*The Xerolithic Geothermal ("Hot Dry Rock")
Energy Resource of the United States:
An Update*

Gregory J. Nunz

Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

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Acknowledgments

The writer wishes to express his appreciation to Dr. Jerry Conner, Dr. David Duchane, and Mr. Morton Smith for reviewing the manuscript and providing helpful comments. He is also deeply indebted to Dr. Kenneth Wohletz for amassing and screening the data needed for the new geothermal gradient contour map. Special thanks are due Ms. Barbara Hahn, Ms. Regina Johnson, and Ms. Lanoette Piotrowski, who typed the manuscript; Ms. Ruth Robichaud and Mr. John Tubb, who prepared the illustrations; and Ms. Anne Garnett, who edited the report.

CONTENTS

	Page
ABSTRACT	1
1. INTRODUCTION	1
2. BACKGROUND	3
2.1. Fluid-Bearing Resources	3
2.2. Xerolithic Resources	3
2.3. HDR Energy-Extraction Demonstration Projects	3
3. RESOURCE ESTIMATION	6
3.1. Definitions	6
3.2. Units	7
3.3. Analytical Approach	7
3.4. The Geothermal Gradient Map	8
3.5. Resource Calculations	8
4. DISCUSSION OF RESULTS	17
5. CONCLUSIONS AND RECOMMENDATIONS	25
6. REFERENCES	26
APPENDIXES	
A. Glossary	29
B. Resource Base Computation Algorithms	30

FIGURES

Figure	Page
1. HDR Energy Extraction Concept for Rock with Low Natural Permeability	5
2. Geothermal Gradient Contour Map of the United States	11
3. Areal Distribution of Geothermal Gradients in the United States	13
4. Comparison of Potentially Useful HDR Energy Resource Base of the US with Projected WORLD Reserves of Fossil Fuels	19
5. Low-Temperature Energy Use in the US and Some Typical Applications	21
6. State Average Areal Densities of Potentially Useful HDR Resource Base	23

TABLES

Table	Page
I. Mean Values for Geothermal Gradient Contour Intervals in Figure 2 (K/km)	9
II. Hot Dry Rock Geothermal Energy Resource Base	14
III. HDR Energy Accessible Resource Base	15
IV. Potentially Useful Hot Dry Rock Geothermal Energy Resource Base	16

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by

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ABSTRACT

This report presents revised estimates, based upon the most current geothermal gradient data, of the xerolithic geothermal ("hot dry rock" or HDR) energy resources of the United States. State-by-state tabular listings are provided of the HDR energy *resource base*, the *accessible resource base*, and the *potentially useful resource base*. The latter is further subdivided into components with potential for electricity generation, process heat, and space heat. Comparisons are made with present estimates of fossil fuel reserves. A full-sized geothermal gradient contour map is provided as a supplement in a pocket inside the back cover of the report.

1. INTRODUCTION

Over the past two decades since its recognition as a potential major source of energy, the xerolithic geothermal energy resource—more popularly known as the "hot dry rock" (HDR) geothermal resource—has been estimated several times (White [1965]; White and Williams [1975]; Muffler [1979a]; Grossling [1972]; Hickel [1972]; Rex and Howell [1973]; National Petroleum Council [1973]; McGetchin [1977]; LASL HDR Project Staff [1978]; Heiken, Goff, and Cremer [1980]; Tester, Brown, and Potter [1989]). Why, then, yet another assessment? There are several aspects to the rationale for generating this document.

First, new geothermal gradient data have become available since the last published national survey (Kron and Stix [1982]), particularly for Alaska and Hawaii, which were not included therein. In the words of the United States Geological Survey (USGS), "Any resource assessment should be periodically updated in response to new information, new assessment methodologies, greater understanding of resource characteristics, improved exploration, extraction, and utilization technologies, and changed economic and social conditions" (Muffler and Christiansen [1978]). Transmitted with this report is an updated geothermal gradient contour map of the United States, which now includes Alaska and Hawaii and on which the contours for the conterminous 48 states have been revised.

Second, with the current data, the resource is estimated "bottoms up" on a state-by-state basis, as well as subsumed by the Department of Commerce's demographic "divisions." This tabular presentation is thus compatible with the department's other published tables of national statistics and would facilitate inclusion of such resource data, when appropriate, in energy-related sections of their publications.

