National Assessment of U.S. Geothermal Resources—A Perspective

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National assessment, geothermal, USGS, reserves, recovery Factor, U.S.

ABSTRACT

The U.S. Department of Interior has assigned to the US Geological Survey ("USGS") the task of conducting an updated assessment of the geothermal resources in the United States. In that connection, we offer an objective analysis of the last such national assessment, made in 1978, and presented in USGS Circular 790, in view of the industry experience accumulated over the intervening 26 years. Based on this analysis we offer our perspective on how such assessment may be improved.

Our analysis was largely based on a comparison of the results of assessment of resources in 37 geothermal fields in California, Nevada and Utah GeothermEx has recently conducted with the resource base estimates for those same fields by USGS in 1978. This recent re-assessment shows that the total resource base in these 37 fields is about 33% of the 1978 estimate. The assessment in 1978 was found to have been optimistic partly because of higher estimates of volumes of some of the reservoirs, but primarily because of the use of too high a value (0.25) for the heat recovery factor (*r*). It was concluded that, had a value of 0.131 been used and the volumes used were the same as in our recent assessment, the 1978 estimates for the 37 fields would have been statistically the same as now. This paper then attempts to estimate semi-empirically the appropriate range of *r* values for such assessment, using a probabilistic simulation approach. The appropriate range for *r* is thus estimated to be 0.03 to 0.17 with a mean value of 0.11.

Finally, from this analysis, the paper points out some statistics on identified hydrothermal fields that should be borne in mind in the proposed national resource assessment: (a) temperatures of the identified hydrothermal systems are a more meaningful parameter than the number of systems identified, for 10% of prospects identified in Circular 790contain 86% of the total resource base; (b) of the 187 prospects with higher than 100°C temperature, only about 15% have been developed to date, with 160 prospects still lying undeveloped; (c) surprisingly few new geothermal fields have been identified in the 26 years since the USGS study even though this period was marked by a most intense exploration and development episode in the history of the geothermal industry; and (d) pending the new national assessment, the total resource base in the identified hydrothermal systems in the U.S. is estimated to be on the order of 10,000 MWe.

Introduction

The U.S. Department of Interior has assigned to the U.S. Geological Survey ("USGS") the task of conducting an updated national assessment of the geothermal resources in the United States. The last such nationwide assessment was made in 1978 and presented in USGS Circular 790 (Muffler, 1979), a singularly professional effort of lasting legacy. For hydrothermal systems, Circular 790 refined and extended the pioneering work of Renner, *et al* (1975), in USGS Circular 726, which presented the first nationwide assessment of geothermal reserves. In this paper we provide an objective analysis of the assessment of the resource base in hydrothermal systems presented in Circular 790 in view of the industry experience accumulated over the intervening 26 years, and offer GeothermEx's perspective on how such an assessment may be improved. Another paper at this conference (Sanyal and Butler, 2004) covers GeothermEx's perspective on the national assessment of the resource base available from enhanced geothermal systems. In an earlier paper we have offered a possible approach to national assessment of the volcano-related geothermal resource base (Sanyal, *et al*, 2002).

In a very recent assessment by GeothermEx of the known hydrothermal systems in California and Nevada for the California Energy Commission, 35 fields evaluated in Circular 790 were re-assessed in light of the exploration, drilling and production data collected, and the advancement of understanding of geothermal systems made, since 1978 (Klein, *et al*, 2004). In addition, we have had the opportunity to recently re-assess two hydrothermal systems in Utah (Roosevelt Hot Springs and Cove Fort) that were originally assessed in Circular 790. In this paper we compare the methodology and results of re-assessment of the 37 above-mentioned systems with the original assessment of the same ones in Circular 790, and draw some conclusions of consequence to the new national assessment of hydrothermal resources to be undertaken by U.S.G.S.

Comparison of GeothermEx and USGS Assessments

Table 1 compares the results of our re-assessment of the 37 hydrothermal fields in California, Nevada and Utah with those for the same fields in Circular 790, the reservoir parameters compared being mean temperature (°F), most-likely temperature (°F), mean volume (cubic miles) and mean resource base (MWe). In addition, Table 1 includes the minimum proven or estimated sustainable capacity (MWe) of each of the 17 fields which have been actually exploited to date; sustainable capacity here is defined as in Sanyal (2004): "the ability to economically maintain the installed capacity, over the amortized life of the power plant, by taking practical steps (such as, make-up well drilling) to compensate for resource degradation (pressure drawdown and/or cooling)". The Geysers (California) steam field is not included in Table 1 because the reserve estimate for this field in Klein, *et al* (2004) was based on plant capacity estimates supplied by the field operators rather than independent assessment based on basic resource parameters. Furthermore, in Circular 790 the resource assessment methodology used for The Geysers was unique and different from that for all other fields.

