft). Their tops are at the 230°C isothermal surface, and the bases are 305 m (1000 ft) deeper, or at 2134 m, whichever is less. Data are from test wells and from Austin et al.,[2] Combs,[4] Dutcher et al.,[5] Griscom and Muffler,[6] Helgeson,[7] and Randall.[8]

U.S. Department of the Interior[9] resource definitions are followed here. Figure 2 shows their breakdown.

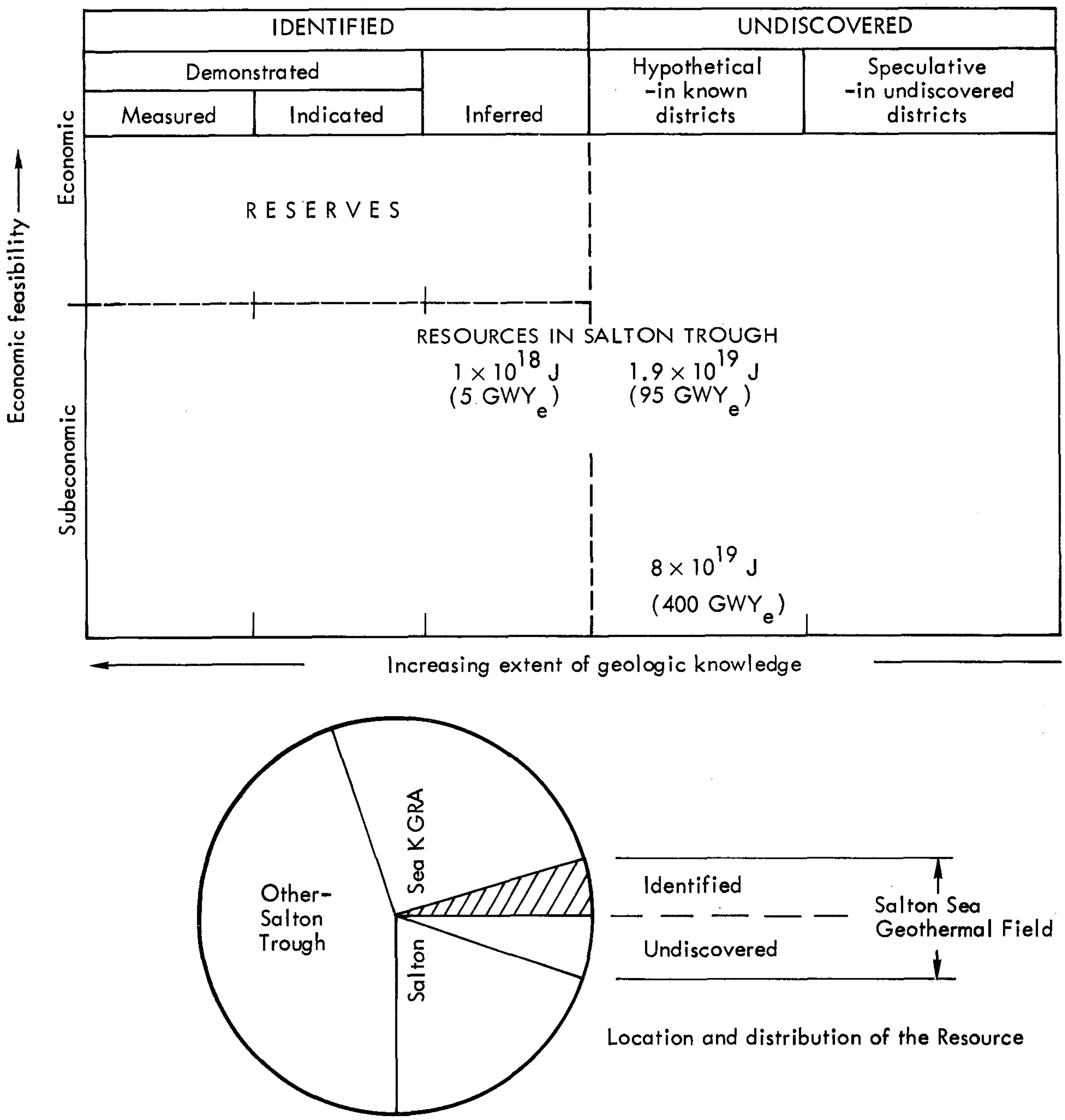

Fig. 2. Classification and distribution of Salton Trough Resources. The expected electric equivalent is given in giga-watt years electric (GWye).

- A Resource is defined as total material in place over a specific geographic area accessible by present technology whether or not it has been tested. Economic extraction is currently or potentially feasible.

- A Reserve is defined as the part of the identified resource (defined below) that can be economically and legally extracted at the time of determination. (In metallic mineral deposits, this is ore.) There are no geothermal energy Reserves in the Salton Trough as of the date of this estimate.

Resources are further defined by the following subcategories (as shown in Fig. 2):

Identified Resources are parts of the Resource whose location, quality, and quantity are known from geologic evidence. Identified material may be divided into Measured, Indicated, and Inferred clases in order of decreasing extent of knowledge of the Resource. A Measured Resource is defined as material for which quality and quantity have been computed from measurements from closely spaced and geologically well-known sample sites, with a margin or error of less than 20%. No Measured Resource is recognized in this report.

Indicated Identified Resource is defined as material for which "the quantity and quality have been computed partly from sample analyses and measurements and partly from reasonable geologic projections."[9]

For the Salton Sea area, the Indicated Identified Resource is shown in Fig. 3. It underlies the S 1/2 sec. 22, sec. 23, W 1/2 sec. 24, sec 27, and sec. 33, T.11S., R.13E. and sec. .4 and N 1/2 sec. 10, T.12S., R.13E.

Inferred Identified Resources are materials "in unexplored but identified deposits for which estimates of the quality and size are based on geologic evidence and projection." The Inferred Resource here lies in five sections that are bounded by areas of drilling north, west, and south and that can reasonably be expected to have similar reservoir characteristics to the area drilled. The Inferred Resource underlies secs. 26, 34, and 35, T.11S., R.13E. and secs. 2 and 3, T.12S., R13E, as shown in Fig. 3.

An Undiscovered Resource is presumed to exist on the basis of broad geologic knowledge and theory.

Identified Subeconomic Resources are not now economically exploitable. The Salton Trough Resources are all now subeconomic, in that some advance in technology is required. Subeconomic Resources may be further divided into paramarginal (bordering on being economically producible) and submarginal (requiring substantially higher price or a major cost-reducing advance in technology).

