MASTER

Final Report on a Resource Assessment of the Imperial Valley

by

Shawn Biehler and Tien Lee

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ABSTRACT

A resource assessment of the Imperial Valley has been made based on the use of the gravity anomalies as indicators of total excess mass. These data indicate a potential of producing electric power of 7 to 80 thousand megawatts for 30 years. Over half of the total potential is located in the Salton Sea Anomaly and approximately half of the potential of the Salton Sea field is water covered. An attempt has been made to assess not only the heat in storage in the fluid but also recoverable from the country rock by reinjection. Based on calculations, the natural recharge rate of heat in the Valley due to sea floor spreading is too small to give the resource an indefinite life-span since the economic rates of withdrawal appear to be at least an order of magnitude greater.

Although the source of heat in the Imperial Valley is unique to most geothermal areas, the types of studies undertaken here may be applicable to other hot water geothermal systems within deep sedimentary sections regardless of their heat source.

INTRODUCTION

A realistic assessment of the geothermal resources in the Imperial Valley is a necessary prerequisite to the development of potential geothermal areas and the estimation of its impact on the economy, environment and society. Several uncoordinated efforts toward the assessment of the geothermal energy in the Imperial Valley have been made by various government agencies, universities and private industry. Because of the lack of coordination and cooperation among the various contributions from different sectors some of the effort has been duplicated and in some cases there appears to be conflicting interpretations. For example, assessment of geothermal resources made by different workers may differ by several orders of magnitude, reflecting the lack of exchange of ideas and data.

An attempt has been made to utilize the existing geophysical and geological data to obtain a realistic assessment of the geothermal resources of the Imperial Valley. This data has been compared to recent assessment based on widely different criteria. There is good agreement among the various recent approximations which indicate sufficient resource to warrant further endeavors toward an economic production of geothermal energy in the Imperial Valley. The total amount of heat which can ultimately be extracted from the reservoir is obviously technology dependent. However, even the most conservative estimates of the potential indicate economic development is feasible.

Care should be exercised in using the resource assessment numbers as set down in this report. These numbers are estimates of the geothermal potential of the various reservoirs and should not be misconstrued as the proven potential in any area. The proven reserves in all instances are much smaller than the estimated potential.

SECTION 201.1. Identify the Potential Geothermal Reservoirs

Identifying the potential geothermal reservoirs in the Imperial Valley is not an exact science. The only sure way of proving the existence of a geothermal reservoir is to drill deep test holes and produce the geothermal fluids. However, a number of geological and geophysical exploration methods have been applied to this area with some success. These techniques have been used to delineate the areas for deep drill tests. Although the application of these methods is by no means fool proof, they have proven fairly reliable in the Imperial Valley.

Only one of the geothermal reservoirs in the Imperial Valley has surface geologic features. It is located at the south end of the Salton Sea where four small volcanic plugs locally extrude the sediments. These plugs mark the approximate center of the Salton Sea geothermal field. Other potential geothermal reservoirs are blind targets which have been located with subsurface geophysical methods. The basic exploration techniques used to locate these potential geothermal targets are as follows:

- (1) Gravity studies within the Imperial Valley indicate that local gravity anomalies are associated with excess mass in the subsurface rocks. There is good correlation between the location of these gravity maxima and the location of potential geothermal reservoirs. The density of the rocks within the geothermal reservoir appears to be locally increased due to silica deposition within the pore spaces as well as hydrothermal alteration of the sediments. These results can be used to deduce the subsurface shape and lateral extent of the potential geothermal reservoirs and the total heat energy in storage. However, caution must be exercised in this extrapolation

because much is not yet known of the subsurface structure and density within the reservoirs themselves. Also, there is the possibility that very young potential geothermal reservoirs have not had sufficient time to develop a gravity anomaly. The gravity anomalies can be used as a method for outlining some targets for further exploration. The technique of gravity exploration is relatively inexpensive to apply, and as a result has been used extensively throughout the Imperial Valley.

(2) Temperature profiles in shallow test wells can be used to measure geothermal gradients from which the amount of heat-flow coming out of the subsurface can be estimated. However, because of problems of both conduction and convection within the sedimentary section and other causes, these data are not clear cut indicators of a reservoir. There does appear, however, to be a very close correlation between those test wells with high temperature gradients and those areas with markedly positive gravity anomalies. There is not a one-to-one correspondance between the size of the maximum gravity anomaly and the maximum thermal gradients measured in the shallow boreholes. Some areas, for example like Heber, have extremely high temperature gradients in the upper shallow portion but a rather small gravity anomaly of only several milligals, whereas a rather extensive gravity anomaly exists over the Salton volcanic domes. The temperature gradients measured there are about the same as those in Heber. An area of rather pronounced gravity maximum is located to the east of Brawley, and there is some indication that this area is also locally hot but it appears on the basis of both the gravity anomaly and the temperature gradients that the source of heat here is deeper seated than in the other potential geothermal reservoirs.

(3) Seismic studies have been applied to locate the subsurface shape of the anomalous mass associated with the geothermal reservoirs. Basically, refraction techniques have been used at three of the proposed geothermal sites. These indicate that the reservoirs are locally higher in velocity as well as density, but because of the very thick paintbrush the picture that is painted by seismic refraction only gives us a very gross structure of the reservoir. The local details of fracturing and faulting cannot be delineated. Passive seismic techniques using inherent ground noise have been applied in the East Mesa Anomaly and Salton Sea Anomaly, and there appears to be a good correlation between the seismic noise and the location of the geothermal reservoir. Studies of this type have not been carried out to date in the other potential geothermal reservoirs. They may be extremely difficult to apply within the central portion of the Valley because of the intensive agricultural noise.

(4) Ground and aeromagnetic methods have been applied to the Imperial Valley. Aeromagnetic surveys have been conducted of the entire Valley by various companies and a portion of the Valley has been flown by the U. S. Geological Survey (Griscom and Muffler, 1971). These surveys indicate that some of the geothermal anomalies are associated with magnetic highs (or positive magnetic anomalies). This is particularly true of the Salton Sea geothermal area. A broad magnetic positive anomaly with very local spikes is associated with the Salton volcanic domes. This data indicates that the explored field is associated with a much larger feature than the surface geology indicates, and probably extends underneath the Salton Sea. The gravity map of this area also indicates that this field is rather extensive, and indeed over half lies under the present boundary of the Salton Sea.

(5) Electrical measurements made in the Imperial Valley are also good indicators of the areas where temperature gradients are locally high. Resistivity surveys which measure changes in the electrical resistance of the sediments in some instances clearly delineate the areas where the temperature gradients are very large. This is because the resistance of the rock decreases as its temperature increases and as the temperature and salinity of the brine increase. It is difficult, however, to clearly separate the effect of temperature from the effect of salinity. Therefore, an area which is relatively cold but has locally high salinity would show up as a resistivity anomaly which would not necessarily indicate a geothermal reservoir.

(6) Remote sensing of the Valley has indicated some major features which are located on the boundaries of the agricultural areas. Here major fault structures can be seen. However, within the agricultural area the ground has been disturbed so seriously by farming that very little can be seen from high altitude photos regarding the near surface geology. Further exploration in this area with remote sensing technique is now going on.

On the basis of geophysical data and local geological features, eight areas have been designated as potential geothermal reservoirs. Of these eight areas only one, the East Brawley Area, has not been designated by the U. S. government as a KGRA (known geothermal resource area). A map showing the boundaries of the KGRAs within the Imperial Valley is shown in Figure 1. As of early 1976 only four of these KGRAs are thought to be potentially economic geothermal reservoirs, including the areas at Heber, East Mesa, north of Brawley, and south of the Salton Sea. The areas at Glamix along the Coachella Canal, and the Dunes are now known to be too small and insignificant to be economically productive. The KGRAs as designated on the figure include about

1000 square kilometers out of a total 10,000 square kilometers in the Imperial Valley, but even this number is not the true measure of the potential geothermal reservoirs. They amount to essentially only 50% of the area set aside by the U. S. government or about 500 square kilometers which appears to be economically productive. This is a total of only 5% of the total land area in the Imperial Valley. The KGRAs were designated on the basis of temperature gradient measurements made within the valley. These temperature gradient measurements have been contoured (Combs, 1971) and are also indicated on Figure 1. The area east of Brawley has not yet undergone extensive exploration, but it does appear that this area is one of a deep seated heat source which is probably not economical at this time.

The question arises as to whether or not there may be other potential geothermal reservoirs within the Imperial Valley which have not yet been delineated. By using the correlation of the excess gravity mass and the thermal gradients, we see that there is a very close correlation between the temperature gradients and the gravity. There are no locations in the valley which are not associated with relative positive gravity anomalies where high temperatures have been measured in shallow drill holes. But several deep test holes by Republic Geothermal southwest of Obsidian Buttes and by Union Oil Company (west of Brawley) have indicated high temperatures on the extreme flanks of the local gravity positive (Figure 2). This does not mean, however, that all of the Valley has been covered with sufficient detail in terms of shallow temperature-depth holes. In order to clearly delineate that no other geothermal areas exist in the Valley, an extensive program of temperature gradient measurement should be made.

Section 201.2. Inferences on the Size, Magnitude, and Life Expectancy

In order to infer the size, magnitude, and life expectancy of the heat sources, one must look at the regional, geological and tectonic setting of the Imperial Valley. The Imperial Valley lies in the southern portion of the Salton Trough which is the northward extension of the Gulf of California. The area within the Salton Trough, much of which lies below sea level, is similar structurally to the Gulf of California, except for a large thick sequence of sediments overlying the basement. The Trough itself is a very complicated structure. It is by no means a simple graben--a downdrop block between parallel faults. There is extensive faulting throughout the Valley some of which cuts obliquely across the trend of the Valley itself. The source of the geothermal reservoir in the Imperial Valley is directly connected with the Valley's origin which is believed linked with an ocean spreading center associated with the East Pacific Rise.

In order to understand the origin of the geothermal system, one should spend a few moments to familiarize himself with the concepts of the source of heat. The reason that this is important is if the source of heat is truly associated with a sea-floor spreading center, then heat is constantly being supplied in the lower portion of the crust and possibly within the basement. To look at the application of this theory to the Salton Trough we must go back a period of four to ten million years. Before this time, the North American plate was being pushed in a westerly direction by spreading forces associated with the mid-Atlantic Ridge. As the plate moved westward, it came in contact with the spreading center associated with the Pacific Ocean--the so-called East Pacific Rise. The continental plate rode over the top of the rise and the East Pacific spreading center began to frac-

ture the continent along a previously existing zone of weakness associated with the San Andreas fault. This began to produce an opening in the Gulf of California which moved Baja California in a northwesterly direction with right-lateral motion along most of the San Andreas system.

One can now look at the Imperial Valley and see how it has developed in time by looking at various cross-sections which are depicted in Figure 3. These cross-sections can be considered either as spatial profiles at various locations across the valley or as temporal profiles at the same location. Let us first consider this figure as a series of snapshots in time back to four million years. The top profile, Figure 3A, would indicate what a typical crustal section would look like in an area which would have been approximately at the south end of the Salton Sea. This depicts a normal continental section consisting of silicic material overlying basaltic material with a depth to the crust-mantle interface of approximately 32 km. As the plate overrode the East Pacific Rise, the temperature gradients increased within the crustal section due to heat which was supplied by the crustal spreading center underneath. These rising geotherms produced thermal expansion causing a slight uplift and extension. The continent was rifted apart along previously existing zones of weakness, causing some of the crustal material to sink within the Valley and a small thickness of sediments to be deposited (Figure 3B). The Valley at this time is very narrow. In Figure 3C we can see the development after approximately two million years. The Valley has now expanded to almost twice its previous width. There is extensive block faulting of the basement rocks along the flanks of the Valley, additional deposition of sediments, and some metamorphism going on within the lower portion of the sedimentary section, with the emplacement of basaltic magma from the mantle material

within the crust. The basement is being thinned and pulled apart. If we continue this process for a period of approximately four million years (Figure 3D), we would see a rather broad flat alluviated valley which has an extremely thin crust underneath a sediment any sequence of considerable thickness. There would also be local rhyolite magmatism coming through the sedimentary section, and a large amount of basaltic magma emplaced in the lower portion of the crust, forming essentially new crust with locally high temperatures along fracture systems in the basement. This is approximately what we see today at the southern terminus of the Salton Sea. The schematic diagrams shown in Figure 3D indicates one of the small rhyolite domes which intrude the sediments at the south end of the Sea. One can also see from these diagrams that we are dealing with a dynamic system.