Table 1 shows at the bottom the total of mean resource base in the 37 fields as reported in Circular 790 (13,622 MWe) and as assessed by GeothermEx (4,474 MWe). The GeothermEx estimate is only 33% of the USGS estimate; moreover, the total minimum sustainable capacity proven to date (1,664 MWe) is only 12% of the USGS estimate. Why was the USGS estimates of 26 years ago so optimistic? As regards sustainability proven to date,

Table 1. Comparison of Results in Klein, *et al* (2004) and Muffler (1979).

No.	Field	Mean Temperature (°F)		Most-Likely Temperature (°F)		Mean Volume (Cubic miles)		Mean Resource Base (MWe)		Sustainable Cap (MWe)
		GeothermEx	USGS	GeothermEx	USGS	GeothermEx	USGS	GeothermEx	USGS	
1	Beowawe, NV	410	444	410	439	1.7	1.97	58	127	30
2	Brady's HS, NV	360	311	360	311	0.82	5.28	22	157	20
3	Colado, NV	272	207	270	214	0.58	0.79	8.3	9.2	0
4	Desert Peak, NV	385	430	385	437	2.59	12.48	79	750	50
5	Empire, NV	307	331	305	365	0.62	0.79	11.6	28	5
6	Fly Ranch, NV	210	226	210	212	1.67	1.06	12.7	15.7	0
7	Gerlach, NV	338	352	340	338	1.57	0.79	36	32	0
8	Honey Lake, CA	240	259	240	262	1.25	2.54	13	51.4	3
9	Kyle HS, NV	356	318	375	322	1.33	3.07	36	97	0
10	Leach HS, NV	276	324	265	320	1.97	2.33	29	77	0
11	Lee HS, NV	314	331	314	324	0.58	0.79	11.4	28	0
12	Rye Patch, NV	360	423	345	446	3.6	0.79	94	47	15
13	Soda Lake, NV	357	315	360	322	2.32	4.7	62	146	15
14	Steamboat, NV	370	392	370	405	2.36	6.96	78	350	50
15	Stillwater, NV	320	318	320	318	2.43	14.16	52	450	30
16	Wabuska, NV	253	268	245	284	1.45	4.39	17	95.6	1
17	Sou HS, NV	275	199	275	187	0.58	0.79	9.5	8.4	0
18	Baltazor, NV	303	316	306	316	1.31	1.46	24	46	0
19	Double HS, NV	257	261	255	261	4.26	3.72	53	78	0
20	Pinto HS, NV	364	343	366	349	1.45	2.4	39	90	0
21	Brawley, CA	510	487	512	482	4.57	8.16	351	640	0
22	Calistoga, CA	298	291	298	286	2.03	1.66	35	43.6	0
23	Coso, CA	533	428	550	446	8.71	11.04	490	650	300
24	Dunes, CA	325	270	325	248	0.96	2.14	18.3	47.3	0
25	East Mesa, CA	310	360	310	356	8.02	8.64	167	360	90
26	Glamis, CA	325	270	325	248	0.58	2.62	10.8	44.3	0
27	Heber, CA	343	347	340	356	6.05	17.04	158	650	80
28	Lake City, CA	335	306	335	290	2.03	50.4	48.5	1490	0
29	Long Valley, CA	362	441	362	446	5.45	32.64	148	2100	70
30	Randsburg, CA	342	342	345	302	3.63	2.26	82	84	0
31	Salton Sea, CA	575	613	575	626	24.57	27.84	1881	3400	800
32	Sespe HS, CA	265	268	265	277	0.58	0.79	7.8	17.6	0
33	Sulphur Bank, CA	425	381	425	381	1.68	1.61	61	75	0
34	Pumpernickel Valley, NV	295	293	295	302	1.31	0.79	22	21.3	0
35	Pyramid Lake Reserv., NV	334	253	240	241	1.02	0.79	23	15.4	0
36	Cove Fort, UT	350	350	350	338	3.07	9.36	105	330	30
37	Roosevelt HS, UT	400	400	400	516	3.91	11.28	120	970	75
							TOTAL :	4,474	13,622	1,664

there are two reasons for this discrepancy: (a) the sustainable reserves in most fields, except The Geysers, exploited to date have proven to be lower than estimated by USGS, and (b) some fields have not yet been exploited, and a larger power capacity has not been installed in some others, because of practical constraints of the power market and regulatory issues. Figure 1 is a cross-plot of mean resource base (MWe) for the 37 fields as estimated in Circular 790 and by GeothermEx. This figure shows that the USGS estimates were higher for 90% of the 37 fields considered, with 10% of the fields having been assessed in 1978 at 10 times the resource base estimated today. The reason for this difference is considered below.

