EAST MESA--GEOLOGY, RESERVOIR PROPERTIES AND AN APPROACH TO RESERVE DETERMINATION

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The East Mesa KGRA is located in an area of anomalously high heat flow on the east flank of the Salton Trough, at the southeast corner of the Imperial Valley of California (see Fig. 1). This geothermal field has been the object of numerous academic and industrial studies, several of which are being reported on at this workshop.

Ten producing wells have been drilled within the East Mesa KGRA, including three by Republic Geothermal in the northern portion, five by the U.S. Bureau of Reclamation in the central area, and two by Magma Power Co. to the south (see Fig. 2). The early drilling by the Bureau at locations near the apparent center of the shallow thermal anomaly unfortunately resulted in wells of low productivity. This information became well known and led to the feeling by some that East Mesa would be disappointing. The more recent drilling by Republic and Magma has shown that high productivity wells can be brought in with flow rates that are commercial for electric power generation.

Due to the already extensive investigations, a great deal is known about the East Mesa reservoir and its properties. Republic now believes this large body of knowledge provides the confidence needed to proceed with commercial development at the northern end of the field, starting with a minimum 48-megawatt project. Development drilling is expected to begin early next year with funds provided by the Bank of America under the ERDA loan guaranty program.

The intent of this presentation is primarily to illustrate an approach to reserve determination applicable to Republic's lease area.

RESERVE DETERMINATION

The reserve determination approach used is analogous to a volumetric calculation for determination of conventional oil and gas reserves. It is comprised of essentially three steps. First, the total initial heat content (enthalpy) of the reservoir was calculated between a bottom of 9000 feet and a top defined by the 300^{o}F surface. Second, an estimate was made of the portion of this initial heat content that can be expected to be recovered during the economic producing life of the area by using reservoir simulation studies of a single five-spot reinjection pattern. Lastly, a conversion efficiency was developed that relates the heat content of the produced water to the electrical energy output.

Note that this approach is very conservative in two major respects. First, no credit is taken for recharge of the reservoir due to thermal convection through the fracture system. There is good geological and geochemical evidence that this will probably occur, with the net effect being higher temperatures and longer reservoir life. Second, the reservoir model assumes that a five-spot pattern will be employed to reinject the cooled residual water. In reality, it is planned to prolong reservoir life and to improve sweep efficiency by using a peripheral flood or an inverted nine-spot pattern. Therefore, the five-spot prediction will probably prove to be pessimistic.

We believe a more sophisticated approach will only be warranted after additional drilling has yielded a refined picture of reservoir property distribution, and after long-term production testing has yielded information on aquifer influx. The following discussion deals with the application of this approach to Republic's reserves in Sections 29 and 30.

Total Initial Heat Content

The first step in calculating the total initial heat content of the reservoir for Sections 29 and 30 was to construct a set of isothermal surface maps which show the depth to each of four selected reservoir temperatures (see Figure 6 for an example of the 350°F map). The maps were based on the static temperatures measured in the wells, with additional input provided by the data from the existing network of shallow temperature observation holes.

Using the maps, the bulk volume of each 1000-foot depth interval and its average temperature were determined from isothermal surfaces by numerical integraion. The total initial heat content of each interval can then be calculated by:

$$\text{Total Heat Content} = \text{Bulk Volume} \cdot (T-T_o) \cdot \rho c \qquad (1)$$

Where T is the reservoir temperature, T_o is the reference temperature (taken as 32°F), and ρc is the effective volumetric heat capacity of the total rock and fluid system. The last term (ρc) may be calculated as follows:

$$\rho c = \rho_r c_r \ (1-\phi \cdot NS) + \rho_w c_w \phi \cdot NS \qquad (2)$$

Where ρ_r and ρ_w are densities of the rock and fluid, respectively, c_r and c_w are the specific heat capacities of the rock and fluid, respectively; ϕ is the porosity of the productive portion of the rock; and NS (net sand) is the fraction of the interval which is productive.