We can now look at these profiles as a series of profiles not in time but one in space. Profile 3D, which shows the rhyolite magmatism, is a profile essentially through the south end of the Salton Sea. Profile 3C would be located approximately through the middle of the Salton Sea at present. Profile 3B is what the current Coachella Valley looks like to the north, and Profile 3A is a normal undisturbed continental section which is observed west of the Banning Pass.

Although these schematic diagrams are rather simplified we have very good reasons, both on the basis of geological and geophysical evidence, to indicate that this development is approximately correct. The details, of course, are not clearly known, but the gross structural features are. The geology clearly indicates, on the basis of the thickness of the sediments, the width of the Valley and the active volcanism, that this set of diagrams is what is happening at present along the axis of the Salton Trough. The

geophysics, especially the gravity anomalies, indicates that we have an extremely thin crustal section underneath the Imperial Valley with a depth to Moho of probably no more than 16-18 km as compared to 32-35 km on either side of the Valley. However, the major oblique right-lateral strike slip faults which cut across the Valley complicate this picture even further. The reason for this complication is that the Valley is not opening in a systematic east-west sense but it is opening by a rotation and northwestward motion of the western side relative to the eastern side. These faults can be conceived as leaking transform faults which may be associated with recent emplacement of basaltic magma within the basement. This could produce very recent potential geothermal reservoirs which have not developed a gravity anomaly. These zones may also be some of the hottest in the Valley and have very low salinity.

We therefore believe that the source of heat that is in storage within the brines is due to magmatic emplacement in the crust and a portion of the lower basement of the Imperial Valley. Within the sedimentary section and the upper portion of the basement no magma has been detected to date. This indicates that if there is a magma in a liquid or plastic form that it probably underlies the Valley at depths greater than 7-8 km. By looking at the localized geothermal anomalies, one can also see that the entire Valley is not a geothermal reservoir even though there are areas which might be undergoing extensive volcanism in the subsurface. One needs to develop a fracture system above this localized volcanic activity to act as a conduit, which brings the heat from great depths near to the surface in a rather short time. In addition, these systems are constantly changing, but changing on the order of geological time scales.

On the basis of magnetic anomalies that have been measured in the southern portion of the Gulf of California, the Gulf is opening at the rate of approximately 6 cm a year. This is the spreading rate associated with the East Pacific Rise crest at the south end of the Gulf and indicates that the Gulf itself has opened up approximately 240 km in four million years. This motion is being transformed to the northwest along a series of fault splays. The actual opening of the Imperial Valley is probably very close to 6 cm a year. Although detailed horizontal control has not yet been established, there is some indication that these numbers are in the right ballpark.

One can make some simple calculations about the emplacement of heat within the basement, using the assumption of a constant spreading rate of 6 cm a year and an approximate length of about 60 km. If this rock is emplaced in the subsurface in a molten or semimolten state at a temperature of about 1200°C, we should be introducing approximately 5×10^{16} Joules into the system per year. If a calculation of this type, as crude as it is with the given boundary conditions, can be used to interpret the amount of heat coming into the Valley, then there is a rate of withdrawal such that the geothermal resources of the Valley has infinite lifespan. However, current estimates regarding the rate of withdrawal are a factor of about 10 to 100 greater than the rate of emplacement. Using these estimates for the rate of withdrawal indicates that the geothermal resource potential in the Imperial Valley has a finite life span. Essentially, to develop the geothermal reservoirs, one needs to mine not only the brine but the heat associated with the brine. Since this is not a renewable resource at the rate of which material is coming in, we will eventually cool the system down. However, by waiting long enough it will regenerate into another active geothermal system.

The very localized geothermal anomalies that were discussed in the previous section are located along boundaries which in many instances can be associated directly with local spreading centers. The Valley itself is not associated with a simple one-place spreading center. There are probably many slivers which are actively undergoing spreading at this time. If one of these systems is sitting upon an area which has fracture porosity and permeability which extends through the sediments and into the basement, then a very localized geothermal reservoir which is potentially economic is developed.

On the basis of the estimates which have been made for the rate of heat withdrawal to produce on the order of 2000 megawatts of electrical energy in the Valley over a period of one year, the life expectancy of the Salton Sea geothermal fields can be estimated to lie somewhere between 20 and 100 years. More detailed calculations than this are not warranted at this time because of the lack of sufficient subsurface temperature depth information and information regarding the opening and spreading of the Valley in detail.

SECTION 201.3 Estimation of the Total Heat in Storage from the Fluid
Temperature and Reservoir Capacity

Estimates of the total heat in storage in the Imperial Valley geothermal reservoirs have been discussed by Anderson and Axtell, Combs, Dutcher et al., Helgeson, Rex, Towes, and Renner et al. These estimates have varied by 4 to 5 orders of magnitude. Many of the early estimates were made from inconclusive data. Some estimates are in error because of mathematical errors. It now appears that two recent estimates, one made by Towes and the other by Renner et al., appear to be within an order of magnitude. These two recent estimates have been based on different approaches to the resource. The study by Renner et al. is based on a simple geometry of each reservoir calculating its volume and assuming a volumetric specific heat of $0.6 \text{ cal/cm}^3\text{C}$ and temperature in degrees C above 15°C . This gives, essentially, the number of calories of heat in storage.

The study by Towes was made on a slightly different assumption, by using essentially the temperature gradients for the very shallow surface drill holes from the maps produced by Combs. These were extrapolated to depth, to find a point at which the 230°C isotherm was crossed. The reservoir was then assumed to extend from here to a depth of 300 meters. The volume of this area was calculated and the heat estimated using the well head enthalpy (Austin et al.), the specific yield (Dutcher et al.) and the thickness of sand (Randall). These two approaches produced numbers on the order of 10^{20} and 10^{19} Joules of energy in storage in the Imperial Valley (see Table 1).

For this study an entirely different approach has been taken. The resource estimates are of the same order of magnitude as those by Towse and Renner et al. but are based on a different set of assumptions and data. By com-

paring a map of the gravity anomalies in the Imperial Valley (Figure 2) with a similar map of the temperature gradients (Figure 1) a very close correlation between the areas of known high thermal gradient and relative maximum gravity anomalies is observed. Some of these anomalies, such as the one at Mesa, are slightly concealed because of the regional gradients in the valley. However, by making studies of the residual gravity anomalies associated with each one of the geothermal reservoirs a resource estimate has been made based predominantly on the size and shape of the reservoir predicted on the basis of the gravity maps.

This approach consists of producing residual gravity anomaly maps for each of the geothermal reservoirs. The total excess mass associated with each one of these anomalies was calculated using the following formula:

$$2\pi\gamma M = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \Delta g(x,y) dx dy$$

where γ = universal gravitational constant

M = total excess mass

$\Delta g(x,y)$ = residual Bouguer gravity anomaly

This formula makes no assumption about the shape or the density of the material. It is based strictly on an integration of the residual Bouguer anomaly. The residual anomalies for five potential geothermal reservoirs were produced by removing the regional effects from the complete Bouguer anomaly map. The integration was carried out numerically on a digital computer and a correction was applied for the missing tails of the anomaly (Grant and West). From this integration the total excess mass is calculated. Now if an assumption is made of the density contrast between the rocks associated with geothermal

reservoirs and those of the surrounding sedimentary section the reservoir volume can be computed. The density contrast that was selected was 0.2 gm/cc. This density contrast is based on seismic data and measurements of densities made on cores.

Once the reservoir volume is calculated the volume of the produceable fluid in the reservoir can be computed. This was done using an estimate of 20% for the average porosity of the sediments as computed from well logs (Dutcher et al.) and an estimated yield of 80% of the total fluid in the reservoir which can be produced. If we now assume a density of the fluid of 1 gram/cc as a minimum then we can compute the mass of fluid that can be produced from the reservoir. In order to calculate the heat in storage we must know the enthalpy of the fluid. The enthalpy of the fluids in the geothermal reservoirs in the Imperial Valley has been computed by Austin and his number is taken here as an estimate. The heat in storage is then equal to the mass of the fluid times the enthalpy of the fluid.

If we look at Table 1 we can see the total excess mass associated with each one of the anomalies and the computed total heat in storage. The numbers in column 3 are the estimates made by Tows on an extrapolation of the temperature gradients from the surface and the numbers in column 4 are computed based on simple geometric considerations by Renner et al. There is a very close agreement between the three sets of data. In most instances the gravity estimation appears to be slightly higher than those of Tows but the overall heat in storage is the same within an order of magnitude. All three sets of data show that over 50% of the total heat in storage is associated with the Salton Sea field. The fields which are extremely small such as Dunes and Glamis are not really commercial but have been listed here for

completeness. This also indicates that the technique of using the gravity anomalies to estimate heat source can be used for reservoirs which are either very large or very small. It also shows that there is a direct correlation between the total excess mass associated with the geothermal reservoir and the total heat in storage. This approach might be more accurate than those made by Towes or Renner et al. because of the smaller number of assumptions that are being used. It also considers the entire volume of the reservoir rather than a section which is arbitrarily defined as being terminated at some lower depth.

These estimates are only for the heat in storage in the fluid of the reservoir. They say nothing about the total heat which can be produced nor about the amount of energy which can be extracted because no process of energy extraction is 100% efficient. These problems will be discussed in a later section. In looking at the calculations the most critical number appears to be that of the total excess mass. Small changes in the density contrast between the reservoir rocks and the country rocks do not appear to affect the calculations markedly. The numbers for the porosity and yield are averages and in some reservoirs where the sands are extremely tight or where there is little fracture porosity or permeability this yield number might be smaller by a factor of two; similarly in some areas this number may be larger by a factor of 2. However, this will not affect the estimates of the total heat storage by more than an order of magnitude.

This approach for estimating total heat in storage is rather unique and probably cannot be applied to other geothermal areas, unless they are associated with a geological setting similar to that of the Imperial Valley. This is because the gravity anomalies are associated with silica deposition

and hydrothermal alteration of the sedimentary section due to convection of the hot brines through the sedimentary section. In areas of volcanic terrain or where fracture porosity or permeability are by far the controlling factors and no sealing of the reservoir occurs, this would probably not be the case.

Table 1A. Resource Assessment by Area in
Thousand Megawatts per 30 Years

Location	Excess Mass kg	Biehler ($\Delta p=0.1$) (gm/cc) $\times 10^{18}$ J	Biehler ($\Delta p=0.2$) (gm/cc) $\times 10^{18}$ J	Biehler ($\Delta p=0.3$) (gm/cc) $\times 10^{18}$ J	Towes $\times 10^{18}$ J	White $\times 10^{18}$ J
Salton Sea	5.1×10^{13}	106.1	53.0	35.4	11.7	87.9
Heber-Alamo	1.2×10^{13}	25.0	12.5	8.3	3.7	46.0
East Mesa	1.5×10^{13}	31.2	15.6	10.4	3.0	23.9
Brawley	1.9×10^{13}	39.6	19.8	13.2	1.0	12.6
Dunes	$.08 \times 10^{13}$	0.2	0.1	0.06	1.2	2.5
Glamis	--				.5	1.5
Total		202.1	101.0	67.4	21.1	174.4

Biehler Computation

$$\text{Reservoir Volume} = \frac{\text{Total Excess Mass}}{\text{Density Contrast}}$$

$$\text{Volume of Fluid (Produceable)} = \text{Reservoir Volume} \times \text{Average Porosity} \times \text{Average Yield}$$

$$\text{Mass of Fluid} = \text{Volume of Fluid} \times \text{Density}$$

$$\text{Heat in Storage} = \text{Mass of Fluid} \times \text{Enthalpy}$$

Assumptions

Density Contrast of 0.1, 0.2, 0.3 gm/cc

Average Porosity = 20% (Dutcher et al.)