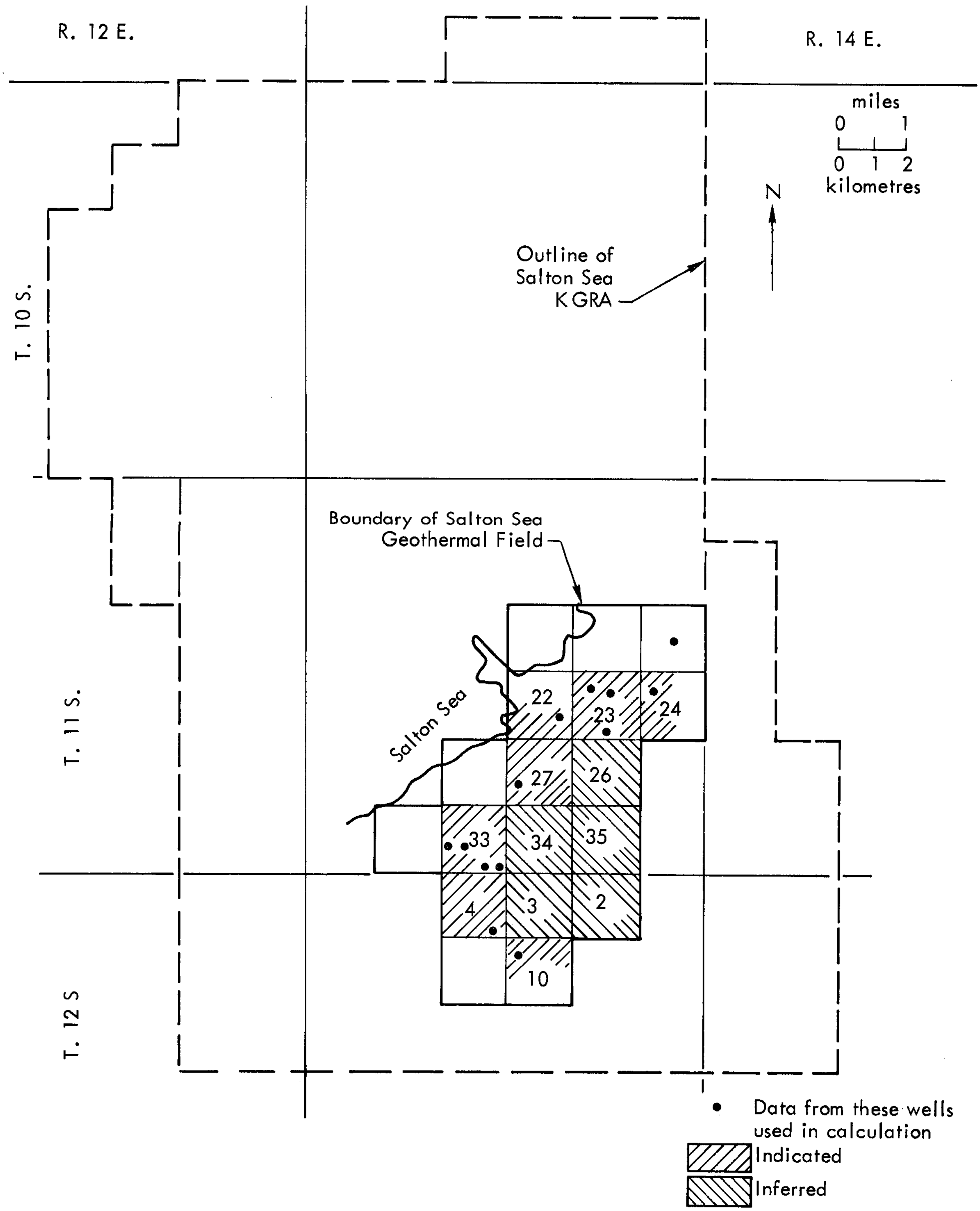

Fig. 3. Location of Identified Resource.

Calculation of the Resource

ESTIMATING THE RESOURCE

Resources are estimated by: (1) calculating the recoverable fluid volume and mass, and (2) calculating the in situ fluid energy by applying a calculated unit enthalpy to the total volume or mass. This is written as:

- Area x thickness of sand x specific yield = volume.
- Volume x density = mass of fluid.
- Mass x specific enthalpy = energy.

Only the fluids in porous sandstones are considered. Although there is some fracture porosity, it is very small, and the bulk of the Resource is believed to be contained in the sandstone pore space. Volumes and masses of geothermal fluid were estimated by:

- Using well data to calculate brine resources in the drilled areas.
- Extrapolating the resource to adjoining undrilled areas.
- Measuring the area of other regions with reportedly high temperature gradients and multiplying by the same area figure used above.
- Projecting in depth.

In this calculation, each geothermal well or group of wells is given an "area of influence" over which the presence of brine can be assured. Enthalpy and electric generating capacity are based on water and a 300°C reservoir temperature. These will vary with salinity and various energy conversion systems as discussed in the appropriate sections.

Thickness of sand is determined as follows. Interpretations of electric logs by Randall[8] of Salton Sea Field wells list per cent of sand for each 152-m (500-ft) interval in the wells considered. Sand is reported to the nearest 10%, i.e., 10 to 20. The figures for the first 305 m (1000 ft) below the 230°C (450°F) isotherm were averaged to find per cent of sand in that interval. Where "30 to 40%" was given, the average was taken as 35%, "50 to 60%" was 55%, etc. (See Table 2.) Most data are in the first 305 m (1000 ft) below the 230°C (450°F) isotherm, and very few wells extend much beyond that depth. To avoid weighting values heavily by the few deeper wells, a uniform 305-m (1000-ft) interval was used.

From Table 2, the thickness of sand = 305 m × 0.59 = 180 m (590 ft). Assume that the sand will produce water but that the shale will not.

Dutcher et al.[5] estimate a specific yield of 0.16 for the Imperial Valley reservoir at this depth and estimate porosity as from 10 to 20%. (Specific yield is the porosity of the rock minus the fraction of water that doesn't drain due to capillary forces.) The 0.16 specific yield figure is used here as a reasonable approximation (equivalent to 20% porosity, with 80% drainage of pore water). Using this value, I calculated the following:

- Volume per km^2 = 180 m × $10^6 m^2$ × 0.16 = 29 × $10^6 m^3$.

Table 2.

Sand per cent, first 305 m below 450°F isotherm.