Basis input and summary results of the calculation for each Section are shown in Table VII. Porosity and net sand values derived from RGI 16-29 and 38-30 were taken to be representative of Sections 29 and 30, respectively. Total initial heat content for the two sections is shown to be 2.14×10^{15} BTU. The amount of this initial heat that can be recovered from the produced hot water and converted to electrical energy is the subject of the following two subsections.

Reservoir Simulation

Simulation studies were carried out using the geothermal simulator developed by INTERCOMP. These studies will be described in detail in INTERCOMP's presentation to this workshop and are merely summarized here for completeness.

The objectives of the numerical model studies were to predict the temperature, pressure, and rate behavior of the producing wells as a function of time. The type of field development considered included: (1) straight depletion without reinjection; (2) peripheral reinjection; and (3) five-spot reinjection. Various rates and pattern sizes were investigated as well as the effect of an infinite aquifer.

In summary, it was found that: (1) An aquifer alone (having the same properties as the reservoir) is insufficient to maintain pressure; (2) For some combinations of withdrawal rate, spacing and permeability, peripheral injection combined with the contributions from the aquifer will maintain adequate pressure; (3) Whenever the peripheral flood fails to maintain adequate pressure for the desired withdrawal rate, pressure can always be maintained by going to a pattern flood such as a five-spot. This last result was true for both the 50 and 10 md permeability models. The average permeability on the RGI Sections 29 and 30 is expected to be approximately 50 md based on the previously discussed data from RGI 38-30 and 16-29.

Although many combinations of pattern size, production rate, porosity and interval thickness were investigated for a five-spot pattern, it was found that the results could be expressed by a single dimensionless curve relating temperature and time. This resultant curve is shown in Figure 7. The producing temperature (T) is made dimensionless by expressing it as a function of the initial producing temperature (T_i) and the reinjected water temperature (T_f) as in the equation:

$$T_D = \frac{T - T_f}{T_i - T_f} \qquad (3)$$

The time (t) is made dimensionless by multiplying it by the flow rate (Q) and dividing by the total pore volume (ϕAh). This is equivalent to the number of pore volumes produced:

$$t_D = \frac{Qt}{\phi Ah} \qquad (4)$$

This curve appears valid over the range of parameters of interest, but in extreme cases a separate simulator run with the actual parameter values may be required. One of the interesting features of the curve without aquifer influx (i.e., no convection) is that the final temperature, namely that of the reinjected hot water (200°F) is approached very slowly because of the heat influx from the cap and base rock. Secondly, thermal breakthrough occurs at about one pore volume, whereas fluid breakthrough in a five-spot occurs at about 0.7 ± PV. This difference is due to heating of the injected fluid by the formation and mixing with the formation water.

A dimensional "base case" is illustrated in Figure 8 for a 40,000 B/D producer on 40-acre spacing, which initially produces at 355°F. The reinjected water temperature is assumed to be 200°F. The economic life of this well is approximately 30 years or 265°F. For the reserve calculation, this "base case" is used to determine the fraction of original heat content of the rock and fluid system which would be produced in the hot water over the economic life of the well. The total amount of heat (enthalpy) contained in the produced fluids is equivalent to over 90 percent of the original heat-in-place in the reservoir, but about half of this heat is returned to the reservoir by means of the reinjected water. Therefore, the net heat produced is about 45 percent of the original heat-in-place. During the 30-year period, approximately three pore volumes of water were produced and reinjected. Thus, it is concluded for East Mesa conditions that the gross producible heat is approximately equal to 90 percent of the original heat-in-place of 1.92×10^{15} BTU for Sections 29 and 30 combined.

Conversion to Electricity

It is desirable to express geothermal reserves in electrical terms (i.e., megawatt-years), rather than in volume or mass of hot water. Reference must therefore be made to a specific power plant design. A number of such studies have been made in the industry, the results of which are in general agreement and widely known. For example, Figure 9 shows a typical power output for the one-stage and two-stage flashed steam process as a function of temperature.

For the proposed 48-megawatt East Mesa power plant, a two-stage flash process is planned. The reasons for selecting this process are: (1) it relies on proven, existing technology; (2) it utilizes standard and well-understood design features; (3) it can be designed and built in time to meet the incremental power needs of the Imperial Irrigation District by 1980; (4) it is well suited to the low salinity and low noncondensables found in Republic wells; and (5) it will probably generate the lowest-cost electricity under the specific East Mesa temperature and water chemistry conditions.