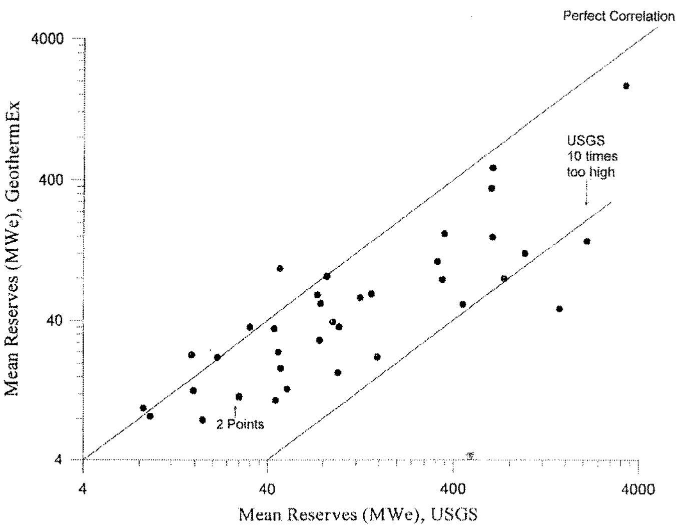

Figure 1. Comparisons of Mean Reserves (GeothermEx vs. USGS).

Why Were Estimates of Resource Base in Circular 790 Optimistic?

Appendix A summarizes the basic formulation for resource base estimation in terms of power capacity (E) in both the USGS and GeothermEx assessments.

Could the USGS estimates have been optimistic because of overestimation of the two basic resource parameters in the formulation (Appendix A), namely, reservoir temperature and reservoir volume? Figure 2 shows a cross-plot of the mean reservoir temperature estimated in Circular 790 and by GeothermEx. From this figure it appears that statistically the estimates of the mean reservoir temperature in 1978 were little different than made today, in spite of the advances in understanding about geothermal resources and data gathered over the past 26 years. The most-likely reservoir temperature values in Table 1, likewise, are statistically the same today as in the 1978 estimate. This puzzle is explained by the fact that both then and now estimation of mean reservoir temperature has been based primarily on fluid geothermometry, the state-of-the-art of which had already matured by 1978 and has changed little since then. Therefore, apparent over-estimation of resource base in Circular 790 could not have been caused by temperature overestimation.

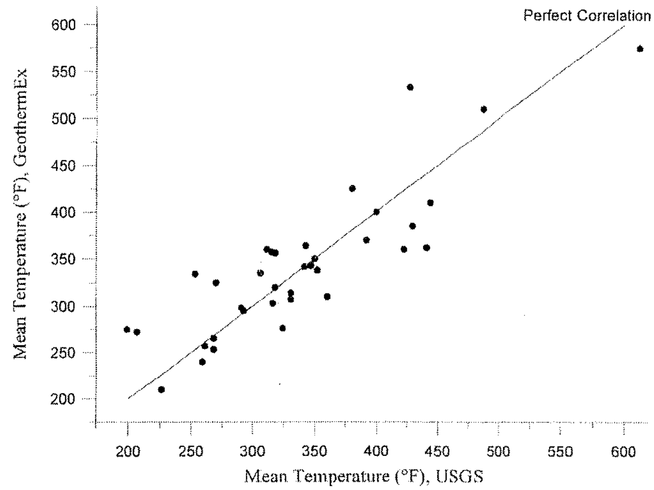

Figure 2. Comparison of Mean Reservoir Temperatures (GeothermEx vs. USGS).

Figure 3 shows a cross-plot of mean reservoir volumes estimated by USGS and GeothermEx for the 37 fields. For about 80% of the fields, the USGS estimates were higher, being as high as 7-times, than the GeothermEx estimates. But this overestimation in reservoir volume is not sufficient to account for the fact that the estimates of resource base by USGS were higher for more than 90% of the fields considered, and were as much as tenfold the GeothermEx estimates (Figure 1). Therefore, some other parameters in the formulation (Appendix A) must have contributed to the overestimation of resource base by USGS. Let us consider these other variables.

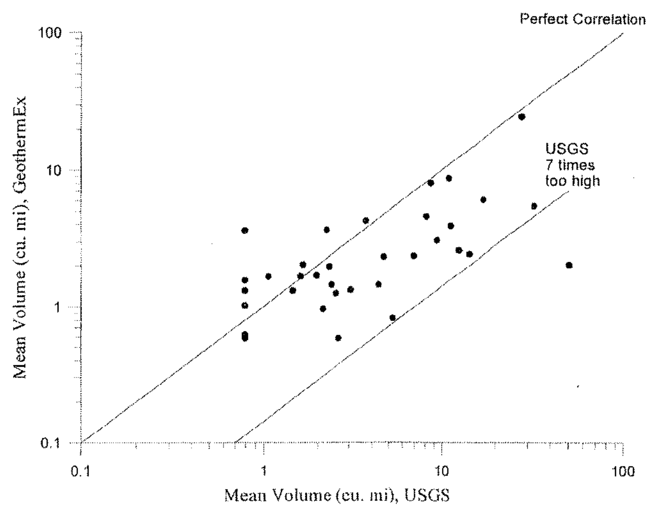

Figure 3. Comparison of Mean Reservoir Volume (GeothermEx vs. USGS).