Well	Location	Depth, m(ft)	Reported sand,%	Average,%
Hudson 1	13-11S-13E	914-1219(3000-4000)	20-30, 30-40	30
IID 2	22-11S-13E	914-1219(3000-4000)	50-60, 70-80	65
IID 1	23-11S-13E	914-1219(3000-4000)	60-70, 80-90	75
Sportsman 1	23-11S-13E	610- 914(2000-3000)	60-70, 40,50	55
State 1	23-11S-13E	610- 914(2000-3000)	50-60, 40-50	50
River Ranch 1	24-11S-13E	914-1219(3000-4000)	70-80, 60-70	70
Elmore 1	27-11S=13E	610- 914(2000-3000)	60-70, 60-70	65
Magmamax 2	33-11S-13E	610- 914(2000-3000)	60-70, 60-70	65
Magmamax 3	33-11S-13E	610- 914(2000-3000)	60-70, 50-60	60
Sinclair 4	4-12S-13E	1006-1311(3300-4300)	50-60, 60-70	60
			Average of above	58.5

- Density is reported[7] as essentially 1.0.
- Mass = $29 \times 10^6 m^3 \times 10^3 kg/m^3 = 2.9 \times 10^{10} kg/km^2$ per 305 m of reservoir (2.6×10^8 lb/surface acre/1000 ft of reservoir).
- Energy per unit area was calculated from the Austin et al.[2] specific enthalpy estimate of $1.3 \times 10^6 J/kg$. (Enthalpy is treated in detail in the following section.) Because of the sand averaging and the poor temperature data, calculations of enthalpy are only approximate.
- Energy (In Place) = $2.9 \times 10^{10} kg/km^2 \times 1.3 \times 10^6 J/kg = 3.8 \times 10^{16} J/km^2$ (9.6×10^{13} Btu/mi^2).

The calculated energy per unit area is in place thermal energy, not the energy that may be converted to electric or other useful forms of energy. To derive the estimated electric figure (in MWh), the in place values were multiplied by an electric conversion factor, as explained under "Expected Electric Capacity."

To summarize, the estimated or assumed values used in the calculations were:

- For volume and mass calculations

Thickness of reservoir zone	305 m (1000 ft)
Net sandstone	180 m (590 ft)
Specific yield	0.16
Specific gravity of the fluid	1.0

- For energy calculations

  Enthalpy of the water: $1.3 \times 10^6 J/kg$ (563 Btu/lb)

- For electric generating capacity

  Water usage per kWh: 19 kg (41 lb) per kWh

The Undiscovered Resource is here calculated by applying the energy/unit area value of the Identified Resource to the other areas in the Imperial Valley that are judged to have geothermal potential from known near-surface temperature gradient measurements.

The implicit assumption is that the undetermined reservoir and brine characteristics will be reasonably similar to those of the areas that have been tested.

Areas were measured from a published temperature gradient map by Combs[4]. In the Salton Sea KGRA, the Identified Resource areas are outlined very closely by the 109°C per km (6°F per 100 ft) isograd. See Fig. 4. A simplistic extrapolation of that gradient places the 230°C surface at about 1930 m (6270 ft) deep. The actual depths are different due to near-surface variations in gradient and due to variations in depth to the reservoir top. In the Salton Sea Field, for instance, 230°C is first reached at depths from 488 to 1494 m.

Table 3 shows the areas enclosed by the 109°C per km isograd.

Much of the Salton Sea Resource area was extrapolated out under the Sea, where there were no temperature gradient

Table 3.

Areas of high temperature gradient

	Area, km^2 (mi^2)
Salton Sea KGRA	307(118)
Heber KGRA	96(37)
East Mesa KGRA	78(30)
Brawley KGRA	26(10)
Glamis KGRA	13(5)
Dunes KGRA	33(5)
Total	533(205)

surveys. This was done by extrapolation from a very few existing gradient data guided by aeromagnetic data, published by Griscom and Muffler,[6] that are believed to show the outline of a rock body that is the source of the geothermal heat.

Although the sediments in the Imperial Valley are very deep, certain facts must set an absolute limit to the depth at which brines (except for capillary-held water) can be present. These are:

1. Metamorphism, due to brine-rock reaction and heat, at some depth destroys effective porosity. This will be shallow in high-heat areas.

2. Magnetic surveys in part of the Salton Sea area[6] indicate an igneous rock body at depths of 2134 to 3048 m (7000 to 10,000 ft) that is closely related to and presumably the source of heat for the geothermal brines.

If (1) and (2) are true, then only 610 to 1524 m (2000 to 5000 ft) of sandy sediments at depths from approximately 1524 to 2134 m or 1524 to 3048 m are available for the high-temperature brine reservoir. We will assume that the same applies to other Imperial Valley geothermal areas.

The total potential, then, can be no more than some multiple of between two and five times the resource in 305 m of reservoir.

ESTIMATING ENTHALPY OF THE BRINES

According to Helgeson,[7] expansion of the fluid in the well bore is isenthalpic, so estimates of the enthalpy in the reservoir can be used to approximate the well-head enthalpies. Reservoir temperatures