Assuming a produced water temperature of 335°F and two-stage flash, the calculated conversion efficiency, based on Figure 9, is approximately 5.5 percent, which is in general agreement with values quoted in the literature. A conversion efficiency of five percent was used in the reserve calculation and was assumed to apply throughout the range of temperatures expected.

The resulting calculated electrical energy reserve for Sections 29 and 30 is shown in Table VII. These calculations are based on a gross producible heat equal to 90 percent of the original heat-in-place (as determined from the five-spot simulation results) and a conversion efficiency of five percent. The total reserve amounts to 3215 megawatt-years, which is 107 megawatt installed capacity for a 30-year life. These reserves are clearly adequate to support the proposed 48-megawatt project, even after discounting for the numerous uncertainties involved.

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TABLE I

EAST MESA WELL FLUID COMPARISON (mg/l)

Water	RGI 38-30	RGI 16-29	RGI 18-28*	RGI (450') Water Well	Bu-Rec 6-1	Bu-Rec 6-2	Bu-Rec 8-1	Bu-Rec 31-1	Bu-Rec 5-1
Total Dissolved Solids	1907	1978	2950	1600	26300.	5000.	1600.	2900.	1575.
Sodium	630	623	980	410	8100.	1700.	610.	730.	593.
Potassium	39	39	40	12	1050.	150.	70.	85.	29.
Calcium	4.3	3.2	0.1	68	1360.	16.4	8.5	8.9	16.2
Magnesium	0.1	0.1	0.1	19	17.2	0.24	0.05	0.05	2.1
Iron	1.5	1.9	2.3	0.1	8.8	0.1	0.1	0.1	N/A
Silicon	518	489	167	10	320.	269.	389.	274.	201.
Boron	2.6	3.2	4.5	0.9	9.7	7.8**	1.6	2.5	N/A
Arsenic	0.13	0.1	N/A	N/A	0.26	0.22	0.053	0.025	N/A
Chloride	565	514	600	760	15850.	2142.	500.	510.	454.
Fluoride	3.2	4.0	2.5	0.5	0.9	1.2	1.6	1.42	N/A
Bromide	0.70	N/A	N/A	N/A	N/A	1.66**	N/A	N/A	N/A
Sulfate	142	169	64	9.0	42.	156.	173.	183.	N/A
Carbonate	128	188	0	4.0	0.0	0.0	0.0	0.0	N/A
Bicarbonate	312	342	1340	76	202.	560.	417.	845.	331.
pH (pH Units)	8.9	9.0	8.3	8.3	5.4	6.1	6.2	6.2	9.1
Chem. Thermometer**									
Alkali	460°F	424°F	417°F	202°F	449°F	429°F	432°F	440°F	332°F
Silica	442°F	436°F	329°F	80°F	383°F	365°F	410°F	369°F	334°F

*Analysis of 18-28 sample made shortly after completion & may be contaminated with drilling fluids.

**RGI measured or calculated

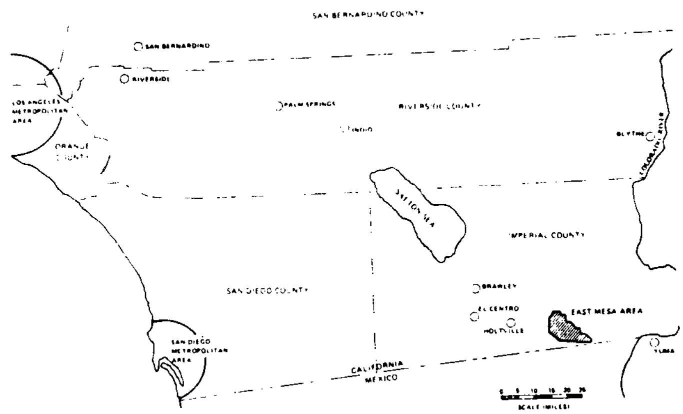


Figure 1. Location Map, East Mesa K.G.R.A.