Average Yield = 80%

Density of Fluid = 1 gm/cc

Enthalpy = 1.3×10^6 J/kg (Austin et al.)

Table 1B. Resource Assessment by Area in
Thousand Megawatts per 30 Years

Location	$\Delta p=0.1^*$ 10^3 MW electric 30 years*	$\Delta p=0.2$ 10^3 MW electric 30 years*	$\Delta p=0.3$ 10^3 MW electric 30 years*
Salton Sea	11.22	5.60	3.74
Heber-Alamo	2.64	1.32	0.88
East Mesa	3.30	1.65	1.10
Brawley	4.19	2.09	1.40
Dunes	0.02	0.01	--
Total	21.37	10.67	7.12

1 MW (electric) $\cdot$ century = 31.52×10^{14} joules (thermal)/ e_c where
 e_c is conversion efficiency.

1 MW (electric) $\cdot$ 30 years = 9.46×10^{14} joules (thermal)/ e_c

* Assume conversion efficiency of $e_c = 10\%$

1 MW (electric) $\cdot$ 30 years = 9.46×10^{15} joules

Table 1C. Resource Assessment by Area in Thousand
Megawatts for 30 Years and Extracting Heat
from both Fluid and Rock*

Location	$\Delta p=0.1^*$ 10^3 MW electric 30 years*	$\Delta p=0.2$ 10^3 MW electric 30 years*	$\Delta p=0.3$ 10^3 MW electric 30 years*
Salton Sea	42.08	21.00	14.03
Heber-Alamo	9.90	4.95	3.30
East Mesa	12.38	6.19	4.13
Brawley	15.71	7.84	5.25
Dunes	0.09	0.04	--
Total	80.14	40.02	26.71

* Assume conversion efficiency of 10%

* See Section 201.10

Section 201.4. Grading of the Geothermal Reservoir

A hot-water dominated geothermal area is characterized by high heat flux, as indicated usually by high geothermal gradient at depths above the cap rocks. Below the cap rocks, the reservoir is characterized by high temperature and low geothermal gradient. Both are indicative of a convection dominated system. Resource evaluations rely on the knowledge of the volume, temperature, porosity, permeability, fluid composition, and heat capacity of the reservoir. Since these data are usually inadequate, certain assumptions are required to estimate the resources. As new data are accumulated, resource evaluations need to be updated.

Although the grading of KGRA should take the economy, technology, and social-environmental impact into account, here we restrict the grading in terms of resource size and fluid quality.

Renner, White and Williams (1975) have estimated the total geothermal resource, defined as the stored heat regardless of its cost of recovery with the present available technology, in the KGRA of the Imperial Valley to be 174×10^{18} joules. Towes' (1975) estimate is 21×10^{18} joules which are derived from the assumption that the usable geothermal fluid extends 305 m (1000 feet) from the 230°C isotherm and the specific yield of the reservoir rocks is 16%. These two estimates differ by a factor of 8 but they seem to agree on the relative heat storage in the six KGRA (see Table 1). Based on the excess mass calculated from the residual Bouguer gravity anomaly map (Fig. 2) the estimates range from 67×10^{18} to 202×10^{18} joules, and lie between the two contemporaneous estimates. It should be pointed out that Towes' and the present estimates are based on the present available fluid for an average specific yield of 16%.

On the basis of the resource size estimated from gradient and temperature, the KGRA may be graded in decreasing order as the Salton Sea, Heber-Alamo, East Mesa, Brawley, Dunes, and Glamis. In terms of excess mass, however, the Brawley field is larger than the Heber-Alamo and the East Mesa fields. It is noted that regardless of the methods of estimation the Salton Sea field contains slightly more than 50% of the estimated geothermal resource in the Imperial Valley.

The usability of a geothermal reservoir depends also on the salinity of its fluid. Supersaline fluid in the Salton Sea geothermal field is one of the major factors inhibiting its development because corrosion and scaling in the machinery requires costly maintenance expenses.

Salinity in the shallow waters or in the aquifers above the impermeable cap rocks is reasonably well known owing to the abundant shallow water wells drilled by various government agencies (U. S. Geological Survey, U. S. Bureau of Reclamation, California Department of Water Resources, Imperial Valley Irrigation District), and private individuals and companies for agricultural usage. In general the salinity increases northwestward to the Salton Sea, except locally contaminated or diluted by the relatively fresh irrigation water. Salinity data in the deeper aquifers or geothermal reservoirs are comparatively scarce. Wherever the data are available, the deeper fluids appear to contain relatively more dissolved solids but there is no other correlative patterns between the salinities of deep and shallow waters. Therefore, one cannot deduce at present the salinity of the geothermal fluid from the salinity of the overlying groundwater.

Several theories have been proposed to explain the origin of the saline waters. The most favored theory claims that the high salinity results from

concentration of dissolved solids by evaporation and semi-membrane filtration. The recharge water descends at the edges of the Valley into the deeper aquifers and on its way to the reservoir it dissolves and carries evaporites to the reservoir. Because of high temperature in the reservoir, part of the water is evaporated and the residual water will hence accumulate more and more dissolved solids. Undoubtedly some cold water may seep from upper aquifers to the lower aquifers and hot water may also rise to the upper aquifers. Thus the salinity of water in the reservoir depends on the discharge-recharge rate, temperature, pressure, original salinity of the discharge water, and age of the reservoir as well as water-rock interactions. The recharge-discharge systems of the Cerro Prieto and Salton Sea geothermal fields are similar but the recharge water of the former contains ~1500 to 2000 mg/l while the latter 25,000 ~ 35,000 mg/l. As a result, the salinity of the brine in the Cerro Prieto field has increased to only 15,000 ~ 20,000 mg/l while in the Salton Sea it increases to 260,000 mg/l if both fields are of the same age.

No evaporites as a distinctive bed have been detected in the driller's logs and geophysical logs. Since the recovery of evaporites from a drill hole is difficult, the existence of thin evaporite beds in the Imperial Valley cannot be ruled out simply because of its absence in the logs. However, in the Mexicali Valley where the Cerro Prieto field is located, the sedimentation "basin" has never been closed, it is very likely that there is no evaporite bed. The evaporites seem to disseminate in the whole sedimentary section. If this is the case, the dissolved solids in the brine of the deep convection system have been concentrated to ten times of the dissolved solids in the discharge water by the convection, evaporation, semi-membrane filtration.

The Salton Sea area has probably been the lowest in elevation since the development of the Salton Trough. It is reasonable to expect the concentration of the disseminated evaporites in the sedimentary rocks becomes higher toward northwest. Thus we may conclude that salinity of deep water increases regionally toward the northwest. In terms of the salinity the quality of reservoirs becomes poorer toward the northwest. Available deep geothermal well data indicate the salinities of deep waters are fairly uniform except the supersaline brine in the Salton Sea geothermal field.

In terms of the recoverable heat content the Salton Sea field is the best but the quality of the geothermal fluid is the poorest. At present it may not be economically and technologically feasible to develop the Salton Sea field but from the long-term viewpoints of the resource development, the Salton Sea field has the largest potential.

201.5. Capacity of Reservoir Rocks

The capacity of a geothermal reservoir is usually estimated from temperature, water-rock ratio, heat capacity and the size of the reservoir. Size estimate is based mainly on temperature gradient measurements in the discrete drill holes and supplemented with other geophysical data. Since no unique relation exists between the reservoir temperature and the measured values of some physical parameters, certain assumptions are needed. Different assumptions may lead to estimates differing by several orders of magnitude.

In the Salton Sea geothermal field, the shale of the Borrego Formation forms the cap rocks of the reservoir. The Borrego Formation becomes more sandy at depth and merges with the sandy Palm Springs Formation, which is the reservoir rocks at the Salton Sea field. At other KGRA, the reservoir rocks consist also of sandy beds.

The porosity and permeability of the Borrego Formation and Palm Springs Formation determined outside the geothermal reservoirs cannot be applied directly to the reservoir and cap rocks because metamorphism has significantly changed the characteristics of the parent materials. The interstitial porosity and permeability are undoubtedly much smaller than those in the equivalent but unaltered rocks. However, fracturing in the reservoir will increase the porosity and permeability. The net effect of the closing of pores by the chemical alteration and re-opening by the fracturing cannot be easily measured in the laboratory because the size and distribution of fractures cannot be determined from cores.

The specific yields of shallow deposit average about 10 to 20%. For depth greater than 1 km the data are scarce. According to Dutcher et al. (1972), the specific yield is about 5% for deposits deeper than 2.4 km. Between 1 and

2.4 km it is 16% if the water temperature exceeds 100°C, otherwise it is about 13%. A detail specific yield data is present in Table 2, along with our estimates of the recoverable fluid volume.

Calculation of excess mass is an independent method to calculate the reservoir capacity. It relies on fewer assumptions as compared to other methods based on geothermal gradient, and the gravity data are more abundant than other geophysical data in the Imperial Valley. However, in detail, one should consider the contribution of cap rocks and the extent of metamorphism. The latter is related to the age of the hydrothermal system and the frequency of fracturing which provides conduits for water-rock interaction. These factors are difficult to evaluate. The fact that the estimates based on excess mass resemble grossly with other estimates indicates the age and fracturing frequency of the various KGRA do not differ from one another drastically.

Table 2. Specific Yield and Resources in the Reservoirs
of KGRA of the Imperial Valley

1. SALTON SEA Area = 460 miles² = 294,400 acres = 1191 km²

Specific Yield	Thickness	Temp.°C	Salinity
0	500'	< 100°	
16%	1200'	100~200°	
16%	6000'	>200°	
5%	10,000' down to the base- ment complex	> 200°	35,000 mg/l

a. low heat reservoir Volume = 0

b. usable reservoir Volume = 51.75 million acre-feet
= 64 km³

c. potential reservoir, which has high temp. and high salinity
(>35,000 mg/l) and could not be used in the present time.
Volume = (6000 x 0.16 + 10,000 x 0.05) x A
= 402,651,060
= 402.65 million acre-feet
= 497 km³

2. HEBER Area = 175 miles² = 104,920 acres = 453 km²

Specific Yield	Thickness	Temp.	Salinity
0	2900'	≈50°	
13%	3500'	< 100°	
16%	1500'	100~150	
5%	5000'	150~200	
5%	8000'	>200	>35,000 mg/l

a. low heat reservoir (T < 100°C)
V = 455A = 47.74 million acre-feet
= 59 km³

b. usable reservoir
V = (240 + 250) A = 51.4 million acre-feet
= 63 km³

c. potential reservoir
V = 41.97 million acre-feet
= 52 km³

Table 2 (continued)

3. MESA Area = 52 miles² = 31176 acre = 135 km²

Specific Yield	Thickness	Temp.	Salinity
15%	2500'	@50°	
13%	1500'	< 100°	
16%	4000'	100~175°	
5%	4000'	175~200°	
5%	a 2000'	>200°	>35,000 mg/l

a. Low heat reservoir < 100°F
 V = 17.77 million acre-feet
 = 22 km³

b. Usable reservoir
 V = 26.19 million acre-feet
 = 32 km³

c. Potential reservoir
 V = 3.12 million acre-feet
 = 3.8 km³

4. DUNE Area = 100 miles² = 59954 acre = 259 km²

Specific Yield	Thickness	Temp.	Salinity
20%	2300'	< 100°	
13%	2600'	< 100°	
16%	4000'	>100° < 175°	

a. Low heat reservoir
 V = 47.84 million acre-feet
 = 59 km³

b. Usable heat reservoir
 V = 38.37 million acre-feet
 = 47 km³

5. BRAWLEY Area = 153 miles² = 91729.6 acres = 396 km²

Specific Yield	Thickness	Temp.	Salinity
0	3000'	< 50°	
13%	1000'	50~100°	
16%	4000'	100~150°	
5%	4000'	150~200°	
5%	7000'	>200°	>35,000 mg/l

a. Low heat reservoir
 V = 11.92 million acre-feet
 = 15 km³

Table 2 (continued)

b. Usable reservoir

$$\begin{aligned} V &= 77.05 \text{ million acre-feet} \\ &= 95 \text{ km}^3 \end{aligned}$$

c. Potential reservoir

$$\begin{aligned} V &= 32.11 \text{ million acre-feet} \\ &= 40 \text{ km}^3 \end{aligned}$$

201.6. Effects of Self-Sealing and Fracturing

A geothermal reservoir of hydrothermal system usually has cap rocks to keep the water from flowing to the ground surface except for occasional or local discharge through the fractures which cut through the cap rocks. The thick, relatively impermeable shale or clay and volcanic units near the surface of the Salton Trough may serve as cap rocks for all the geothermal reservoir as exemplified in the Salton Sea and Cerro Prieto fields.