The rejection temperature (T_0) assumed in the USGS assessment was 59°F, while in the GeothermEx assessment it was varied form 59° to 70°F reflecting the geographical variation in ambient temperature. Based on equations (A-1) through (A-4), the USGS estimates could be normalized for the differences in both mean reservoir temperature and rejection temperature by multiplying the USGS estimates by a temperature normalization factor (F_T), defined as:

$$F_T = \frac{(T'-T_0)-(T_0+460)\ln\{(T'+460)/(T_0+460)\}}{(T-59)-(59+460)\ln\{(T+460)/(59+460)\}}, \quad (1)$$

where T = mean reservoir temperature (°F) in the USGS assessment,
T' = mean reservoir temperature (°F) in GeothermEx assessment, and
T_0 = rejection temperature (°F) in GeothermEx assessment.

The USGS estimates were normalized for the differences in reservoir volume by multiplying them by the following volume normalization factor (F_v):

$$F_v = \frac{V'}{V}, \quad (2)$$

where V' = mean reservoir volume in GeothermEx assessment, and
V = mean reservoir volume in USGS assessment.

Finally, the utilization efficiency (e) used in the USGS assessment was 0.40 compared to 0.45 in the GeothermEx assessment and the plant capacity factor (F) values used in the USGS and GeothermEx assessments were 100% and 90%, respectively. The USGS estimates, therefore can be further normalized for utilization efficiency and plant capacity factor differences by multiplying them by the factor (0.45/0.40)(1.0/0.9), that is, 1.25. All other variables, except recovery factor (r), were assigned essentially same values in both assessments. Hence, the USGS estimates, normalized as follows, should differ from GeothermEx estimates only to the extent the r values were different between the two assessments:

Normalized USGS Resource Base
= USGS Resource Base $*F_T * F_V * 1.25$ (3)

Normalization for the difference in recovery factor (r) values used in the USGS and GeothermEx assessments is made awkward by the fact that while USGS assumed a fixed value of 0.25 for r, the GeothermEx assessment considered r to have a value anywhere between 0.05 and 0.20 with equal probability for non-sedimentary formations and between 0.10 and 0.20 with equal probability for sedimentary formations. The r value that would bring the GeothermEx estimates of resource base and the USGS estimates as normalized in (3) was arrived at statistically. The statistical fit was obtained by calculating the value of a factor x by which the fixed recovery factor of 0.25 used by USGS needed to be reduced to make the normalized USGS resource base values and the GeothermEx resource base values for the 37 fields statistically indistinguishable, a condition represented as:

$$\frac{d}{dx}\sum_{i=1}^{37}(R_{G,i} - x * R_{U,i})^2 = 0, \quad (4)$$

where $R_{G,i}$ and $R_{U,i}$ are the GeothermEx estimate and the normalized USGS resource base estimate, respectively, for field i. From (4), x is calculated as 0.524. Therefore, statistical correlation shows that if USGS had used a fixed recovery factor of 0.524x0.25, that is, 0.131 rather than 0.25, the difference between thus modified USGS estimates and GeothermEx estimates would become statistically insignificant, as illustrated by the cross-plot shown in Figure 4.

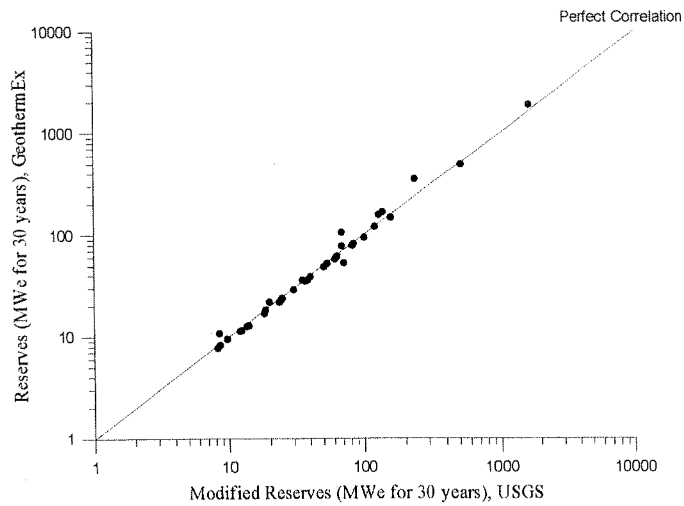

Figure 4. Comparison of Reserves (GeothermEx vs. Modified USGS).

The underlying assumption in the above comparison between the two estimates was that the GeothermEx estimates, being more recent, were more representative. This assumption may be justified to the extent that the resource parameters used for the recent estimates were generally based on more data, better understanding of geothermal systems gained over the past 26 years, and more industry experience in actual exploitation of geothermal fields. It should be noted that when Circular 790 was issued, no hydrothermal reservoir, and no geothermal field except The Geysers, had yet been commercially produced in the U.S. Nevertheless, how realistic is the rectangular probability density function for r used in the GeothermEx assessment (ranging from 0.05 to 0.20 for non-sedimentary formations and from 0.10 to 0.20 for sedimentary formations)? This question is considered below.