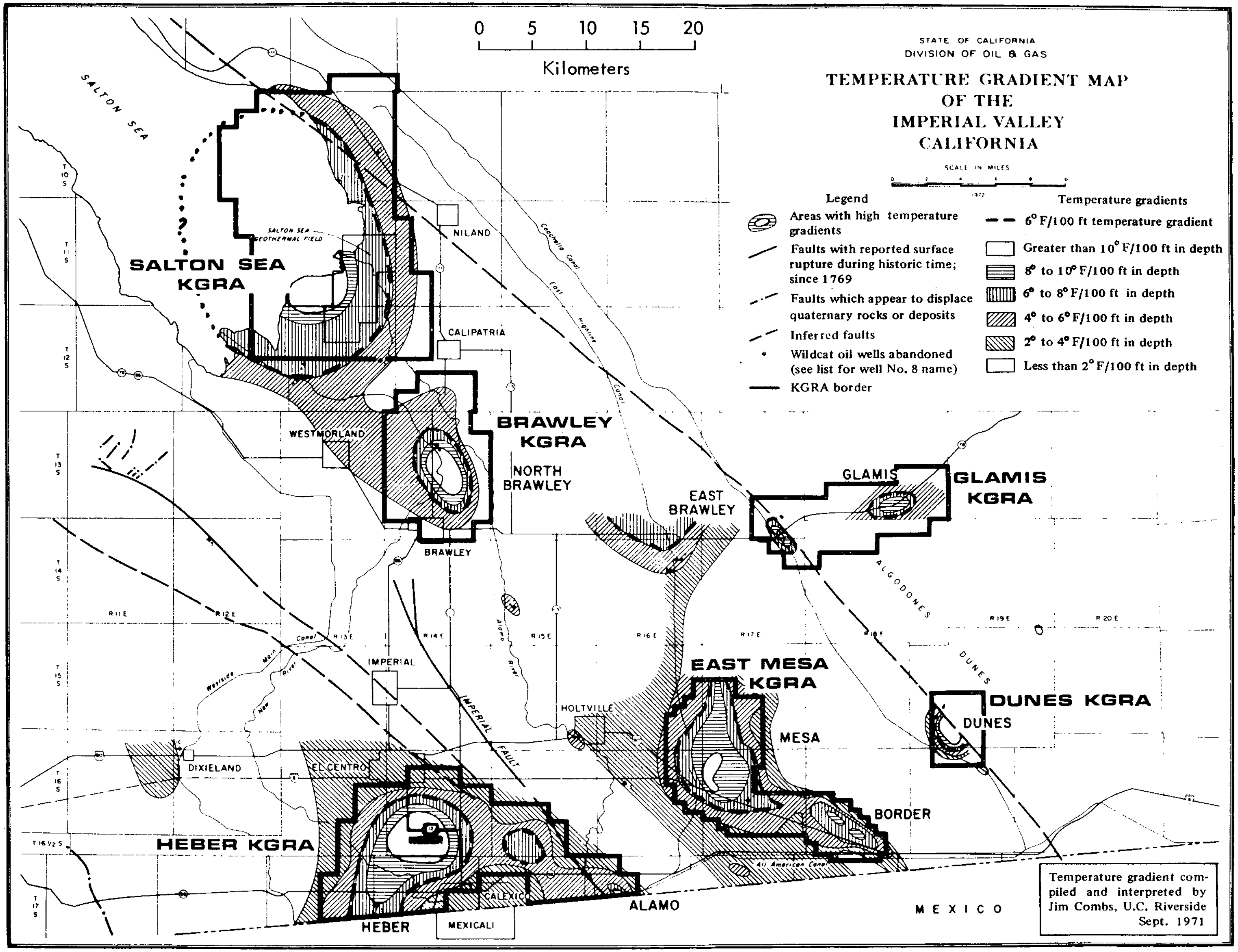

Fig. 4. Temperature gradient map.

have been or can be reasonably estimated, as can reservoir pressures. Enthalpy of a pure water system could be calculated from published tables, but in a highly saline brine the calculation is much more complicated. In the pressure-temperature regime existing in the Salton Trough reservoirs, where the fluid is single-phase liquid, the practical effects of pressure differences can usually be ignored. This is not the case with salinity, however.

Austin et al.[2] estimated electric capacity of the brines from consideration of the water enthalpy, neglecting the effect of dissolved salts. In their discussion of chemical problems, they noted this and pointed out that theoretical enthalpy might be calculated by separately calculating the contribution of the water and the dissolved salts.

If the relations between salinity and enthalpy could be quantified by experimental studies, they would be very helpful when detailed reservoir work has established good temperatures and brine analyses. Such is not the case in the areas studies here, however. Because most of the Resource in the Salton Trough is in the Salton Sea area, a typical high-salinity well there was used to construct an empirical chart to be used for routine estimates of brine enthalpy where temperature is known or can be estimated. Helgeson's[5] data on the IID #2 well (259,000 ppm brine) were extrapolated here to 3100-m (10,000-ft) depths and 350°C to determine the difference between steam table data and his values. In the reservoir conditions here studied and with the single-phase liquid in the reservoir, pressure is not an important factor. Temperature is and it increases with depth. Data obtainable are neither numerous nor accurate enough to make very accurate enthalpy estimates that take into account all possible variables. Data on brine salinity at various depths, especially, are lacking. Accordingly, Helgeson's experimentally determined enthalpy values corresponding to depths from 610 m (2000 ft) to 3100 m (10,000 ft) and temperatures from 200 to 350°C were examined for the variation between them and corresponding steam table values for pure water. Brine enthalpies are 11 to 29%, or an average 17%, less than steam table enthalpies. Brine enthalpy is thus, on average equal to 0.83 × steam table value. These values are shown in Fig. 5, which was used to estimate enthalpies from down-hole temperature measurements. The estimated values are judged to be at least as accurate as other calculated enthalpies, temperatures, and other available reservoir data. For most of the temperatures, they are well within Helgeson's 10% uncertainity range.

EXPECTED ELECTRIC CAPACITY OF THE RESOURCE

However crude it may be, a statement needs to be made of the amount of final product (electricity) that might be realized from a given resource.

In their study of the Total Flow conversion system, Austin et al.[2] developed the following parameters, which are used here to estimate the electricity to