Heat transfer in a hydrothermal system is dominated by convection. The cap rocks act to confine the convection in the reservoir and hence drastically reduce the rate of heat loss to the space and preserve the geothermal energy. However, from the viewpoint of steady-state heat transfer, the cap rocks cannot stop the conductive heat loss to the space. This is why high geothermal gradients are usually found in areas overlying geothermal reservoirs.

No hot springs have been found to be associated with the KGRA in the Imperial Valley with the exception of mud pot activity in the Salton Sea area. It appears that the cap rocks have effectively sealed the reservoir. This effectiveness is probably in part due to self-sealing. Because of high temperature, water-rock interactions have significantly altered the characteristics of the sediments in the reservoir and cap rocks. Metamorphism and metasomatism are better studied in the supersaline Salton Sea field and the tiny Dunes anomaly. Both fields are not typical of the KGRA in the Imperial Valley. However, the knowledge obtained from these can be applied to other fields to understand the self-sealing mechanism if the excess mass calculated from the residual Bouguer gravity anomaly indicates the extent of metamorphism.

Diagenesis may occur both in the impermeable shale layers and permeable sand layers. In addition, potassium and silica metasomatism, a type of water-rock interaction involving the exchange of ions, may occur in the permeable layers and around the conduits (e.g., fractures) of water flow. Such metasomatism may lead to further reduction of porosity and increase in the effectiveness of the sealing. Both interstitial and fracture metasomatisms are found in the Dunes anomaly and are likely to occur in the other fields.

Fracture retrograde mineralization in the Dunes anomaly indicate that the seals or cap rocks can be fractured and exposed to cold water after they have been once subjected to the K-Si metasomatism. The closing and opening of fractures may change the flow patterns. The net effect of the two will control the amount of the recoverable resource. The intrinsic porosity and permeability in the reservoir are probably reduced to a small fraction of their original values owing to cementation by mineralization. Most of the fluids are contained in the fractures, not in the intrinsic pores.

Salton Trough is structurally an intracontinental rift valley, which is probably an extension of the East Pacific Rise through the Gulf of California. It is also part of the mega-shear zone along the San Andreas fault along which the North American plate and the Pacific plate pass each other. The Salton Trough is thus tectonically active, characterized by crustal rifting and shearing. Recent focal mechanism study and seismicity study suggest that the Imperial Valley is underlain by sets of en echelon spreading centers and transform faults. Microearthquake studies over the KGRA have revealed or confirmed the existence of several active faults. Ground noise and seismicity suggest that fracturing occurs frequently in the geothermal field. Because of high temperature, aseismic creep as a response to the regional tectonic stress may

have also occurred in the reservoir (it has not yet been studied). From the level of seismic activities, we may conclude that fracturing will certainly keep pace with self-sealing.

Withdrawal of hot fluids and reinjection of cold water may change the state of thermal stress-strain relation, in addition to the possible gravitational readjustment. Water reinjection may induce seismic activity as reported elsewhere. Thus, from the viewpoint of water extraction, reinjection may increase the fracturing rate (this will be further studied later in 201.9).

Section 201.7. Physical Properties of the Geothermal Fluid

a. Temperature

Temperature of the geothermal fluid has been measured in the known geothermal areas in the Imperial Valley. Since the temperature gradients in the hydrothermal convection systems are close to or slightly higher than the adiabatic gradient, the measured temperature can reasonably represent the temperature of the system at the accessible depth. They range from high temperature systems ($>150^{\circ}\text{C}$) to intermediate temperature systems (90° to 150°C): Salton Sea (340°C), Brawley (200°C), Heber (190°C), East Mesa (180°C), Border (160°C) and Dunes (135°C).

b. Flow Rate and Pressure

Flow rates of the geothermal fluid through the wells are related to the well head pressure, size of orifice, and duration of flow. These data are tabulated in Table 3 in which the data for the Salton Sea area are from a compilation made by Palmer (1976) and the data for the East Mesa field are from U. S. Bureau of Reclamation. For the other areas the information is not currently available.

The fluids will not flow usually through the wells unless the borehole water column is stimulated by injecting nitrogen to the well bottom to lift the water column and allowing thermal expansion to occur. Once the flow is initiated, the fluid will continue to flow unaided.

c. Source of Water

In a reconnaissance study of the geohydrology in the Imperial Valley, Loeltz et al. (1975) conclude on the basis of stratigraphy and chemical composition that the Colorado River is the most important source of ground-

Table 3. Production Characteristics

Well	Production Rate (lb/hr)	Wellhead Pressure (psi)	Date	Steam (%)	Orifice (in.)
Magma max #1	542,000	160	4-28-72	13	8
Magma max #1	405,000	96	4-29-72	14	8
Magma max #1	349,000	102	4-30-72	14	8
Magma max #1	339,000	122	5-1-72	15	8
Magma max #1	369,000	117	5-2-72	10	8
Magma max #1	399,000	103	5-3-72	13	8
Magma max #1	467,000	110	5-4-72	14	8
Sinclair #3	593,000	185	5-23-63	12	8
Sinclair #4	450,000	250	5-2-64	20	-
IID #1	625,500	200	6-62 90-day Test	25	7
IID #1	172,000	585	12-8-65	10	-
IID #1	375,000	485	12-9-65	11	-
IID #1	462,500	385	8-2-65	14	-
IID #1	500,000	285	-	17	-
IID #1	532,000	185	-	20	-
IID #2	377,000	212	3-64	18	8
IID #2	440,000	225	3-64	18	8
IID #2	349,700	263	3-64	16	8
IID #2	319,700	215	3-64	15	8
IID #2	395,400	225	3-64	14	8
Sportsman #1	327,000	248	4-61	15	5-1/2
Sportsman #1	293,000	205	4-61	16	5-1/2
Sportsman #1	324,000	200	-	17	5-1/2
State #1	305,000	465	6-64	15	8
State #1	364,000	400	6-64	18	8
State #1	405,000	347	6-64	20	8
Elmore #1	316,000	-	-	35	-
Hudson #1	432,333	-	8-64 4-day Test	22	7
River Ranch #1	244,700	-	10-65	20	7
Mesa 6-1	222,000	22		12	
Mesa 6-2	117,720	13.5		19	Open 8" pipe
Mesa 6-2	76,200	18		16	6" orifice
Mesa 6-2	49,800	45		11	8" pipe
Mesa 6-2	12,960	94		none	3" orifice
					8" pipe
					nearly closed
					6" pipe

water recharge in the Imperial Valley. Precipitation, local runoff, and underflow from tributaries contribute only a small fraction of the total storage in the deltaic, lacustrine deposits which lie over the marine Imperial Formation. Recharge is primarily northward underflow from Mexicali Valley and underflow through the alluvial section between the Cargo Muchacho Mountains and Pilot Knob when the Colorado River meanders into the Gulf of California.

Since the construction of the All American Canal and subsidiary canals, recharge to the shallow part of the groundwater reservoir has increased owing to the leakage from the canals and overirrigation. The groundwater table has risen 40 feet along the All American Canal between 1939 and 1960. Near the head of the Coachella Canal it was 40 feet and increased gradually northward to 70 feet. However, because of the extensive drainage network in the irrigated area, most of the water leaked from the canals drained via the Alamo River and New River to the Salton Sea. Therefore, recharge from canals is not important for aquifers deeper than a few hundred feet.

At present there is little knowledge about the hydrologic connection between the shallow, less saline groundwater and the deeper geothermal brines. Hence the determination of the sources of the geothermal brines must rely on the isotope studies. The technique is based on the fractionation of D/H and O^{18}/O^{16} . Precipitation from colder areas is lower in δD and δO^{18} than precipitation from warm regions. The δD is defined as

$$\delta D \text{ (in o/oo)} = \left(\frac{(D/H) \text{ sample}}{(D/H) \text{ standard}} - 1 \right) 1000$$

δO^{18} is similarly defined.

In the geothermal system δD is particularly useful for the determination of the sources of brines. The change in the isotopic composition D/H of water flowing through the system is negligible because the rocks contain little hydrogen. On the basis of δD study, Coplen et al. (1975) have concluded that the geothermal fluids in the Dunes, East Mesa, and Heber anomalies originated from the Colorado River.

The origin of the Salton Sea geothermal brines is not yet understood beyond any controversies. Helgeson (1968) proposed that the brine was the interstitial connate Colorado River water and the salinity was increased by evaporative flashing. On the other hand, Craig (1966, 1969) suggested the brines were formed by leaching of sediments by local precipitation circulating downward to a geothermal reservoir. Semi-membrance filtration by the impermeable clay layers is also an important mechanism for the increase of salinity.

The Colorado River water as a source for the geothermal brines means the present underflow water or the connate water. The former is less saline and dominates the southern part of the Imperial Valley. The latter, because of evaporative flashing, is more saline and becomes more important toward the north. Since some aquifers are not connected hydrologically, large variation in the salinity may occur, depending on where the well is perforated. The variation of TDS among the East Mesa wells (Table 4 and Fig. 4) testifies to this hypothesis. As a whole, waters from local meteoric water and juvenile water released from magma are negligible compared to the Colorado River waters.

d. Recharge Rate

Because the origin of the geothermal fluid is not yet clear, the estimate on the recharge rate can only be made indirectly. Observation of the

Table 4. Salt Contents (mg/liters) of Brine in the Geothermal Fields

	Na	K	Ca	Mg	HCO ₃	Cl	SO ₄	SiO ₂	TDS
<u>East Mesa</u>									
5-1	798	48.9	46.5	4.01	705	825	196	130	2,390
6-1	9,002	1,047	896	15	126	15,868	192	128	28,110
6-2	918	65.3	40		1,248	776	206	195	2,830
8-1	723	42	41.1	1.6	668	556	225	263	2,463
31-1	782	25	96.6	1.1	467	490	172	88	2,311
<u>Salton Sea</u>									
IID.1	55,500	18,200	30,500			168,000	30		278,000
IID.2	53,000	16,500	27,800	10	390	155,000			258,765
Sportsman 1	70,000	24,000	34,470	18		201,757	34		334,987
Sinclair 3	36,340	7,820	14,550	780	60	93,650	58		183,700
Sinclair 4	78,000	20,690	37,735	2,225		210,700	75		387,500
Brawley	19,900	2,400	2,560	1,360	1,562	31,000	865		59,949
Western Geothermal	14,500	3,000	3,880	194	200	31,600	162		53,975

pressure drop in the production wells may reveal the information on recharge rates. Since these data are not available, we have to rely on the isotopic composition in the fluid and rock. From that we may estimate how much water and rocks have interacted to produce the present isotopic composition. This estimate represents long-term average whereas the value obtained from well test indicate the present flow rate.