Estimating Recovery Factor

Estimation of recovery factor is an insidious issue because it is dictated by not only a host of site-specific resource conditions but also the production/injection strategy employed by the field operator. While r can be estimated for a specific reservoir under a given production/injection scenario by appropriate numerical simulation of the reservoir behavior, such simulations cannot be adequately generalized for a nationwide assessment. It should be noted that the fixed value of 0.25 used in 1978 for r originated from the observation, from the experience in petroleum industry, that in an ideal sedimentary formation the recovery factor should be around 0.50. Assuming that statistically 50% of the volume of a geothermal reservoir would prove porous and permeable, an r value of 0.5 x 0.5, that is, 0.25 was deduced. However, based on the industry experience over the last three decades, the recovery factor for fractured, non-sedimentary geothermal reservoirs has proven to be invariably lower. For this reason, Klein, *et al* (2004) assumed a higher minimum r value for sedimentary formations (0.10) than for non-sedimentary formations (0.05). We have approached the problem of estimating the applicable range of r values in a semi-empirical and probabilistic fashion as described below.

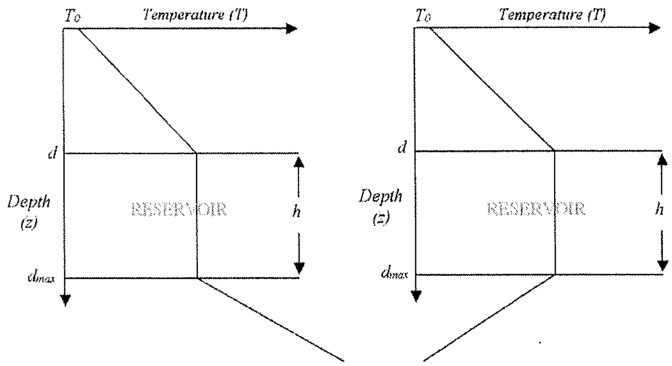

Figure 5. Idealized Vertical Temperature Profiles.

Figure 5 shows an idealized representation of two possible vertical temperature profiles associated with a hydrothermal reservoir, with and without temperature reversal below the reservoir. For this idealized model the conductive heat discharge rate, D_{cond}, at the surface is given by:

$$D_{cond} = K\int_0^A \left(\frac{dT}{dz}\right) dA = KA\left(\frac{dT}{dz}\right)_{av} \qquad (5)$$

where A = area of the heat flow anomaly (see Figure 6),
K = thermal conductivity of overburden,
z = depth, and
$\left(\frac{dT}{dz}\right)_{av}$ = average vertical temperature gradient within the anomaly.

Figure 6 represents an idealized thermal anomaly, with primarily conductive heat discharge at the surface with or without a small convective component from hot springs or fumaroles.

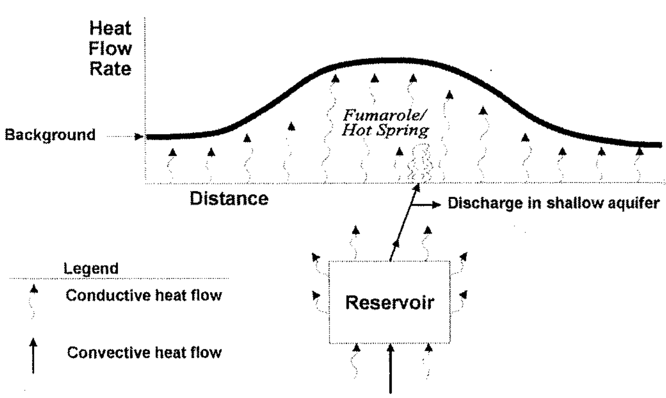

Figure 6. An Idealized Thermal Anomaly.

Then, recoverable heat resource base in the reservoir (H) is given by

$$H = rA_{res}hC_v(\overline{T} - T_0), \qquad (6)$$

where r = heat recovery factor, A_{res} = reservoir area, h = reservoir thickness, C_v = volumetric specific heat of water-filled rock, $\overline{T}$= average reservoir temperature, and T_0 = rejection temperature.

$$\text{or,} \quad H = rA_{res}hC_v\left(\frac{dT}{dz}\right)_{av} d, \qquad (7)$$

where d is depth to the top of reservoir. From (5) and (7),

$$H = rhdC_vD_{cond}\left(\frac{A_{res}}{KA}\right). \qquad (8)$$

The maximum rate of heat mining from the reservoir (E_m) is H/L, where L is plant life (assuming a 100% plant capacity factor). Therefore, from (8)

$$E_m = \frac{r}{L}\left(\frac{hdC_v}{K}\right)\left(\frac{A_{res}}{A}\right)D_{cond} \qquad (9)$$

The sustainable heat production capacity (E_s) from the reservoir is the sum of natural heat discharge rate (D_{cond}) over the entire thermal anomaly and the maximum heat mining rate (E_m). Therefore,

$$E_s = \left\{\left(\frac{C_v}{LK}\right)rhd\left(\frac{A_{res}}{A}\right) + 1\right\}D_{cond} \qquad (10)$$

Sanyal (2004) argues that the sustainable capacity (E_s) of a hydrothermal reservoir is a multiple, α, termed the "Sustainability Factor," of the surface heat discharge rate from the thermal anomaly associated with the reservoir, α being 5 to 45 with 10 most likely. Furthermore, surface heat discharge rate over the entire anomaly essentially equals the convective heat recharge rate into the reservoir, the conductive heat recharge rate being relatively small (Figure 6).