Third, and perhaps most important, this document may serve as a timely reminder. Since accommodation was reached with the OPEC¹ cartel in the late 1970s, national awareness of, and interest in, alternative

¹ Technical terms and acronyms are defined in the glossary, Appendix A.

energy source development has greatly diminished. Yet, although the cognoscenti may disagree in detail about the size and projected endurance of the world's fossil fuel supplies, it is crystal clear that these supplies are exhaustible in the foreseeable future and that petroleum, in particular, could be exhausted in the first half of the next century at the present rate of consumption. As petroleum is the only significant near-term energy source for serving the transportation sector and is not easily replaceable as a feedstock for many vital organic products, it must be conserved for these purposes and not squandered in the generation of heat for stationary applications. Further, from the environmental perspective, there is a growing concern that the earth cannot tolerate the continual outpouring of carbon dioxide (CO_2) from the oxidation—combustive or catalytic—of *any* fossil fuel, because of CO_2 's greenhouse effect. Nor can the earth tolerate the sulfur dioxide (SO_2) also produced (predominantly by combustion of coal), which leads to acid rain. This consideration also argues for expeditious development of long-lived "clean" alternative energy sources. The ubiquitous geothermal energy of HDR holds the promise of serving a large part of this need.

This report is therefore not primarily directed toward the geology/geophysics fraternity, but rather toward the "movers and shakers." Its intent is to provide them with information and (hopefully) motivation to promote continued development of economical extraction technology for, and subsequent commercial exploitation of, this huge neglected resource.

2. BACKGROUND

Geothermal energy is, in the most general sense, the virtually inexhaustible supply of heat energy contained within the earth's interior. Geothermal energy resources, specifically, are concentrations of this geothermal energy resident in (potentially) accessible subsurface rocks and their indigenous fluids, which are being heated by underlying molten rock and/or proximate radiogenic heat sources. Such resources may be broadly characterized as one of two general types: fluid-bearing or xerolithic. These are further defined and categorized as follows:

2.1. Fluid-Bearing Resources

The fluid-bearing resources comprise *hydrothermal convective systems* and *geopressured systems*. The hydrothermal convective systems (usually called simply "hydrothermal") include hot water and/or steam that are trapped in porous or highly fractured rock. Hydrothermal systems are further classified as either liquid-dominated ("hot water") or vapor-dominated ("steam") systems, depending upon the principal physical state of the fluid. Such systems are the easiest to exploit because the hot indigenous fluid can simply be tapped by conventional drilling, brought to the surface, and used for the generation of electricity or for heating. Indeed, hydrothermal systems have been used commercially for some time both in the United States (notably The Geysers in California and Klamath Falls in Oregon) and elsewhere in the world (e.g., Iceland, Indonesia, Japan, Mexico, the Philippines, and New Zealand). Currently, hydrothermal-electric power plants are producing more than 5 gigawatts of baseload electricity in addition to comparable amounts of thermal energy for numerous direct heating applications.

The geopressured systems (typified by those found along the Gulf Coast of the US) are sediment-filled reservoirs that also contain indigenous pore fluids at moderately high temperatures but at confining pressures significantly higher than normal hydrostatic. The high pressures promote solubility of gases in the liquid, and much of the potential value of geopressured systems lies in the chemical energy of the sizable quantities of dissolved methane gas contained in their geofluids. To date, energy extraction from geopressured systems has been demonstrated experimentally but, primarily for reasons of noncompetitive economics, these systems are not being commercially exploited.

2.2. Xerolithic Resources

The xerolithic geothermal resources, which are the subject of this report and which we will hereafter refer to by the more mundane and popular name of "hot dry rock" (HDR), are characterized by a lack of naturally occurring in situ geofluid. Whereas the fluid-bearing resources are relatively rare, occurring in only a few fortunate locations, the HDR resource is widespread, comprising essentially "all the rest" (previously estimated at greater than 95%) of the total geothermal resource base.

A more formal definition of hot dry rock is *that portion of the unmelted crustal rock underlying a given geographic area which is at temperatures of potential commercial interest but which does not spontaneously produce hot fluids at an adequate rate for economical extraction of its energy*. To utilize HDR's energy, it is therefore necessary to "mine" the heat by *artificially creating or increasing the permeability* of the rock units and by *introducing the heat transfer fluid*. An HDR reservoir is therefore manmade, as opposed to the fluid-bearing ones, which occur naturally.