Rocks and waters contain large quantity of oxygen. Originally they have different isotopic composition. As times go on, one will be enriched and the other depleted. δO^{18} data indicate that 1 to 4 times the amount of water now in the East Mesa geothermal system over the interval 2500 to 8000 feet has flowed through the system undergoing oxygen isotope exchange (Coplen, 1976). In the Salton Sea geothermal field, at depths of about 3000 to 6000 feet, the volumes of water and rock that have undergone exchange are roughly equal. Because the ages of the reservoirs are not known at present, we cannot estimate the natural recharge rates.

Section 201.8. Salinity and Chemical Composition of the Geothermal Fluid

Chemical analysis is usually made for the unflashed geothermal fluid collected at the well head. The reported composition of fluid varies from wells to wells in a given geothermal field. The composition may also vary for different production zones. Measurements made at different times show occasionally some minor variation too. Available data are listed in Table 5-1 for the Salton Sea geothermal field (compiled by Palmer, 1976), Table 5-2 for the East Mesa geothermal fields (anonymous, U. S. Bureau of Reclamation, 1976), and Table 5-3 for the Dunes anomaly (Coplen, 1976). It should be noted that these analyses were made with various techniques and conditions. Absence of certain chemical species or elements in the list does not imply their absence in the geothermal flux.

Complete chemical analyses are costly. To estimate the total dissolved solid in the geothermal fluid, it is easier, faster, and cheaper to measure the electrical conductivity of the fluids. For this purpose, 8 data points have been plotted to give an empirical relation for the total dissolved solid and the conductivity of the geothermal fluids based on data from the Salton Sea; Cerro Prieto, and East Mesa geothermal field (Fig. 4). A theoretical relation is difficult, if not impossible at present, to derive for the highly concentrated fluid. A few data points for the Salton Sea water, groundwater, and spring waters are also shown there. These points fall to the upper left of the empirical curve, indicating the total dissolved solids in the near surface waters are more than the quantities suggested by the conductivity measurements.

Geothermal brine from the Salton Sea field is dominated by NaCl with salinity commonly exceeding 250,000 ppm (total dissolved solid, TDS).

Other characteristics include pH $\approx$ 5, sulphate $<$ 100 ppm, boron $>$ 200 ppm, ammonium $\approx$ 400 ppm, specific gravity $\approx$ 1.2 to 1.3, potassium/sodium ratio $\approx$ 15 and high trace element concentrations (particularly Ba, Fe, Mn, Pb, and Zn).

The geothermal fluids from the East Mesa and the Dunes anomalies are less saline than sea water. In general TDS is less in the East Mesa field than the Cerro Prieto field but values as high as 2.6% has been reported for the Mesa 6-1 well (see Fig. 4).

Care should be taken not to confuse the TDS in the shallow groundwater and geothermal brines. Both appear to be more saline toward the Salton Sea but the two water bodies are not connected. They are separated by the impermeable layers (or cap rocks) which cover the geothermal reservoir. Chemical composition of the shallow ground water can be found in the publication compiled by the California Department of Water Resources (Bulletin 143-7) and the U. S. Geological Survey (Loeltz and others, 1975; Dutcher et al., 1972).

Table 5-1. Chemical analysis of geothermal well brines.
(Salton Sea)

Brine composition (ppm)		
Constituent	Pioneer Dev. Co. #3 ^{a,b} (Ref. 9)	State of Calif. #1 ^{a,c} (Ref. 5)
Aluminum	-- ^d	--
Ammonia (NH ₄)	--	--
Antimony	--	--
Arsenic	--	--
Barium	--	190
Boron	--	290
Bromine	--	--
Calcium	16,000	21,200
Cesium	--	17
Chlorine	68,000	127,000
CO ₂ as HCO ₃	300	6,900 ^e
Copper	--	2
Fluorine	--	--
Iodine	--	--
Iron	--	1,200
Lead	--	80
Lithium	--	180
Magnesium	--	27
Manganese	4,000	950
Nitrate (NO ₃)	1,050	--
Potassium	--	14,000
Rubidium	--	65
Silica	--	--
Silver	--	<1
Sodium	20,400 ^f	47,800
Strontium	--	--
Sulfate (SO ₄)	200	--
Sulfide Sulfur	--	30
Zinc	--	500
Summary Data		
Total of the above constituents ^g :	109,950	220,432
Total dissolved solids reported:	110,000 ^h	219,500
pH:	6.5	--
Specific gravity:	--	--
Bottom hole temperature:	>70°C	305°C

Table 5-1 (Continued)

Constituent	Sportsman #1 ^{a,b} (Ref. 10)	Magma Max #1 ^b (Ref. 7)	Magma Max #1 ^b (Ref. 7)
Aluminum	--	--	--
Ammonia (NH ₄)	--	--	--
Antimony	--	--	--
Arsenic	--	--	--
Barium	--	--	--
Boron	149 ^e	--	500
Bromine	--	--	--
Calcium	34,470	2,818	25,000
Cesium	--	--	--
Chlorine	201,757	20,548	--
CO ₂ as HCO ₃	--	--	--
Copper	--	--	--
Fluorine	--	--	--
Iodine	--	--	--
Iron	4,200	93	--
Lead	--	--	--
Lithium	150	28	--
Magnesium	18	46	--
Manganese	--	10	200
Nitrate (NO ₃)	--	--	--
Potassium	24,000	142	5,000
Rubidium	--	--	--
Silica	5	108	500
Silver	--	--	--
Sodium	70,000	8,562	52,500
Strontium	--	--	--
Sulfate (SO ₄)	34 ^e	--	--
Sulfide Sulfur	--	--	--
Zinc	--	--	--
Summary Data			
Total of the above constituents ^g :	334,783 ^g	32,355 ^g	83,700 ^g
Total dissolved solids reported:	334,987 ^h	38,072 ^h	--
pH:	4.82-6.10	6.65	--
Specific gravity:	1.207 ⁱ	1.022 ⁱ	--
Bottom hole temperature:	310°C	265°C	--

Table 5-1 (Continued)

Constituent	Woolsey #1 ^b (Ref. 7)	Woolsey #1 ^b (Ref. 7)	Woolsey #1 ^b (Ref. 7)
Aluminum	--	--	--
Ammonia (NH ₄)	--	--	--
Antimony	--	--	--
Arsenic	--	--	--
Barium	--	--	--
Boron	--	--	--
Bromine	--	--	--
Calcium	8,550	7,284	12,658
Cesium	--	--	--
Chlorine	59,015	49,342	83,183
CO ₂ as HCO ₃	--	--	--
Copper	--	--	--
Fluorine	--	--	--
Iodine	--	--	--
Iron	84	141	244
Lead	--	--	--
Lithium	65	63	90
Magnesium	651	113	136
Manganese	121	150	488
Nitrate (NO ₃)	--	--	--
Potassium	2,881	3,055	6,510
Rubidium	--	--	--
Silica	112	141	181
Silver	--	--	--
Sodium	49,257	28,195	49,729
Strontium	--	--	--
Sulfate (SO ₄)	--	--	--
Sulfide Sulfur	--	--	--
Zinc	--	--	--
Summary Data			
Total of the above constituents ^g :	120,735	88,484	153,219
Total dissolved solids reported:	131,732 ^h	98,624 ^h	151,237 ^h
pH:	6.2	6.45	6.25
Specific gravity:	1.076 ⁱ	1.064 ⁱ	1.106 ⁱ
Bottom hole temperature:	238°C	238°C	238°C

Table 5-1 (Continued)

Constituent	IID. #1 ^{a,c} (Ref. 11)	IID. #1 ^{a,j} (Ref. 9)	IID. #1 ^{a,b} (Ref. 12)	IID. #1 ^{a,b} (Ref. 12)
Aluminum	--	450	--	--
Ammonia (NH ₄)	409	482	--	--
Antimony	<1	<1	--	--
Arsenic	12	15	--	--
Barium	235	200	--	--
Boron	390	520	432	745 ^e
Bromine	120	146	--	--
Calcium	28,000	40,000	34,430	30,500
Cesium	16	22	--	--
Chlorine	155,000	185,000	200,000	168,000
CO ₂ as HCO ₃	>150	--	--	--
Copper	8	10	--	--
Fluorine	15	18	--	--
Iodine	18	22	--	--
Iron	2,090	3,200	3,416	2,000
Lead	84	104	--	--
Lithium	215	300	--	--
Magnesium	54	35	486	--
Manganese	1,560	2,000	30	1,300
Nitrate (NO ₃)	--	35	--	--
Potassium	17,500	24,000	29,900	18,200
Rubidium	137	168	--	--
Silica	400	>110	26	10
Silver	<1	1	--	--
Sodium	50,400	51,000	76,000	55,500
Strontium	609	740	--	--
Sulfate (SO ₄)	5	56	--	30
Sulfide Sulfur	16	--	--	--
Zinc	790	970	--	--
Summary Data				
Total of the above constituents ^g :	258,235 ^g	309,605 ^g	344,720 ^g	276,285 ^g
Total dissolved solids reported:	258,360 ^h	319,000 ^h	340,816 ^e	278,000 ^h
pH:	--	--	5.1	3.9
Specific gravity:	--	1.264 ^k	1.235 ^k	1.239 ^k
Bottom hole temperature:	316°C	316°C	316°C	316°C

Table 5-1 (Continued)

Constituent	IID. #2 ^{a,c} (Ref. 11)	IID. #3 ^{a,c} (Ref. 13)
Aluminum	--	2
Ammonia (NH ₄)	--	321
Antimony	--	--
Arsenic	--	<1
Barium	250	3
Boron	390	100
Bromine	--	15
Calcium	28,800	1,130
Cesium	20	--
Chlorine	155,000	19,700
CO ₂ as HCO ₃	690	1,880
Copper	3	--
Fluorine	--	1
Iodine	--	5
Iron	2,000	<1
Lead	80	--
Lithium	210	40
Magnesium	10	74
Manganese	1,370	6
Nitrate (NO ₃)	--	9
Potassium	16,500	1,250
Rubidium	70	--
Silica	400	120
Silver	<1	--
Sodium	53,000	10,600
Strontium	440	85
Sulfate (SO ₄)	--	621
Sulfide Sulfur	30	--
Zinc	500	--
Summary Data		
Total of the above constituents ^g :	259,764 ^g	35,964 ^g
Total dissolved solids reported:	258,765 ^h	35,600 ^h
pH:	--	7.5
Specific gravity:	--	1.023 ^k
Bottom hole temperature:	332°C	188°C

Table 5-1 (Continued)

Constituent	Sinclair #3a,b (Ref. 14)	Sinclair #3a,b (Ref. 14)
Aluminum	--	--
Ammonia (NH ₄)	340	570
Antimony	--	--
Arsenic	10	10
Barium	540	570
Boron	210	--
Bromine	--	--
Calcium	14,550	23,000
Cesium	--	--
Chlorine	93,650	141,500
CO ₂ as HCO ₃	60	--
Copper	--	1
Fluorine	2	5
Iodine	--	--
Iron	--	--
Lead	80	200
Lithium	49	80
Magnesium	780	1,940
Manganese	410	1,000
Nitrate (NO ₃)	--	--
Potassium	7,820	13,200
Rubidium	--	--
Silica	--	--
Silver	--	--
Sodium	36,340	50,600
Strontium	360	510
Sulfate (SO ₄)	58	--
Sulfide Sulfur	--	--
Zinc	--	--
Summary Data		
Total of the above constituents ^g :	155,259	233,186
Total dissolved solids reported:	183,700 ^h	276,100 ^h
pH:	5.3	4.3
Specific gravity:	1.114 ^k	1.180 ^k
Bottom hole temperature:	252°C	252°C