Therefore, from (10),

$$\left\{\left(\frac{C_v}{LK}\right)rhd\left(\frac{A_{res}}{A}\right) + 1\right\}D_{cond} = \alpha . D_{cond} \qquad (11)$$

$$\text{or,} \quad r = \left(\frac{LK}{C_v}\right)\left(\frac{\alpha - 1}{hd}\right)\left(\frac{A}{A_{res}}\right) \qquad (12)$$

If we assume $h = d_{max}$-d, where d_{max} is the maximum economically drillable depth (assumed as 3 km in Circular 790), then

$$r = \left(\frac{LK}{C_v}\right)\frac{(\alpha - 1)}{(d_{\max} - d)d}\left(\frac{A}{A_{res}}\right) \qquad (13)$$

It should be noted that strictly speaking, the small background (regional) heat flow outside the anomaly (Figure 6) should be subtracted from the estimates of E_s and E_r, as shown in the Appendix B to this paper. However, given the uncertainties in the parameters in (13), the error in the range of r values due to ignoring the background heat flow should not be of much consequence.

Either (12) or (13) can be used to empirically estimate a value of r for a hydrothermal reservoir. For example, let us consider the case of the Heber geothermal field in California, for which $A/A_{res} \approx 10$, h = 6,000 ft, and d = 3,000 ft. Lippman & Bodvarsson (1985) estimated, from numerical simulation of the Heber reservoir, a steady-state heat recharge rate equivalent to 1.7 MWe, and subsequent production history of this field has confirmed a minimum sustainable capacity of 70 MWe from this field. Therefore α is equal to 70/1.7, or 41, and assuming typical values for C_v(40.3 Btu/Ft^3/°F), K(43.0 Btu/D/Ft/°F) and L (30 years), r is calculated as 0.26 from equation (12). Since for this case d_{max} (= d+h) is 9,000 feet, the same r value of 0.26 can also be calculated from (13). If the background heat flow is to be subtracted, from equation (B-6) in Appendix B and assuming a Q_0/Q value of 0.2, r is calculated as 0.21. The r value for Heber is relatively high reflecting its sedimentary nature.

A probabilistic assessment of the appropriate range of r values was conducted using equation (12) and assuming the following probability density functions for the various independent variables based on our experience as well as assumptions in Circular 790:

Variable	Minimum Value	Most-Likely Value	Maximum Value	Probability Distribution
α	5	10	45	Triangular
A/A_{res}	5	-	20	Rectangular
h (km)	1.0	1.5	2.5	Triangular
d (km)	0.5	1.5	2.0	Triangular

The distributions of h and d above are the same as assumed in Circular 790. In addition, following Circular 790, a maximum drilling depth (d_{max}) of 3 km, was assumed for this probabilistic assessment.

A Monte Carlo simulation of the r value from (12) using the probability density functions listed above, and subject to the constraint, $d + h \leq d_{max}$, was conducted. The histogram of the recovery factor values thus calculated is shown in Figure 7. This figure indicates that an r value range of 0.03 to 0.017 is reasonable. The mean value of r from Monte Carlo simulation is 0.11 with a standard deviation of 0.08, the range of 0.03 to 0.17 being defined by 2 standard deviations around the mean. The r value of 0.131 that makes the modified USGS and GeothermEx estimates of resource base statistically equivalent is within the above range and not far from the above mean value. Therefore, we recommend that USGS consider using an r value in the 0.03 to 0.17 range and use a rectangular probability density function. If a single value of r is to be used, perhaps an r value around 0.11 should be considered. Alternatively, a triangular probability density function similar to the histogram in Figure 7 may be considered. However, for sedimentary formations, a fixed r value of 0.15 may be more appropriate. In Klein, *et al* (2004), the approximate mean value of r was 0.125 for non-sedimentary formations and 0.15 for sedimentary formations.

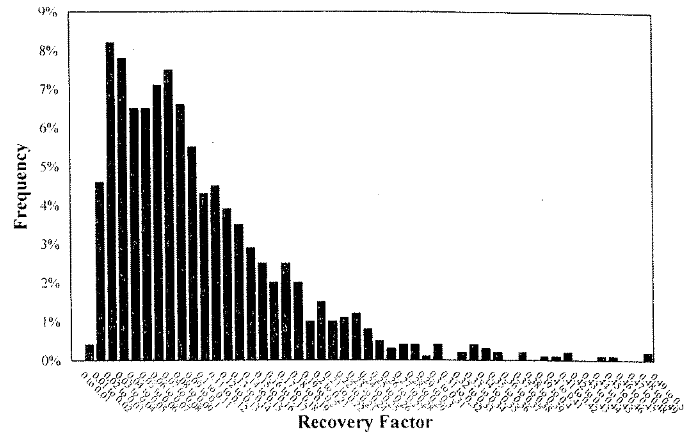

Figure 7. Histogram of Recovery Factor.