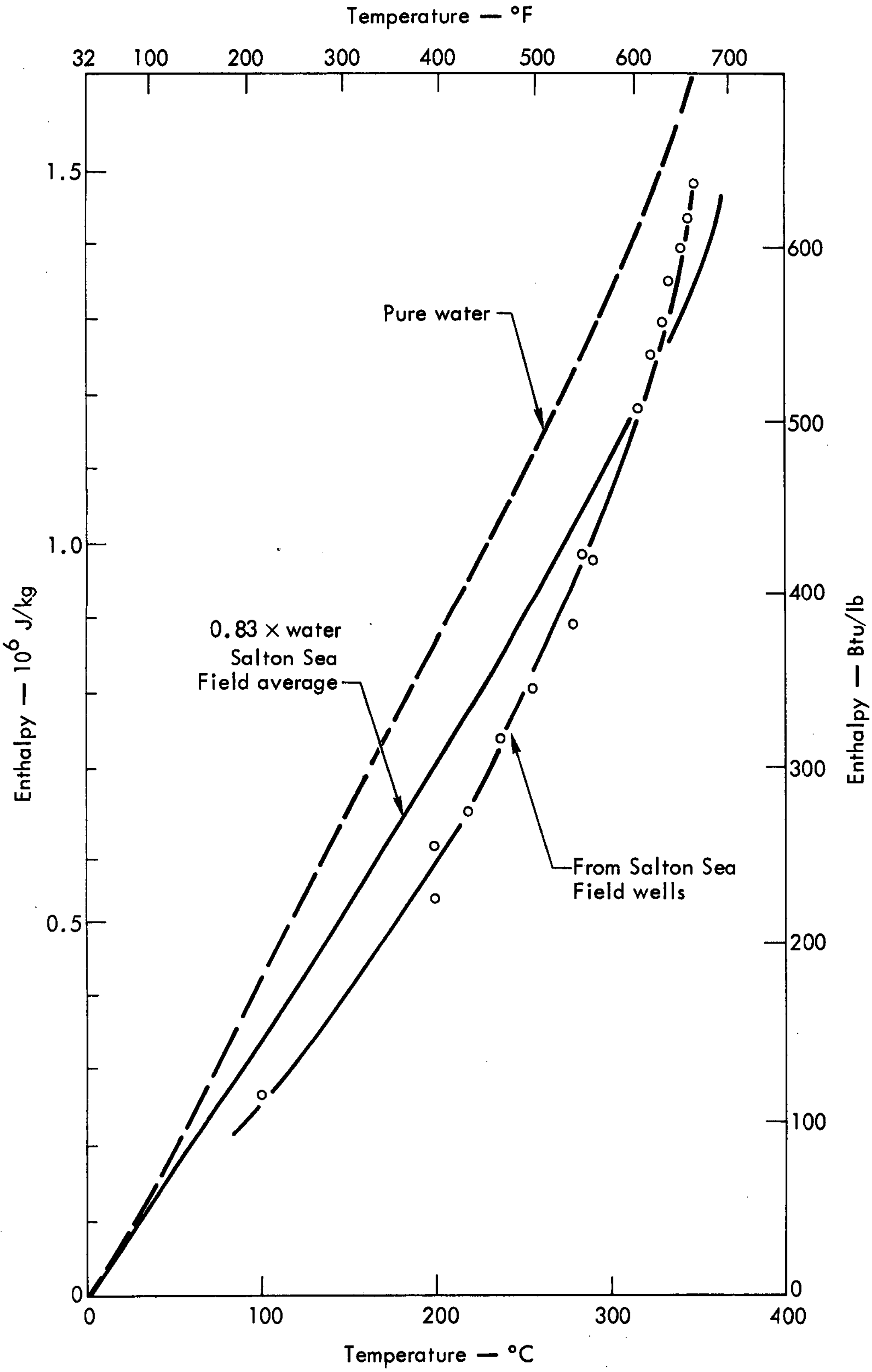

Fig. 5. Brine and water enthalpy. Salton Sea Field data from Helgeson.[7]

be generated from the Resource with such a system:

- Well-head enthalpy of brine:

  1.3×10^6 J/kg at 221°C
  (562.5 Btu/lb at 434°F).

- Amount of brine used will be 19kg/kWh (41 lb/kWh).

Should the production of electricity in the Salton Trough be like that expected from the Total Flow system, it will be similar to that at The Geysers, and the estimates here would be quite accurate. Should experience be more like that at Cerro Prieto, then these estimates of generated electricity should be reduced by approximately 30%.

The electricity realized from a given Resource depends not only on the enthalpy and the temperature of the Resource fluid, which can be specified at the time of the estimate, but also on plant equipment (i.e., the gathering and separation systems), the heat exchanger and turbine designs, and the generating efficiency. These factors can vary in many ways.

Austin and Lundberg[10] made a very useful calculation of net power output as a function of reservoir temperature, using estimates of typical well production for the Salton Sea Geothermal Field, steam-table values for water, and assumed energy conversion parameters for three conversion systems. The estimate in this report corresponds to their Total Flow curve at a reservoir temperature of 300°C. Figure 6 is their chart with power output for high-saline brine (enthalpy = 0.83 × enthalpy of pure water) added, and the power output of their 470,000-lb/h well recalculated to MWh per million kg. This can be used for direct estimates of expected power output.

ALTERNATIVE RESOURCE CALCULATIONS

The basic estimates here were made by considering the sands in the shallowest 305 m (1000 ft) of reservoir with temperatures above 230°C (450°F). The temperature requirement ensures a high-temperature fluid and the depth limit was chosen to correspond to a realizable draw-down limit. Other depth and temperature limits could result in estimates as much as 150% higher. (Table 4 shows the base and alternative estimates.)

These alternative net sand calculations include: sandstones with: (1) temperatures over 100°C to a total depth of 1524 m (5000 ft) and (2) temperatures over 230°C to a total depth of 1524 m (5000 ft). This last depth is the practical limit of information; few wells are much deeper, and most temperature measurements are above that depth. Preliminary economic studies also indicate 1524 m is probably the present limit of profitable wells. Temperatures above 100°C include all fluids of any use in electric generation. For the major part of the Resource, the temperature at the top of the sandstone reservoir is well above 100°C. Using a lower limit of 230°C ensures a temperature suitable for any of the three major conversion schemes. Average fluid temperatures can be calculated from known or estimated temperatures and porosities.

Table 4.

Average energy and electric potential calculated by various methods

Minimum temperature, °C	Average temperature, °C	Average enthalpy, 10^6J/kg	Net sand, m	Energy and electric potential				
				10^{16}J/km^2	10^{10}kg/km^2	kg/kWh$_e$	10^9kWh$_e$/km^2 (10^6kWh$_e$/acre)	Maximum depth, m
100	270	1.0[a]	549	8.6	8.6	23	3.7(15)	1524
230	290	1.1[a]	427	7.4	6.9	21	3.2(13)	1524
230	290	1.1[a]	180	3.2	2.9	21	1.5(6)	b
230[c]	300[c]	1.3[d]	180	3.7	2.9	19	1.5(6)	b

[a]Estimated from Fig. 5.

[b]Maximum depth is 305 m below the 230°C temperature line.

[c]These values were used for the estimates in this report

[d]Taken from Austin et al.[2]

Assuming a constant specific yield, average temperatures are weighted by net sand values to estimate an average temperature of the fluid in place between the selected depths. Enthalpies can be calculated from the stated temperatures and can be similarly weighted to estimate an average enthalpy for the selected intervals. An arithmetic average from the wells is used because the few wells available are not spaced so that a meaningful area-of-influence weighting can be made. Electric generating capacity is estimated from Fig. 6.

Geology and the Resource Estimates

The geology of the Salton Trough and its relation to geothermal energy deposits have been discussed by Anderson and Axtell,[13] Combs,[4] Dutcher et al.,[5] Helgeson,[7] Rex,[14] and others. In this section, I briefly describe the setting and discuss the geologic features with a bearing on the estimate.

The Trough is a graben-like depression bounded northeast and southwest by the San Andreas and San Jacinto-Elsinore fault systems, and cut by a number of parallel NW-SE strike-slip faults, whose location and geometry are known only in a general way. These faults are shown in Fig. 7.