Table 5-1 Continued)

Constituent	Sinclair #4 ^{a,b} (Ref. 14)	Sinclair #4 ^{a,c} (Ref. 15)
Aluminum	<100	--
Ammonia (NH ₄)	--	--
Antimony	--	--
Arsenic	--	10
Barium	1,100	--
Boron	--	332
Bromine	--	25
Calcium	37,735	26,992
Cesium	--	--
Chlorine	210,700 ^e	154,590
CO ₂ as HCO ₃	--	--
Copper	3	--
Fluorine	--	14
Iodine	--	13
Iron	1,300	1,148
Lead	60	--
Lithium	400	287
Magnesium	2,225	736
Manganese	1,700	1,025
Nitrate (NO ₃)	--	5
Potassium	20,690	14,918
Rubidium	--	--
Silica	625	90
Silver	1	--
Sodium	78,000	58,443
Strontium	455	434
Sulfate (SO ₄)	75	19
Sulfide Sulfur	--	--
Zinc	600	--
Summary Data		
Total of the above constituents ^g :	355,769	259,523
Total dissolved solids :	387,500 ^h	266,560 ^h
pH:	5.0	5.3
Specific gravity:	--	1.22 ^k
Bottom hole temperature:	260°C	260°C

Table 5-1 (Continued)

Constituents	Sinclair #4 ^{a,b} (Ref. 16)	Sinclair #4 ^{a,b} (Ref. 16)	Sinclair #4 ^{a,b} (Ref. 16)	Sinclair #4 ^{a,b} (Ref. 16)
Aluminum	--	--	--	--
Ammonia (NH ₄)	--	--	--	--
Antimony	--	--	--	--
Arsenic	--	--	--	--
Barium	--	--	--	--
Boron	--	--	--	--
Bromine	--	--	--	--
Calcium	26,300	20,200	22,200	23,400
Cesium	--	--	--	--
Chlorine	--	--	--	--
CO ₂ as HCO ₃	--	--	--	--
Copper	--	--	--	--
Fluorine	--	--	--	--
Iodine	--	--	--	--
Iron	--	--	--	--
Lead	--	--	--	--
Lithium	--	--	--	--
Magnesium	--	--	--	--
Manganese	--	--	--	--
Nitrate (NO ₃)	--	--	--	--
Potassium	18,000	13,300	12,400	13,700
Rubidium	--	--	--	--
Silica	--	--	--	--
Silver	--	--	--	--
Sodium	53,800	52,000	46,600	52,500
Strontium	--	--	--	--
Sulfate (SO ₄)	--	--	--	--
Sulfide Sulfur	--	--	--	--
Zinc	--	--	--	--
Summary Data				
Total of the above constituents ^g :	98,100	85,500	81,200	89,600
Total dissolved solids reported:	--	--	--	--
pH:	--	--	--	--
Specific gravity:	--	--	--	--
Bottom hole temperature:	--	--	--	--

Table 5-1 Footnotes

^a Average analysis.

^b Not known if corrected for steam loss.

^c Corrected for steam loss.

^d Spaces marked with dashes indicate values not reported.

^e Computed.

^f Sodium and potassium.

^g The number is determined by summing all the constituents identified above - but it does not necessarily include all those present in the brine.

^h The number is determined by analyzing all the dissolved solids present in the brine.

ⁱ Specific gravity at 20°C.

^j Not corrected for steam loss.

^k Specific gravity at 25°C.

Table 5-2. (Continued)

Ammonia (NH ₄)	40.75	14.7	4.95	2.45
Beryllium (Be)	<0.02	<0.02	<0.02	<0.01
Cesium (Cs)	2.75	0.38	0.14	0.20
Bismuth (Bi)	3	0.005	<0.005	<0.005
Mercury (Hg)	0.002	0.002	0.014	0.008
Arsenic (As)	0.26	0.22	0.053	0.025
Selenium (Se)	<0.1	<0.1	0.5	1.8
Antimony (Sb)	5.5	0.90	1.2	1.0
Tantalum (Ta)	0.14	0.17	0.12	0.10
Niobium (Nb)	0.40	0.40	0.40	0.40
Sodium (Na)	8,100	1,700	610	730
Calcium (Ca)	1,360	16.4	8.5	8.9
Strontium (Sr)	320	6.4	2.1	1.4
Germanium (Ge)	<0.1	<0.1	<0.1	<0.1
Indium (In)	<0.1	<0.1	<0.1	<0.1
Gold (Au)	0.01	0.01	0.024	0.080
Palladium (Pd)	<0.1	<0.1	<0.1	<0.1
Platinum (Pt)	<0.1	<0.1	<0.1	<0.1
Cobalt (Co)	0.06	<.01	<0.01	<0.01
Iridium (Ir)	<0.1	0.1	<0.1	<0.1
Tungsten (W)	<0.1	<0.1	<0.1	<0.1
Aluminum (Al)	0.04	0.03	0.02	0.02
Boron (B)	9.75	7.45	1.60	2.50
Chromium (Cr)	0.01	<0.01	<0.01	<0.01

Table 5-2. Chemical Composition of Geothermal Brines from East Mesa

Chloride (Cl^-)	15,850	2,142	500	510
Sulfide ($\text{S}^{=}$)	3.0	1.5	1.0	0.3
Conductivity (at 25°C)	40,000	6,000	3,200	4,700
Silica (SiO_2)	320	269	389	274
pH	5.45	6.12	6.27	6.27
Total Dissolved Solids (TDS)	26,300	5,000	1,600	2,900
Titanium (Ti)	<0.10	<0.10	<0.10	<0.10
Iron (Fe)	8.8	<0.10	<0.10	<0.10
Lithium (Li)	40.0	4.0	1.1	0.60
Potassium (K)	1,050	150	70	85
Copper (Cu)	<0.10	<0.10	<0.10	<0.10
Magnesium (Mg)	17.2	0.24	<0.05	<0.05
Molybdenum (Mo)	<0.005	<0.005	<0.005	<0.005
Zinc (Zn)	0.07	<0.01	<0.01	<0.01
Manganese (Mn)	0.95	0.05	<0.05	<0.05
Nickel (Ni)	0.10	<0.10	<0.10	<0.10
Barium (Ba)	14	0.25	0.15	0.15
Bicarbonates (HCO_3^-)	202	560	417	845
Carbonates ($\text{CO}_3^{=}$)	0.0	0.0	0.0	0.0
Sulfate ($\text{SO}_4^{=}$)	42.8	156	173	183
Fluoride (F)	0.99	1.23	1.60	1.42
Nitrate (NO_3^-)	0.02	0.1	0.34	0.43
Phosphate ($\text{PO}_4^{=}$) Total	<0.01	<0.2	<0.1	<0.1
Cadmium (Cd)	<0.01	<0.01	<0.01	0.02

TABLE 5-3
CHEMICAL AND ISOTOPIC COMPOSITION OF
WATER SAMPLES FROM DWR DUNES #1

	From 259-271-meter perforation in ppm September, 1972	From 259-271-meter perforation in ppm May, 1974	From 104-116-meter perforation in ppm May, 1974
lithium	0.4	1.85	1.85
sodium	609	980	1262
potassium	72	107	103
magnesium	3.0	1.4	1.7
calcium	17	101	136
strontium		0.5	0.6
manganese	0.0	0.07	0.07
iron	0.03	0.03	0.36
copper	0.12	0.09	0.00
zinc	0.15		1.14
cadmium	0.0	0.05	0.10
arsenic	0.0	0.02	0.06
lead	0.05	0.00	0.00
fluoride	8.9	1.9	4.6
chloride	583	2040	2021
bromide		1.28	1.26
iodide	0.01	0.13	0.094
sulfate	497	140	178
nitrate		0.0	0.0
bicarbonate ¹		67	76
carbonate ¹		0.03	0.04
ammonia			0.84
pH ¹		6.43	6.58
boron	1.5	1.9	2.2
silica			118
TDS	1870	3950	3940
δD	-102 ‰	-88 ‰	-88 ‰
δO^{18} (SMOW)	-12.33 ‰	-10.80 ‰	-10.87 ‰
δC^{13} of bicarbonate (PDB)			-8.6 ‰

¹Field analysis; all other analyses are laboratory analyses

Section 201.9. Effects of Fluid Withdrawal and Injection

(Earthquake potential due to geothermal withdrawal is assessed in Section 201.9.1.)

The effects of fluid withdrawal on the temperature depends on the following variables: production rates, injection rates, heat capacity, thermal diffusivity, viscosity, pressure, porosity, permeability, and water-rock chemical interaction. The temperature change will certainly be a function of position. Since one is not very interested in the detail temperature distribution, we may estimate the temperature change as a whole in the reservoir by the following relation

$$(\rho sv)_{\text{fluid}} + (\rho sv)_{\text{rock}} \Delta T = MW/\epsilon$$

where ρ = density, s = specific yield, v = volume, ϵ = efficiency. For the Salton Sea geothermal field, the temperature change is

$$\Delta T \approx 0.23 \times 10^{-10} \text{ }^{\circ}\text{C/sec/MW}$$

and for each MW·Y power production, it decreases by about $7.2 \times 10^{-4} \text{ }^{\circ}\text{C}$ per year. In this estimate, the reservoir is assumed to have been fully recharged and a uniform reservoir temperature at all times. At this rate it will take ~0.3 million years to cool the Salton Sea field from 340°C to 100°C at 1 MW, and 300 years at 1000 MW power production.

Pressure variations are expected to be small. All wells drilled to the geothermal reservoirs are not artesian wells. However, if the water column is lifted by injecting nitrogen to the bottom of the wells, the fluids continue to flow unaided. Since the reservoir is so large compared to the

fluid mass withdrawn or injected, pressure variation will not be appreciable. To a certain extent temperature and pressure variation depend on how the production and injection wells are spaced horizontally and vertically.

Fluid composition will not change if there is no recharge. If the reservoir is recharged naturally or artificially, the chemical composition is expected to change. This change can be estimated from the quantities and compositions of the fluids withdrawn and recharged by a simple mixing model if there is rock-water interaction. However, the interaction is definitely going to happen. Suppose the fluids and rocks are initially at equilibrium. The introduction of the alien water to the reservoir will offset the equilibrium. So the fluid composition cannot be estimated from a simple mixing model. The fluid-rock interaction will tend to minimize the magnitude of the variations expected of a mixing model. In other words, the rocks act as a buffer to the chemical compositional change. The evaluation of the composition change is more difficult than the estimation of temperature and pressure changes because many chemical species are involved in the complicated water-rock interactions.

Section 201.9.1. Earthquake Potential Induced by Geothermal Energy Extraction

Geothermal power production may induce a sequence of earthquakes owing to thermal strain release. The likely magnitudes and frequency of the induced earthquakes are constrained by the volumetric seismic moment M_0 as calculated from thermal contraction of reservoir rocks. If the tectonic and thermal stress drops are equivalent, the estimated magnitude agrees within 0.4 unit (Richter scale) of the observed magnitude for three events of different stress drops which occurred along a fault running through the Salton Sea geothermal field, Imperial Valley, California. An empirical earthquake frequency curve and the calculated M_0 are used to estimate the increased earthquake frequency and the cutoff magnitude. For 100 megawatt-year power production the cutoff magnitude is 4.1 and for 1000 megawatt-year it is 4.8, while the earthquake frequencies increase 2 and 6.5 times per year, respectively. Natural conduction cooling in the Salton Sea field at a rate of 58 megawatts may yield one event with magnitude 3.4 per year. Events with magnitude 3.4 ± 0.2 occur three times a year there in response to both tectonic and thermal stresses.