Statistics on Identified Hydrothermal Fields

Notwithstanding the fact that in hindsight one finds the estimates of resource base in Circular 790 optimistic, that monumental effort by the U.S. Geological Survey in 1978 revealed many statistical facts that remain valid today, and should be borne in mind in the forthcoming national resource assessment effort.

Figure 8 is a plot of the cumulative frequency versus mean temperature for all 187 identified hydrothermal reservoirs considered in Circular 790 at temperatures of 100°C or higher; this database does not include the fields located in national parks, and as such, not exploitable (Lassen, Yellowstone and Newberry Crater). Figure 8 shows that 70% of the identified fields (131 out of 187) are in the low temperature category, defined in Circular 790 as those at lower than 150°C temperature. It should be pointed out that only 3 such low-temperature reservoirs (only 2.3% of the total number of identified low-temperature ones) to date have been exploited commercially for power generation: Wabuska (Nevada), Empire (Nevada) and Wendel-Amedee (Honey Lake, California), with a total

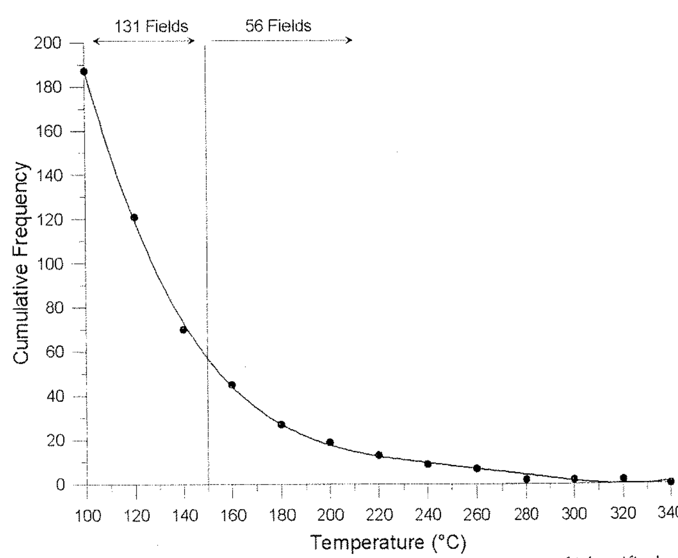

Figure 8. Cumulative Frequency versus Mean Temperature of Identified Hydrothermal Fields.

installed capacity of less than 10 MWe. By contrast, of the 56 reservoirs at a temperature of 150°C or higher, 27%, that is, 15 reservoirs, have been developed commercially with a total installed capacity of over 2,500 MWe.

Figure 9 shows a plot of cumulative resource base (from Circular 790) versus mean reservoir temperature for the 187 identified hydrothermal reservoirs. The 131 low-temperature reservoirs have a total resource base of 8,000 MWe, while the 56 remaining reservoirs have a total of 19,000 MWe. Thus, low-temperature reservoirs, which make-up 70% of the number of hydrothermal systems identified in Circular 790, contain less than 30% of the total national resource base. Therefore, temperatures of the identified hydrothermal systems are a more meaningful parameter than the number of systems identified. Furthermore, the higher the reservoir temperature the more likely it is that the reservoir has been identified already from the occurrence of surface manifestations (hot springs, fumaroles, altered ground, etc.), surface heat flow anomaly or drilling results.

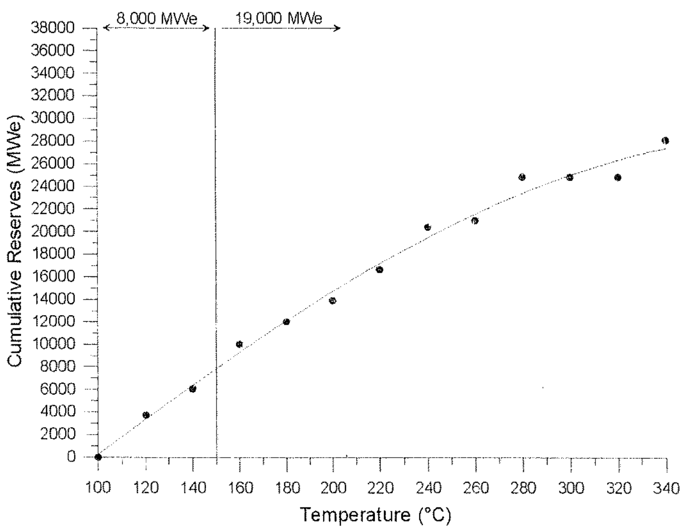

Figure 9. Cumulative Reserves versus Mean Temperature of Identified Hydrothermal Fields.