The Trough is filled with mostly continental and some coarse-grained near-shore marine sediments resulting from almost continuous sedimentation since Miocene time. The important geothermal reservoirs are in the younger deltaic

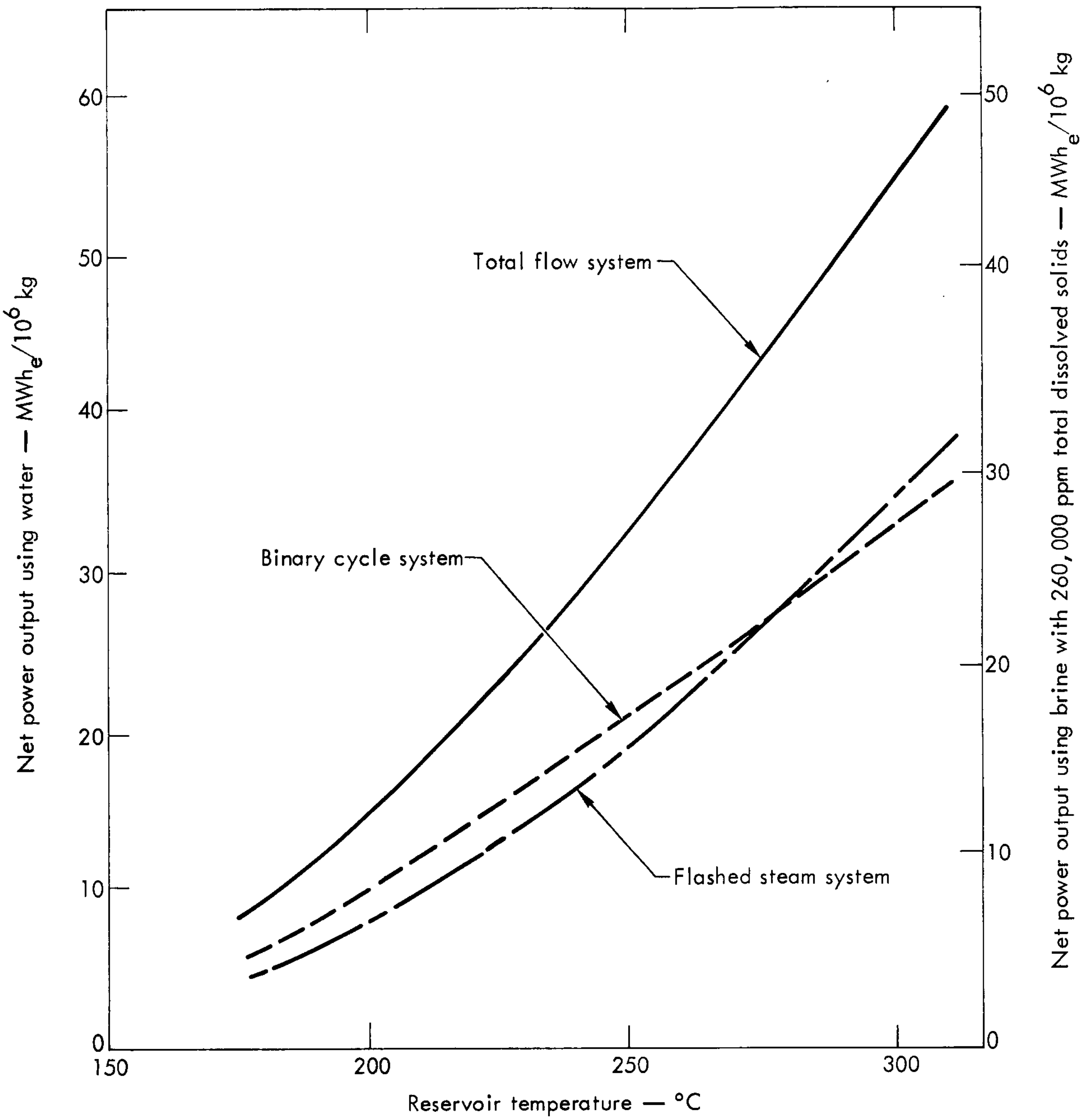

Fig. 6. Net power output vs reservoir temperature. (Modified from Ref. 10.)

sands, gravels, and siltstone sequence of late Tertiary and Quaternary age. These are penetrated by volcanic rocks to the surface at the Obsidian Buttes area at the south end of the Salton Sea and at Cerro Prieto in Mexico, and elsewhere in the subsurface. The sediments are irregularly deposited so detailed stratigraphic correlation is difficult over long distances, although it can be done in local areas, except where complicated by faulting.