For detail: see Appendix

Section 201.10. Total Recoverable Heat

Heat in the hydrothermal systems is stored in the fluid and rocks of the reservoirs. The heat capacity of the geothermal fluid is $1 \text{ cal/cm}^3\text{ }^\circ\text{C}$ and that of the rocks is $0.6 \text{ cal/cm}^3\text{ }^\circ\text{C}$. Since the porosity of the reservoirs on the average is 20%, the heat stored in the rocks is approximately 2 1/2 times greater than the heat storage in the fluid, which is estimated in Section 201.3 for individual geothermal fields on an assumed specific yield of 16%. Total heat storage, therefore, should be multiplied by 3.75. That is for a density contrast of 0.2 gm/cm^3 , the total heat is 379×10^{18} joules instead of 101×10^{18} joules listed in Table 1 for all the known geothermal fields in the Imperial Valley.

Heat for the electrical power production can be recovered only by means of liquid media. If specific yield remains constant and the recharge keeps pace with discharge, almost all of 300×10^{18} joules will be utilized, provided that the extraction rates are not in excess of several kW from a given field. If there is no recharge at all, the total heat recoverable will be those listed in Table 1. Because natural recharge rates are very small compared to the commercial production rates, fluid injection is required for the recovery of any additional heat.

Since the Salton Sea geothermal field was formed, a quantity of fluids nearby equal to the present fluid volume has interacted with the reservoir rocks while in the East Mesa anomaly the interacted fluid mass is roughly 3 to 4 times of the present one. It appears, hence, the natural recharge by the underflow of the Colorado River is greater to the south and smaller to the north. This implies more fluid injection is needed toward the north of the Imperial Valley.

Some heat is stored in the fluids trapped in the impermeable layers (e.g. shale, clay). These fluids are usually not available. However, as the fluid in the permeable zones are extracted, the pore pressure in the permeable zones will decrease, and pore pressure in the impermeable zones will appear to increase relatively. Inequilibrium in the pore pressures may create microfractures through which the trapped fluid may communicate with the fluids in the permeable zones. The fluids in the impermeable layer act as an additional fluid reserve. The size of such reserve cannot be evaluated at present for lack of sufficient observational and experimental data.

201.11. Evaluation of the By-Products of the Geothermal Resources

An extensive investigation into the use of the geothermal fluids for producing desalinated water has been made by the Bureau of Reclamation for the East Mesa area and is reported in their status report. The production of water from the agricultural portion of the Valley would be complicated by the subsidence problem unless sufficient low quality mark-up water could be found to supplement the reinjection fluids.

201.12. Estimation of the Life Expectancy of the Resource

The life expectancy of the resource depends critically on the estimates of the total heat in storage, the rate at which additional heat is supplied, and the production rate.

The estimates of total available heat in storage in the fluid as given in Section 201.3 range from 65×10^{18} joules to 202×10^{18} joules. If we consider extracting heat from the rocks as well as the fluid these estimates would range between 245×10^{18} and 757×10^{18} joules (see Section 201.10). These estimates also assume that all of the geothermal areas in the Valley are associated with gravity anomalies. If this is not true, these numbers represent a minimum for the total heat available.

The rate at which additional heat is supplied was estimated in Section 201.2 based on an average spreading rate of 6 cm/yr and an approximate length of 60 km. About 5×10^{16} joules/year of heat is added to the system. This value must be looked at as a crude estimate average over long periods of geologic time. The actual value for any given year could conceivably vary by a couple of orders of magnitude. However, this number indicates that it would take approximately 5,000 to 15,000 years to replace all of the heat in storage at the present time, assuming there is no heat loss from the system. About 4 to 5 times (~20,000 to 60,000 years) appears to be a more realistic number considering both convective and conductive heat loss as well as leakage to the surface directly or the geothermal fluids.

To produce 5000 MW/year from the entire Imperial Valley System assuming an electrical conversion efficiency of 10% would require the extraction of 1.5×10^{18} joules of heat in storage.

$$1 \text{ MW/year} = 7.53 \times 10^{18} \text{ Cal} = 31.52 \times 10^{12} \text{ joules}$$

$$5000 \text{ MW/year} = 150 \times 10^{15} \times e_c = 1.5 \times 10^{18} \text{ J} - e_c = 10\%.$$

This estimate is about 100 times larger than the rate at which heat would be supplied by spreading. Thus based on these calculations the resource has a finite life span. This life span can be estimated on the basis of the total heat in storage (245 to 757×10^{18} joules) divided by 1.5×10^{18} joules which gives a range of 150 to 500 years if 5000 MW is produced every year and the effects of thermal recharge are neglected.

These estimates should be regarded as rather crude because of the uncertainty in the underlying assumptions. We have tried to error on the conservative side in all instances. Thus these estimates are probably a minimum. Development of new technology which would increase the efficiency of thermal conversion or the discovery of additional geothermal reservoirs could easily double or triple these estimates.

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Figure 1

Figure 2

Figure 3

Figure 4. Salinity vs electrical conductivity.

APPENDIX I

An Evaluation of Earthquake Potential Induced by
Geothermal Energy Extraction

Institute of Geophysics and Planetary Physics
University of California, Riverside
Riverside, California 92502

December, 1976

ABSTRACT

Geothermal energy extraction may induce a sequence of earthquakes in areas with significant tectonic stress owing to the addition of thermal stress. We attempt to estimate the likely magnitudes and frequency of the induced earthquakes, using the volumetric seismic moment M_0 calculated from thermal contraction of reservoir rocks as a constraint. If tectonic stress drops and thermal stress release are equivalent, the estimated magnitude agrees within 0.4 unit (Richter scale) of the observed magnitude for three events of different stress drops which occurred along a fault running through the Salton Sea geothermal field, Imperial Valley, California. An empirical curve of earthquake frequency distribution and the calculated M_0 are used to estimate the increased earthquake frequency and the cutoff magnitude. For 100 and 1000 megawatt·year power production the earthquake frequencies are expected to increase 2 and 6.5 times per year, respectively and the corresponding cutoff magnitudes are probably less than 4.1 and 4.8.

INTRODUCTION

Extraction of geothermal fluid from a reservoir may induce thermal stress and volume contraction. Seismic hazards and rates of land subsidence may hence be increased in the vicinity of the geothermal development. Even if the extraction is compensated by fluid injection or natural recharge, subsidence and strain accumulation in a geothermal area are still expected owing to thermal contraction in a reservoir with decreasing temperature. Here we attempt to evaluate the earthquake potential from the inferred seismic moment as functions of the energy extraction from the Salton Sea geothermal area which is the largest in the Imperial Valley, California. From the total seismic moment we may estimate the maximum magnitude of earthquakes to be expected as a result of the geothermal energy extraction.

A microearthquake study in the north-central California indicates most of the events occur in or near the area of The Geysers geothermal development (Bufe and Lester, 1975). They are shallow and of normal-faulting type. Because the seismicity in The Geysers area was not known before the commercial development, we do not know how much the activity is caused by the geothermal energy extraction. The Salton Sea geothermal area is not yet commercially developed, it is imperative to estimate the earthquake potential in advance. This paper presents the results of an evaluation based on several empirical relations and assumptions which can be refined in the future. The method used here may or may not be applicable to other geothermal areas located in different seismotectonic regimes.

SEISMIC MOMENT

The volumetric seismic moments M_o is related to volume change ΔV by

$$M_o = K\mu |\Delta V| \quad (1)$$

where μ = rigidity, and K = a factor ranging from 1/2 to 4/3 depending on the orientation of stresses. McGarr (1976) has shown some convincing correlations between volumetric seismic moment with those calculated by other means for earthquakes associated with the extraction of mine stopes in South Africa, the collapse of a caldera in the Galapagos Islands, the injection of waste fluid into impermeable strata in Colorado, and the ground movement in Matsushiro, Japan.

We use the thermal contraction to calculate the seismic moment. This is because in the case of permeable reservoirs such as oil fields and geothermal fields, the volume change cannot be directly obtained from the volume of fluid withdrawn. From the definition of volume expansion coefficient

$$\alpha = d \ln V / dT \quad (2)$$

the volume change ΔV of the reservoir with initial volume V_o due to temperature change from T_o to T is

$$\Delta V = V_o \left[\exp \left(\int_{T_o}^T \alpha dT \right) - 1 \right] \quad (3)$$

assuming that the fluid withdrawal is compensated by the natural recharge or artificial fluid injection.

Temperature change is coupled to the rate of power production $\dot{J}$ from time t_0 to time t by the principle of energy conservation,

$$\int_{T_0}^T (\rho_f S_f V_f + \rho_r S_r V_r) dT = \int_{t_0}^t (\dot{J}/\epsilon + \dot{G}) dt \quad (4)$$

assuming the fluid in the reservoir is well stirred by convection to have an uniform temperature. Here ρ = density, V = volume, S = specific heat, $\dot{G}$ = rate of heat gain or loss in the reservoir besides the loss through the production wells, ϵ = efficiency in converting heat energy into electrical energy, and the subscripts r and f refer to reservoir rocks and fluid respectively. The assumption of a uniform reservoir temperature represents a first order approximation. A more realistic approximation seems unwarranted at present for lack of adequate data. The reservoir temperature before any commercial production is not necessarily uniform even in a convective system. Under production the reservoir temperature will be affected by various factors controlling the mass and heat transfer such as the flow rate and duration of production and injection, well distribution, physical and chemical properties of rocks and fluids.

Since the physical properties of the reservoir rocks and fluids as functions of temperature are usually poorly known, the estimate of seismic moment can be simplified to a first approximation by taking the mean values of the physical parameters in the temperature range of interest,

$$M_0 \approx K \mu V_0 \alpha \frac{\dot{J} \Delta t}{\epsilon (\rho_f S_f V_f + \rho_r S_r V_r)} \quad (5)$$

where Δt = duration time for the stress build-up, i.e., the time interval between successive events assuming the thermal stress is released as stress drop. In the derivation of eq. (5), the $\dot{G}$ term is neglected because in geothermal energy production $\dot{G} \ll \dot{J}/\epsilon$.

From the empirical relation between seismic moment and magnitude (Brune, 1968; Thatcher and Hanks, 1973)

$$\log M_o = a + b M \quad (6)$$

we have the expected earthquake magnitude as a function of the rate of power generation and the duration of stress build-up.

$$M \approx C + \frac{1}{b} \log (\dot{J} \Delta t) \quad (7)$$

where the constant C is defined by

$$C \equiv \left\{ -a + \log \left[\frac{K \mu V_o \alpha}{\epsilon (\rho_f S_f V_f + \rho_r S_r V_r)} \right] \right\} / b \quad (8)$$

Eq. (7) is exemplified in Fig. 1 by

$$M = 3.06 + 0.67 \log \Delta t \dot{J} \quad (9)$$

where Δt is in years and $\dot{J}$ is in MW assuming $K = 1$, $\mu = 4 \times 10^{11}$ dyne/cm², $\alpha = 9 \times 10^{-6}/^\circ\text{C}$, $\epsilon = 0.10$, $\rho = 1$ g/cm³, $S = 4.18 \times 10^7$ ergs/g $^\circ\text{C}$. The porosity of the reservoir rocks V_f/V_r is assumed to be 0.20, and the regional values of $a = 16.0$ and $b = 1.5$ in southern California (Thatcher and Hanks, 1973) are taken as the expected values in the Imperial Valley. The heat capacity for ordinary rocks is $\sim 2.59 \times 10^7$ ergs/cm³ $^\circ\text{C}$ and that of water is $\sim 4.18 \times$

10^7 ergs/cm³°C. As an example for the interpretation of eq. (9), a 100 MW-power plant may generate an earthquake with maximum magnitude of 4.4 if the thermal stress has accumulated for one year without any strain release before that event occurs. The maximum magnitude will be 5.4 if the total thermal strain accumulated over 30 years is released in one event.