The 187 prospects were identified and assessed in Circular 790 based on all known surface indications, exploration efforts and drilling results as of 1978. Surprisingly few new prospects have been added to that list in the intervening 26 years, a period in which DOE and industry have both vastly improved and extensively utilized numerous exploration techniques. It should not be forgotten that the decade following 1978 saw a most intensive exploration for geothermal fields; the catalysts for this momentum were the lucrative power prices offered under the Federal PURPA regulation and the Standard Offer 4 contracts in California, new development incentives (such as, the Loan Guarantee Program of the U.S. Department of Energy), and attractive tax incentives (such as, new energy tax credit and investment tax credit). Unless more attractive prices or new tax incentives for geothermal power become available again, the spate of exploration and drilling seen in the 1980s is unlikely to be repeated.

Of the 187 identified prospects, those under exploitation today, or exploited in the past, or being developed for exploitation in the near future, total only about 21. An additional 6 or so prospects remain undeveloped for environmental or regulatory reasons, or because of demonstrated lack of commercial productivity. This leaves 160 prospects identified by USGS still remaining undeveloped 26 years later. The point here is that identifying a plethora of prospects, by itself, is not the holy grail of this industry. And as discussed above, the number of prospects in itself does not tell the whole story; it is astounding to note that 10% of the prospects (19 out of 187) identified by USGS apparently contain 86% of the resource base!

Figure 9 indicates that the above-mentioned 187 systems had a total resource base of 27,000 MWe. But Table 1 shows that the recent GeothermEx assessment estimated the resource base in 37 fields to be 33% of the USGS estimate. If this trend holds true for all 187 identified hydrothermal systems, the resource base would total 0.33x27,000, that is, about 9,000 MWe. Adding to this the remaining reserves (on the order of 1,000 MWe) at The Geysers (California) steam field, the total resource base in the identified fields would amount to about 10,000 MWe. Therefore, pending the new USGS estimate we believe this is a realistic rough estimate of the hydrothermal resource base in the identified systems in the United States.

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Appendix A: Resource Base Assessment Methodology

In terms of power capacity (E), the resource base is estimated as:

$$E = V\,C_v(T-T_o)\,R/F/L \quad \text{(A-1)}$$

where V = volume of the reservoir,
C_v = volumetric specific heat of the reservoir,
T = average temperature of the reservoir,
T_o = rejection temperature (equivalent to the average annual ambient temperature),
R = overall recovery efficiency (the fraction of thermal energy in-place in the reservoir that is converted to electrical energy at the power plant),
F = power plant capacity factor (the fraction of time the plant produces power on an annual basis), and
L = power plant life.

The parameter R can be determined as follows:

$$R = \frac{W \cdot r \cdot e}{C_f \cdot (T - T_o)} \quad \text{(A-2)}$$

where r = recovery factor (the fraction of thermal energy in-place that is recoverable as thermal energy at the surface),
Cf = specific heat of reservoir fluid,
W = maximum available thermodynamic work from the produced fluid, and
E = utilization factor to account for mechanical and other losses that occur in a real power cycle.

The parameter W in (A-2) is derived from the First and Second Laws of Thermodynamics as follows:

$$dW = dq\,(1-T_o/T) \quad \text{(A-3)}$$

and

$$dq = C_f dT, \quad \text{(A-4)}$$

where q represents thermal energy and T represents absolute temperature.

Appendix B: Subtraction of Background Heat Flow

If the background (regional) heat flow is to be subtracted from the estimates of E_r and E_s, then

$$E_r = D_{cond} - AQ_0\,, \quad \text{(B-1)}$$

where Q_0 is background heat flow rate per unit area.
In this case, from (9),

$$E_s = \frac{r}{L}\left(\frac{hdC_v}{K}\right)\left(\frac{A_{res}}{A}\right)D_{cond} + E_r \quad \text{(B-2)}$$

If $E_s = \alpha E_r$, from (A-1) ad (A-2),

$$r = \left(\frac{LK}{C_v}\right)\left(\frac{\alpha-1}{hd}\right)\left(1-\frac{AQ_0}{D_{cond}}\right) \quad \text{(B-3)}$$

But $D_{cond} = AQ$, (B-4)

where Q is the average heat flow rate per unit area over the anomaly.
Therefore, (A-3) becomes

$$r = \left(\frac{LK}{C_v}\right)\left(\frac{\alpha-1}{hd}\right)\left(\frac{A}{A_{res}}\right)\left(1-\frac{Q_0}{Q}\right) \quad \text{(B-5)}$$

$$\text{or,}\quad r = \left(\frac{LK}{C_v}\right)\frac{(\alpha-1)}{(d-d_{\max})d}\left(\frac{A}{A_{res}}\right)\left(1-\frac{Q_0}{Q}\right) \quad \text{(B-6)}$$