Reservoir sands are irregular and separated by silt- and clay-stone beds,

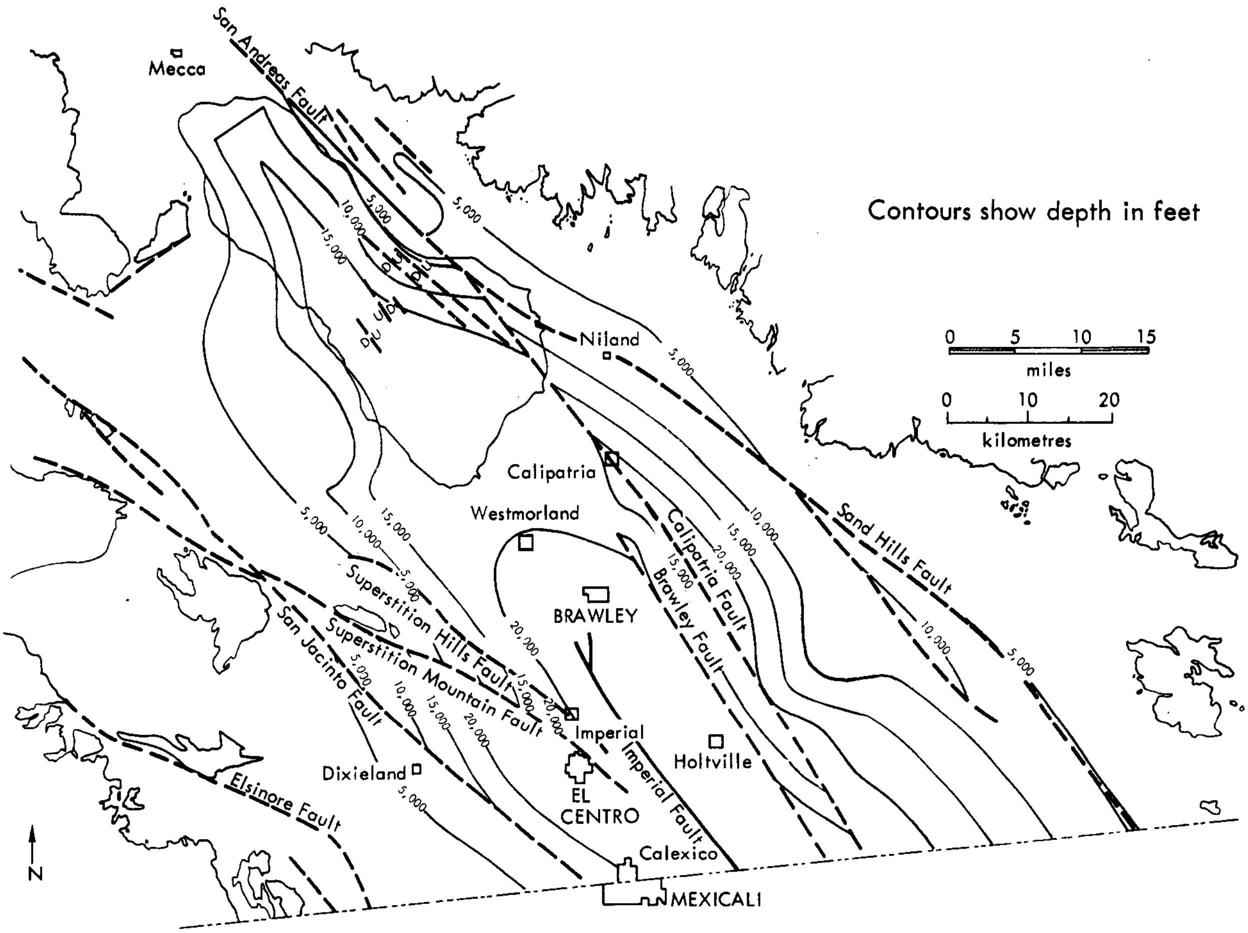

Fig. 7. Depth to basement, Imperial Valley, Cal. (Modified from Ref. 14.)

and the reservoir section is overlain by a variable thickness of impermeable shale and clay. The clay cap is thickest in the Salton Sea Field, where it is as much as 7000 m thick. It thins to the south to less than 200 m and is absent in places south to the Salton Sea Geothermal Field. Below the cap, heat transmission is assumed to be convective and temperature increases very slowly with depth. Both the average temperature within this region and the temperature at the cap base increase with cap thickness.

Helgeson[7] reported that the rocks become silicified and metamorphosed where temperatures reach 280 to 300°C, with development of such minerals as epidote, chlorite, potash micas and feldspars, and some metal sulfides. These brittle rocks are apparently extensively fractured in the subsurface. Intergranular porosity and permeability decrease with temperature and depth. Dutcher et al.[5] estimate specific yield of 5% for deposits below 2400 m, about 16% for rocks shallower than 2400 m with temperatures exceeding 100°C, and about 13% for those at temperatures below 100°C. They state that "where temperatures exceed about 250°C most of the original interstitial sediment permeability has probably been greatly reduced or entirely eliminated." At some depth then, original stored water is trapped, and only water in fractures can be produced.

Airborne magnetic surveys by Griscom and Muffler[6] indicate a possible igneous intrusive body at depths of 2100 to 3100 m in the Salton Sea area. This also would limit the depth of the reservoir.

Geology, then, indicates irregular reservoirs, a limit in depth of perhaps 3000 m or less, and the importance of fracture permeability.

Except for the drilled areas and a few surface indications near the Salton Sea and at Cerro Prieto, the only direct evidence of high temperatures at economic target depths are the abnormal temperature-depth gradients reported by Combs.[4] Although the U. S. Government has designated about 1000 km^2 of the 10,000-km^2 total Trough area as KGRAs, temperature gradient data indicate that only about 5% of the total surface (530 km^2) is underlain by geothermal energy resources.

Economic and Operational Consequences

ECONOMICS AND WELL CAPACITY

Assuming conditions given in Table 4 (including initial flow rates and production decline), electric generating capacity of each well can be calculated from Fig. 6, and working estimates of return-on-investment can be made with various combinations.

Return-on-investment on a discounted-cash-flow basis was calculated by a U. S. Bureau of Mines graphical method (Garland et al.[11]) developed for evaluation of development oil wells. Capital costs for standard materials are from the Heber (Imperial County), California area.[12] The estimate for the cost of additional special materials is by Austin et al.[2]

It is assumed that wells will be operated by an energy producer and the product delivered to a utility on a generated kWh basis, as is done at The Geysers Field. Capital cost of injection wells is included.

Table 5 shows capacity of representative wells and the estimated return, for wells using either standard oil-field materials or special corrosion-resistant materials, and with either Total-Flow or conventional energy conversion units. Present (1974) costs and revenue per kWh are used.

All capacities are shown for a normal well with 0.19 m (7-5/8 In.) o. d. production string. Bigger holes would improve capacity (if the reservoir delivers) and economics.

Land cost and miscellaneous are estimated at $1000 per acre, calculated on the area required for a 10-yr well life. Exploration cost is not included.

Table 5. Summary of financial analyses for Salton Sea field wells.[a]

	Resource Data			Financial analyses for: 1524-m well[a] — using standard materials					1524-m well[a] — using special materials or a 2134-m well — using standard materials				
					Flash steam system		Total flow system			Flash steam system		Total flow system	
Well[b]	Brine, 10^6 J/kg	Reserve Temp, °C	Thickness of net sand, m	Capital cost[c]	Capacity,[d] MW_e	ROI[e] (DCF), %	Capacity,[d] MW_e	ROI[e] (DCF), %	Capital cost[f]	Capacity,[d] MW_e	ROI[e] (DCF)	Capacity,[d] MW_e	ROI[e] (DCF), %
1	1.2	310	549	$643,000	7	18	10	29	$893,000	7	0	10	10
2	1.0	280	549	641,000	6	15	9	27	891,000	6	<0	9	9
3	0.8	230	518	659,000	5	10	7	25	909,000	5	<0	7	0
4	0.7	200	488	661,000	4	<0	6	10	911,000	4	<0	6	<0

[a]Notes: Flow: Initial 56.8 kg/sec, declining 10% per year. Revenue: 4 mills/KWh, 80% load factor. Enthalpy: From Fig. 5. Annual operating cost $6,000 per well, plus $25,000 if special materials required.

[b]Wells: (1) Northeast part of field, (2) Central part, (3) South part, (4) Marginal edge well.

[c]Standard well cost from producers' experience 1974 (from Ref. 12).

[d]Electric generating capacity. See Fig. 6.

[e]Return on-investment discounted cash flow method, 1974 oil well tax and 22% depletion conditions assumed.