STRESS DROPS

Earthquakes are associated with stress drops in the focal region. The induced thermal stress will be added to the existing tectonic stress. The resultant total stress, if large enough, may fracture the rocks or cause movement along pre-existing fractures. If the thermal stress is released as the stress drop during an earthquake, it is interesting to see whether the inferred earthquake magnitude is comparable to the observed magnitude for a given stress drop. According to the generalized Hooke's law the thermal stress caused by temperature change ΔT in an elastically constrained, isotropic medium is

$$\sigma = - \frac{E}{1-2\nu} \alpha \Delta T \quad (10)$$

where E = the Young's modulus, ν = Poisson ratio, and we neglect the nonlinear thermal interaction with tectonic stress. Substituting eq. (4) into eq. (10), we have

$$\sigma = - \frac{E\alpha}{1-2\nu} \frac{J\Delta t}{\epsilon(\rho_f S_f V_f + \rho_r S_r V_r)} \quad (11)$$

$$\approx 9.83 \times 10^{17} \text{ J } \Delta t / V$$

taking $E = 0.5 \times 10^{12} \text{ dynes/cm}^2$ and $\nu = 0.25$, where σ is in 10^{-3} bars and V in cm^3 .

The size of a geothermal reservoir is usually estimated from the inferred temperature distribution or by other geophysical means. Depending on what assumptions are made, the size estimates may differ by one to two orders of magnitude for the same reservoir. In the Imperial Valley the known

geothermal areas are usually associated with local positive gravity anomalies which result probably from the metamorphism of the sediments. We have therefore estimated the volume ($1.5 \times 10^{17} \text{ cm}^3$) of the Salton Sea geothermal reservoir from the excess mass ($3 \times 10^{16} \text{ g}$) assuming a density contrast of 0.2 g/cm^3 between the reservoir and its country rocks. This density contrast is chosen because the heat content estimated by Biehler (1976) from excess mass and well-head enthalpy (Austin et al., 1973) falls between those estimated by Renner et al. (1975) and Towse (1976) from temperature data. The thermal stress induced by one yearly production of 1 MW electricity is accordingly 6.6×10^{-3} bars in the Salton Sea geothermal area.

The stress drops of earthquakes in the Imperial Valley range from 0.3 to 5.7 bars for the Richter local magnitudes of 3.6 to 5.4 (Thatcher and Hanks, 1973) (Table 1). Assuming that thermal stresses are released as stress drops, we can relate the energy extraction and the expected magnitude. This is done by dividing the observed stress drops listed in Table 1 by the calculated rate of thermal stress to give the required energy extraction in units of megawatt-year (MWY electricity). The extracted thermal energy is then used to calculate the expected magnitude (M) according to eq. (9). The calculated values agree to within 0.4 of the observed magnitudes for events along the Brawley fault which cuts through the Salton Sea geothermal field; but the agreement is relatively poor for events along the Imperial fault which does not extend to the Salton Sea geothermal field. It is noted, however, that the variation in the seismic moment according to the empirical relation eq. (6) may be up to a factor of 10 for a given magnitude, a discrepancy of 1 in the estimated magnitude is not unreasonable, considering the assumptions made.

The lack of apparent correlations between the observed magnitudes and stress drops reflect different physical conditions at various places and probably at different times of occurrence. The Imperial Valley is known to have the lowest stress drops for a given magnitude of earthquakes in southern California (Brune and Allen, 1967; Thatcher and Hanks, 1973). If the relation of magnitude and stress drop for three events along the Brawley fault is considered normal, then the relation for two events associated with the Imperial fault appears abnormal. Available data are insufficient to conclusively define the relations for different areas within the Valley.

One may argue that the stress drops for Imperial Valley earthquakes are underestimated because of high attenuation along the propagation path in the crust of relatively high temperature. If this is significant, the magnitudes are probably underestimated also because the estimated stress drop is proportional to the amplitude and the magnitude and the seismic moment are determined from the logarithm of the amplitude of the recorded seismic wave. The underestimation of the calculated magnitude (eq. 9) is therefore the same as that of the observed magnitude in terms of percentage and the stress drop is not significantly underestimated.

EARTHQUAKE FREQUENCY

Thermal strain, like tectonic strain, is probably to be released by a sequence of events with various magnitudes or by aseismic creep. Thus the magnitudes predicted by eq. (9) must be regarded as the maximum magnitudes. Within a given area the number of events per year with magnitudes of $M \pm \Delta M$ on the average follows the relation

$$\log N = A + B M \quad (12)$$

where A and B are empirically determined coefficients within a limited range of magnitudes. On the basis of two monthly observations in the Salton Sea geothermal field (from July to September, 1975) with 5 portable seismographs, we find $A = 3.42$ and $B = -0.87$ for $0.5 < M < 3.0$ and $\Delta M = 0.2$ (number of locatable events = 106). The corresponding values for the entire Imperial Valley based on 30-year data (Brune, 1968) are 4.07 and -0.80 respectively, for $0.75 < M < 5.75$ $\Delta M = 0.25$.

Eq. (12) indicates implicitly the statistical distribution of the size of stress drop or strain release. If the additional thermal stress can bring total stress to the state of causing earthquakes, the thermal stress will be released in a similar manner and the induced earthquake frequency distribution will follow a pattern described by eq. (12). Since the slope (B value) of eq. (12) is nearly identical for the Salton Sea geothermal field and the Imperial Valley as a whole, we may assume the frequency distribution of earthquakes induced by geothermal energy extraction to have a similar slope but different value for the constant term. In other words, we assume $N'_1 = kN_1$, where N'_1 = number of events due to energy extraction and k = a constant

of proportionality. Then, the possible magnitude and number of the induced earthquakes are constrained by the total volumetric seismic moment

$$\begin{aligned}
 M_o &= \sum N_i' M_{oi} \\
 &= k_i \sum_{10} [a + A + (b + B) M_i] \\
 &= k 10^{19.42} \sum_i 10^{0.63 M_i}
 \end{aligned} \tag{13}$$

where the upper and lower bounds in the summation are unknown and M is at an increment of 0.4.

It is reasonable to assume that there exists a cutoff magnitude M_c above which earthquakes caused by energy extraction will not occur. Such a cutoff magnitude should be less than the maximum magnitude calculated from eq. (9). Because the seismic moment decreases exponentially ($\propto 10^{1.5M}$) with decreasing magnitude, the lower bound can be conveniently set at $M = -\infty$. Eq. (13) thus becomes after summing an infinite geometric series

$$M_o = k 10^{19.78 + 0.63M_c} \tag{14}$$

The proportionality constant k and the cutoff magnitude M_c are determined with a trial-and-error method to satisfy the condition that the number N_i' of events per year with magnitude greater than M_c is less than one. The cutoff magnitude calculated this way is approximately 0.30 less than the maximum magnitude (Fig. 1). The frequency distributions of the induced events for different power productions are also shown in Fig. 1. For 100 MWY the earthquake frequency increases 2 times whereas for 1000 MWY the frequency

increases 6.5 times. The anticipated increase in earthquake frequency is significant enough to be detected by earthquake monitoring before and after geothermal development for production greater than 100 MWY.

The predicted frequency of earthquakes based on eq. (12) seems to be slightly higher than the frequency observed with a permanent seismographic network by Hill et al. (1975) from June 1973 to May 1974 (Fig. 2). Discrepancy between prediction and observation becomes greater toward smaller magnitudes. This is caused by incomplete sampling of smaller local events with a widely spaced permanent network. Furthermore, the recorded number of events actually was much more than the locatable 106 events which are used to obtain eq. (12). The slope of eq. (12) will become steeper for higher magnitudes, as observed by other workers elsewhere. Hence, both facts indicate that the actual cutoff magnitude is less than the one estimated in Fig. 1 and the events with smaller magnitudes will occur more frequently.

DISCUSSION

Most earthquakes in geothermal areas are of tectonic origin. Production may change the stress pattern drastically so as to cause earthquakes in ways other than the one described here from the viewpoint of thermal contraction. Change of pore fluid pressure will affect the strength of rocks and the rate of land subsidence. Nonuniform cooling may create internal strain which propagates to and concentrates along some preexisting weak zones. Induced seismic hazards are perhaps greater for high rates of fluid injection or withdrawal than for low flow rates.

In the derivation of the maximum equivalent magnitudes and earthquake frequency we have assumed discharge is compensated by recharge at the same rate. Without any recharge, the rocks may be strengthened owing to decreasing temperature and pore fluid pressure. If recharge lags discharge, the consequences may be analogous to the earthquake dilatancy-diffusion process even though the causes of increase in fluid volume for these two cases are quite different.

For a confined elastic medium the volume change as calculated from free thermal contraction is probably overestimated. The volumetric seismic moment may have been overestimated too if aseismic creep occurs. These two, plus the limitation of the empirical equation of earthquake frequency distribution mentioned earlier, indicate the actual cutoff magnitude is smaller than the estimated value perhaps by as much as one unit.

The average potential energy released by the ground subsidence due to volume contraction ΔV is

where M , ρ , and h are mass, density, and average thickness of the rocks involved in the subsidence, Δh = average height of subsidence, g = gravitational acceleration. If $\rho = 2.5 \text{ g/cm}^3$ and $h = 1.5 \times 10^5 \text{ cm}$, then for each MWY power production $E \approx 5.5 \times 10^{17}$ ergs, which is only $\sim 0.02\%$ of the thermal energy extracted (1 MWY for an efficiency of 0.1). The radiated seismic energy is $E_s = 1.7 \times 10^{14}$ ergs according to the empirical relation (Thatcher and Hanks, 1973)

$$\log E_s = 2.0 M + 8.1 \quad (16)$$

Thus E_s in turn is a small fraction (0.03% in this case) of the released potential energy, and is less than one millionth ($\sim 5.9 \times 10^{-8}$) of the geothermal energy removed.

CONCLUDING REMARKS

Various assumptions have been made to find the maximum equivalent magnitude for a given volume contraction caused by geothermal energy extraction. The validity of our approach to estimate the earthquake potential unfortunately depends on many assumptions and empirical relations. The predicted change in earthquake frequency before and after the geothermal power production, however, is significant and may be verified by field observation.

For a given stress drop, the calculated magnitudes agree very well with the observed magnitudes for three events near the Salton Sea geothermal field. These three events were so clustered in space and time, however, that we are uncertain whether such remarkable agreement will be found elsewhere or at other times.

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Table 1. Estimated earthquake magnitudes for a given stress drop in the Salton Sea geothermal area.

Observed Earthquakes				Observed		Calculated	
Date	Epicenter			<u>M</u>	<u>σ</u>	<u>MWY</u>	<u>M</u>
25 Apr 55	Imperial	32°20'N	115°00'W	5.2	0.3	46	4.2
04 Mar 66	Fault	32°51'N	115°32'W			76	4.3
28 Jul 50	Brawley	33°07'N	115°34'W	4.5	0.3	46	4.2
				4.7	1.3	198	4.6
	Fault			5.4	5.7	870	5.0

*Brune and Allen's (1967) value is 1.1 bar; σ = stress drop in bars

Figure Caption

Fig. 1. Earthquake magnitude (solid curves) and number of events per year (dashed-dotted curves) versus power production. Maximum equivalent magnitude is calculated from eq. (9). The cutoff magnitudes are calculated from eq. (14) for Salton Sea geothermal field. The increases in earthquake frequency is plotted for different power productions. Natural earthquake frequency curve is marked by 0 MWY and $k = 0$.

Fig. 2. Earthquake frequency distribution. The straight line is based on two-month observations from July to September, 1975. Crosses denote number of events observed between June 1973 and May 1974 by Hill et al. (1975). The integer numbers show the difference between calculated and observed number of events.

Figure 1

Figure 2