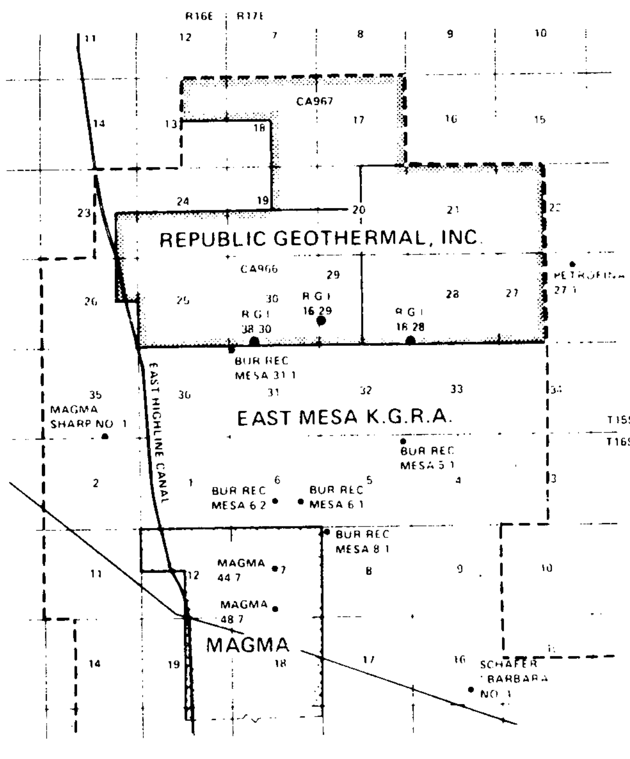


Figure 2. Plat of East Mesa

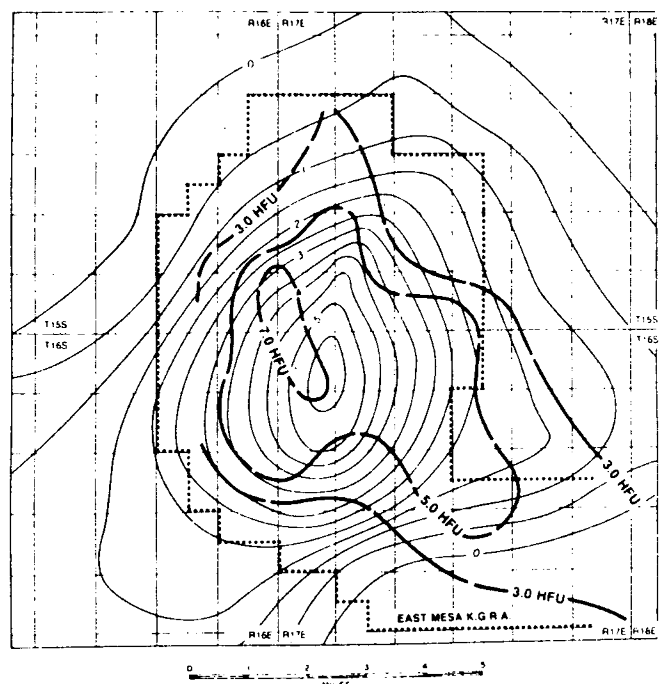


Figure 3. Residual Gravity Anomaly Map of the East Mesa Geothermal Field (Biehler, 1971) with superimposed Surface Heat Flow Anomaly Contours (U.S.B.R. 1974).