[f]Cost of special materials per Austin et al.[2]

Several conclusions are apparent:

- These wells could be economic with improvements in materials and energy conversion. Research and development resulting in a reduction of capital costs and an improvement in energy recovery could result in a return of 20% or more, enough to make production attractive to private investors.
- Deep wells may be of doubtful value. Unless much more energy can be tapped, the economic depth limit with present conditions may be 1500 to 1800 m (5000-6000 ft). Table 5 indicates a maximum 10% return on a 2134-m (7000-ft) well.
- Development of lower-cost effective brine-handling systems and materials is necessary. Solution of the materials problem with materials less expensive than something like titanium will make power generation practical. If material costs approach those of normal oil-field materials, this development will make the most important economic contribution in improving return from unacceptable to nearly adequate.
- Addition of a successful Total Flow system[2] could result in acceptable economic return. As these preliminary results indicate, the development of a

Total-Flow system, as proposed by Austin et al.,[2] could improve power capacity and revenue to very acceptable levels. An additional benefit would be that lower enthalpy brines could be economically produced in areas where materials and corrosion are not such serious problems as they are in the Salton Sea Field.

OPERATIONAL CONSIDERATIONS

The importance of the Salton Sea KGRA is evident: about 55% of the total energy resource is in the KGRA. All of the Identified Resource cited in this report is there. This is the site of the highest measured water temperatures in the Trough and the highest brine salinities. Solution of the problems of scaling and corrosion and the design of brine-handling systems are necessary for utilization.

About two-thirds of the Salton Sea Resource probably lies under the Salton Sea, in a game refuge and recreational area that includes a significant amount of Federal land. The combination of these factors have to date prevented surface heat-flow surveys or deep drilling because of environmental and legal restrictions and the unavailability of geothermal leases on Federal land.

Land units are large. The apparent resource is about 1.5×10^6 MWh/km^2 (6000 MWh/surface acre), so 20 km^2 (~8 mi^2) will be needed for a 220-MW complex, assuming 80% load factor and 20-yr life.

If generating modules of 55 to 110 MW are used and wells have 5 to 11 MW capacity, then 20 to 44 wells and 2 to 4 generating plants would be needed for 220 MW. Modules larger than 110 MW will probably not be practical because flow lines will become excessively long, but slant drilling from a central location might partially solve that problem. Capacity and number of wells, the size of generating plants, and the area required is roughly equivalent to that at The Geysers. Actual surface usage at the Salton Sea would be from 1 to ~1.5% of the total area. The plants will be a highly visible change to the scenery, however, even if their impact on other uses is small.

In the Salton Sea area alone, there are at least three major operator-lessees and three or four times as many major surface and mineral owners. This implies that major (200 MW plus) development will require pooling or unitization. Similar land and lease patterns are common elsewhere in the Trough.

Enormous quantities of water must be produced. It is estimated that a 220-MW plant in the Salton Sea area will require 10 wells producing 7000 kg (2000 gallons) of water per minute. In oil field terms, this is a total of 615,000 barrels/day, or nearly 4.5 billion barrels in 20 yr.

Design and guidelines for producing and generating systems must correspond to the realities of the resource distribution.

Unresolved Technical Issues

A number of technical issues remain unresolved at this time due to a lack of detailed knowledge about the Resource itself, reservoir performance and production systems, and environmental effects.

More Resource data are needed. Laboratory determination of the enthalpy of brine mixtures and actual bottom-hole samples from all depths are needed. Exploration with deep holes or geophysical surveys is needed in the major areas where there is no information at all, such as the subsea portion of the Salton Sea KGRA.

Reservoir and production data are needed. The variations in physical properties in the reservoir are not well known, and actual flow-testing for production history is needed. The effect of production on the reservoir and the long-term effect of massive re-injection on reservoir temperature and chemistry are unknown. These may result in plugging and scaling in the reservoir and decrease production as well as have adverse environmental effects. Production experiments should be performed to test this.

Optimized designs and good cost estimates for production, transport, and generating systems are needed, and design of brine-tolerant production systems is vital.

Discussion and Other Estimates

The Salton Trough geothermal estimates made here are summarized in Table 1. The effect of specifying other temperature and reservoir values is shown in Table 4. Such changes could increase the estimate by 150%.

Should there be unexpected technological developments or major economic changes such that drilling into and producing from 600 to 1500 m (2000 to 5000 ft) of reservoir at depths to 3050 m (10,000 ft) might be potentially economic, then total in-place resource of the Salton Trough would be increased up to five times to 10^{20} J (10^{17} Btu) with an electric capacity then of approximately 25,000 MW for 20 yr.

A number of estimates, with electric generating potentials as much as 30,000 and 90,000 MW, have been published. When the areas and depths used and the economic and geologic premises are known, these can be compared with the estimates in this report. Correspondence is often surprisingly good, considering the varied data used and the common lack of critical measurements.

This report corrects the 92,000-MW electric generating estimate reported by Austin et al.[2] In that report, a mathematical error was made in calculating annual well production rates. Based on their data, capacity should have been stated as 9200 MW for the drilled portion of the Salton Sea Field.

Helgeson[7] reported 1.4×10^{12} kg (5×10^{10} ft^3) brine and 4×10^{18} J (10^{15} kcal) of heat in the reservoir brine in the drilled portion of the Salton Sea Field. These figures agree exceptionally well with my total resource estimate for the Salton Sea Field of 1.3×10^{12} kg and 2×10^{18}J, because the data are from close wells in a well-drilled portion of the field.

Rex[14] published the most widely quoted high estimate, 20,000 - 30,000 MW electric generating capacity for the Trough south of the Salton Sea Field. Using the parameters chosen for the estimate, I calculated that 30,000 MW for 20 yr would require approximately 10^{20} J of thermal energy in 10^{14} kg of water. These values are about five times as large as my estimate of 2×10^{19} J and 15×10^{12} kg for the Trough and nearly the same as my upper limit of possible Resources requiring major technological or economic changes.

Defining Resources as "potentially economic", as is now done, places a depth limitation on the producing interval. My economic estimates place a depth limit of 1800 to 2100 m (6000 to 7000 ft). In addition, the estimate considers a maximum area (of high temperature gradient) of 530 km^2 (205 mi^2), or 11% as much area as that considered by Rex,[14] Combs,[4] and Dutcher et al.[5]

Summary

The 5000-MW geothermal electric capacity for the Trough is approximately one-quarter of Southern California's present electric generating capacity. On the basis of 12,900 barrels of oil per mega-watt year, 5000 MW of geothermal energy would replace 65 million barrels of oil per year or 1.3 billion barrels in 20 yr.

On the lower end of the scale, the Identified Resource capable of generating 250 MW would replace 3.2 million barrels of oil per year, or 65 million barrels in 20 yr.

There is no currently economic Reserve in the Trough. These Resources will be subeconomic until practical technology for production, for control of scaling and corrosion, and for energy conversion is developed.

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