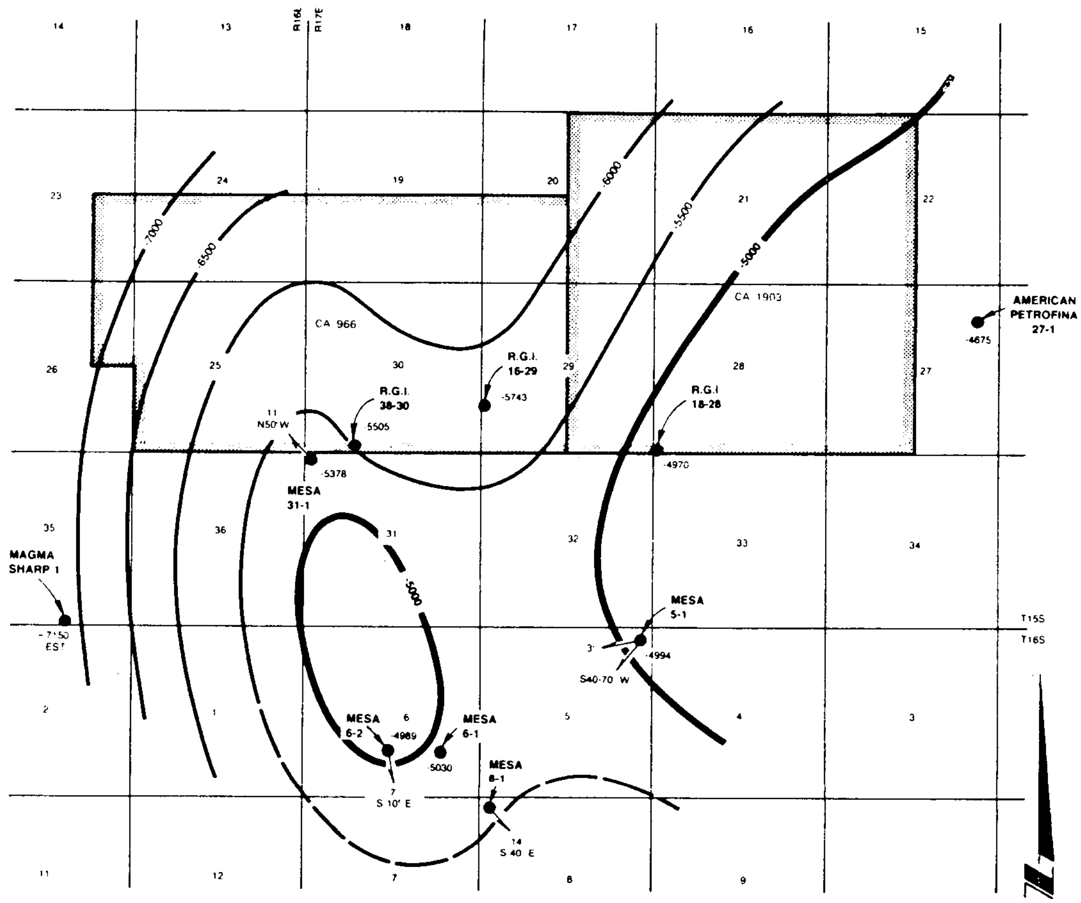


Figure 4. East Mesa Structure Contour Map.

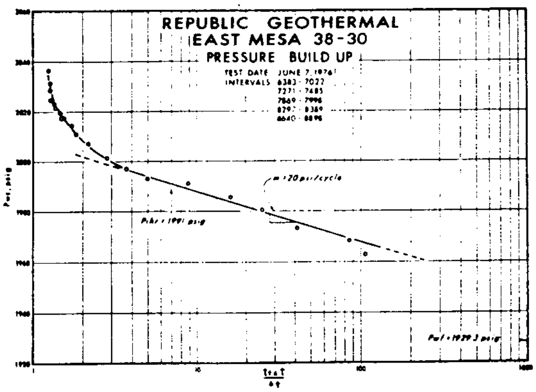


Figure 5

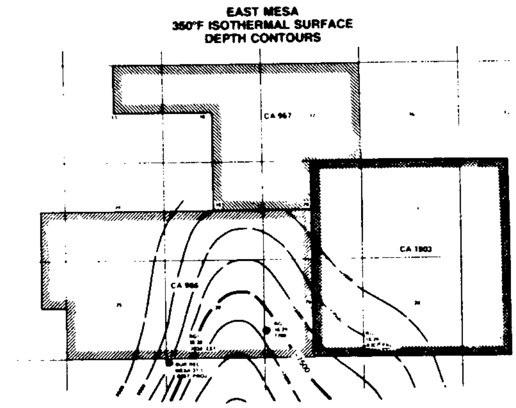
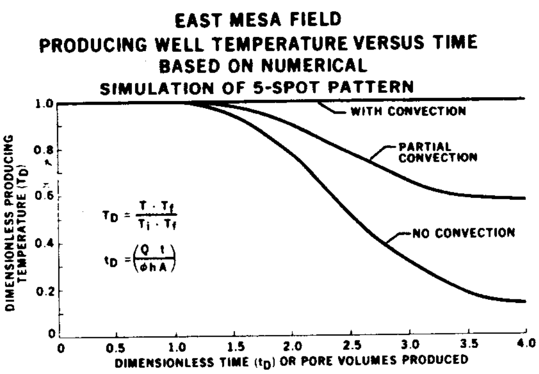


Figure 6



$$T_D = \frac{T - T_f}{T_i - T_f}$$

$$t_D = \left(\frac{Q\ t}{\phi h A}\right)$$

Figure 7

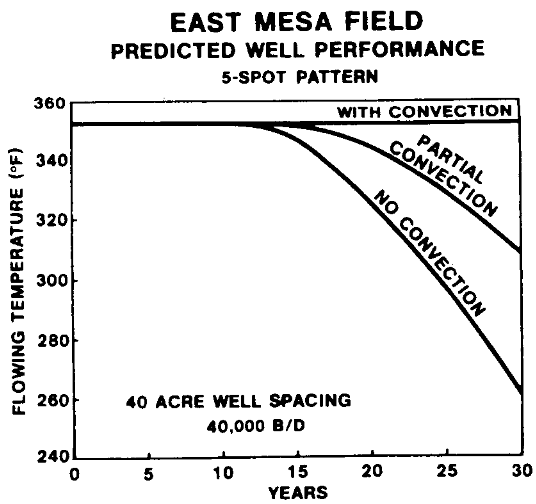


Figure 8

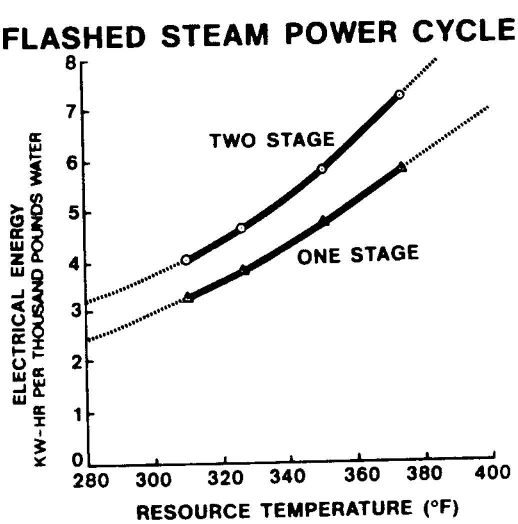


Figure 9

TABLE II

CHEMICAL ANALYSIS OF FLASHED STEAM — REPUBLIC 16-29

Total Noncondensables	—	0.64 wt. % of steam
Constitutents		
Carbon dioxide	—	91.4 vol. % of noncondensables
Nitrogen	—	4.3
Methane	—	3.9
Alkanes	—	0.4
Hydrogen sulfide	—	None detected

TABLE III

EAST MESA WELL DATA

Well	T.D.	Temp. at T.D.	Flowing downhole Temp. (Above Producing Interval)	lb mass/hr	Flow Rate 10^6BTU/hr	MW	Net Sand	Completion Date
Republic Geothermal								
38-30	9009	374°F (est)	338°F	670,000**	5000	3.5	736	10/75
16-29	7998	365°F	332°F	419,000**	3060	2.1	827'	12/75
18-28	8001'	326°F	310°F (est)	36,000	230	0.1	794'	1/76
Bureau of Reclamation								
31-1	6231'	323°F	300°F (est)	300,000	1800	0.9	593'	6/74
8-1	6205'	354°F	320°F (est)	228,000	1580	1.0	916'	6/74
6-1	8030'	399°F	330°F	211,000	1530	1.0	942'	8/72
6-2	6005'	370°F	304°F	152,000	990	0.6	904'	8/73
5-1	6016'	315°F	305°F	117,000	770	0.5	790'	5/74

NOTES
All data are actual measured values unless indicated to be estimated.
* Fill at 6910' (348°F)
** Liquid rate only — vapor phase (10 ± %) not measured)

TABLE V

PRESSURE BUILDUP DATA AND RESULTS

	RGI WELLS		
TEST DATA	**18-28**	**16-29**	**38-30**
Flow duration, hrs	21.5	5.53	5.47
Shut-in time, hrs	9.3	22.40	24.39
Cumulative production, STB	1,264*	4,525	5,907
Last rate before shut-in, STB/D	2,517	19,668	25,462
Producing time, hrs	17.05	5.902	6.097
RESERVOIR AND FLUID PROPERTY DATA			
Water viscosity, μ_W	0.210	0.185	0.185
Water FVF, RB/STB	1.078	1.085	1.088
Porosity, fraction	0.220	0.223	0.249
Total compressibility, psi^{-1}	7.570×10^{-6}	7.904×10^{-6}	8.202×10^{-6}
Wellbore radius, ft	0.375	0.443	0.510
Estimated net thickness, ft	794	827	736
Open intervals	6105-6210 6440-8000	6413-6984 7231-7996	6383-7022 7271-7485 7869-7998 8297-8384 8640-8898
RESULTS			
Average permeability, md	7.95	41.96	56.61
Flow capacity, md-ft	6,309	34,698	41,666
Formation damage (skin)	−0.91	−2.28	−2.81
Distance to nearest boundary, ft	451	893	692

*Estimated

TABLE IV

REPUBLIC GEOTHERMAL WELLS ZONE SUMMARIES

Well	Interval	Net Sand (ft)	Average Porosity ϕ	Geometric Average Permeability (md) $\bar{k}_{(h)}$	$\bar{k}_{(v)}$	Perm-Thickness (Darcy-ft)
38-30	4001-5000	640	0.29	174	115	111
	5001-6000	735	0.27	109	74	80
	6001-7000	782	0.29	170	112	133
	7001-8000	399	0.19	9	7	4
	8001-8900	293	0.10	1	<1	<1
16-29	5001-6000	746	0.23	26	19	20
	6001-7000	768	0.24	44	32	34
	7001-7900	431	0.21	12	9	5
18-28	5100-6000	733	0.29	126	85	93
	6001-7000	608	0.22	16	12	10
	7001-7900	325	0.23	35	25	11

TABLE VI

COMPARISON OF PERMEABILITY AND FLOW CAPACITY OF EAST MESA WELLS

Well	Max. observed flow rate, BD	Avg. Permeability from buildup (md)	Permeability-Thickness (Darcy-ft) buildup	logs
Republic Geothermal				
38-30	50,300	57	41.7	44.
16-29	31,400	42	34.7	30.
18-28	2,600	8	6.3	14.*
Bureau of Reclamation				
31-1	21,200	30	22.2	N/A
5-1	8,300	6	5.7	N/A
6-1	14,800	0.5	0.3	N/A
6-2	10,700	N/A	N/A	N/A
8-1	16,100	13	13.5	N/A

Lawrence Berkeley Laboratory Interference Results:
38-30 and 31-1 pair: kh = 29.8 Darcy-ft
6-1 and 6-2 pair: kh = 11.2 Darcy-ft

*RGI 18-28 has 14 Darcy-ft in the slotted interval plus another 99.7 Darcy-ft behind blank pipe (below 5100 ft).

TABLE VII

EAST MESA FIELD — SECTIONS 29 & 30 (Republic) PRELIMINARY RESERVE ESTIMATE

Section	Average Reservoir Temperature (°F)	Average Sand Porosity (fraction)	Net Sand (fraction)	Bulk Volume (ft³x10¹⁰)	Total Initial Heat Content (Btu x 10¹⁴)	Reserve (MW-Years)
29	334	0.17	0.60	8.363	8.732	1315
30	335	0.23	0.58	11.701	12.625	1900
	335	0.20	0.59	20.064	21.357	3215

$\rho r = 165 \frac{lbs}{ft^3}$, $\rho w = 56.7 \frac{lbs}{ft^3}$, $c_r = .19 \frac{Btu}{lb°F}$, $c_w = 1.12 \frac{Btu}{lb°F}$