2.3. HDR Energy-Extraction Demonstration Projects

The foregoing definition implies a wide spectrum of rock types and permeabilities. Indeed, techniques borrowed from the oil and gas industry have been proposed (for instance, Tester and colleagues [1980, 1990]) for extracting HDR energy from rock units with various ranges of permeability. However, the only type of formation for which HDR energy extraction has thus far been demonstrated in an engineering sense is low-permeability crystalline basement rock. The archetypical and flagship demonstration project of this nature is

the Fenton Hill² HDR Project, which has been carried on at that site in New Mexico by Los Alamos National Laboratory (LANL) since the mid 1970s. This project was initially supported solely by the US Department of Energy (DOE) and its predecessor organizations. In 1980, under a limited-term International Energy Agency agreement, the Fenton Hill Project was expanded into the International Hot Dry Rock Geothermal Energy Development Program with technical participation and additional funding provided by the governments of (then West) Germany through its Kernforschungsanlage-Jülich GmbH (KFA) and Japan through its New Energy Development Organization (NEDO). Since 1986, the Fenton Hill effort has continued under DOE's sole sponsorship and will probably so continue through its completion. After the Fenton Hill project was well underway, complementary parallel projects were initiated, first in Cornwall, UK,³ and subsequently in Japan, Germany, France, and Russia.

The energy extraction technique developed for hot low-permeability rock is conceptually simple. A high surface-to-volume region of flow passages is created in the desired hot rock unit and connected to the surface through one or more each of injection and production wells, effectively producing a subterranean heat exchanger. A closed flow loop is completed by the surface system. Cool water is pumped down the injection well and then returns to the surface, under the pressure level maintained, as superheated water whose energy is extracted by the surface heat exchange device appropriate to the application. The water is then reinjected, completing the cycle as shown in Fig. 1.

Keeping the extracted fluid in a superheated liquid state serves to minimize the pumping power requirements and also to inhibit deleterious scale deposition. Some makeup water must be added to the reinjected fluid to compensate for the small percentage of water lost to the underground formation. In addition to maximizing the energy extraction efficiency (Tester and Herzog [1990]), this closed-loop approach also reduces the operational effluents of the HDR energy system to virtually nil, providing an extremely environmentally clean source of power.

In practice, the underground HDR reservoir is created, with equipment and technology adapted from the oil and gas industry, as follows: (a) the injection well(s) is drilled to the requisite depth for the temperature desired; (b) a 3-dimensional matrix of permanently opened and interconnected fractures and joints is formed by using hydraulic pressure to open and propagate the fracture system in the hot rock unit; and (c) the production well(s) is drilled to appropriately access the fractured region and receive the fluid delivered by the injection well(s). The wells may have somewhat inclined lower sections to afford sufficient fracture volume within the desired temperature regime and, although the conceptual system of Fig. 1 shows only one well pair, a commercial HDR system would utilize one or more injection wells and multiple production wells. The energy extraction concept for low-permeability rock units and the LANL Fenton Hill Project are documented elsewhere in detail by Smith et al. (1975), LASL (now LANL) HDR Staff (1978), Nunz (1980), Heiken et al. (1981), Nunz and Franke (1983, 1987), Smith (1987), and Tester et al. (1989).

² A site located about 55 km west of Los Alamos, NM, on the western rim of the Valles Caldera, a geologically young silicic volcano.

³ Conducted by the Camborne School of Mines under the sponsorship of the United Kingdom Department of Energy (UKDOE).

Fig. 1. HDR energy extraction concept for rock with low natural permeability (adapted from Tester et al. [1989]).

3. RESOURCE ESTIMATION

In resource-related discussions by the mining industry, the oil and gas (O&G) industry, the United States Geological Survey (USGS), and others, there is not general agreement on the definitions of resource terminology. Consequently, it is appropriate at this juncture to introduce and define the terminology used herein specifically to quantify the HDR energy resource.

3.1. Definitions

Three terms are used in this report in discussing the size of the United States' HDR energy resource: *resource base*, *accessible resource base*, and *potentially useful resource base*. These are defined and characterized as follows:

Resource Base, Q_B —*all of the heat energy contained in the rock units underlying the specified area or region (exclusive of hydrothermal and geopressed systems) to a depth of 10 km at temperatures above a reference of 15°C.* This definition is consistent, if not identical, with that of the US Geological Survey (Nathenson and Muffler [1975] and Muffler [1979b]). If all of the requisite temperature and rock property data were available to accurately and incontrovertibly calculate the resource base's value, it would be a fixed and relatively "immortal" number, independent of technology and economics.

Accessible Resource Base, Q_A —*that part of the resource base at temperatures above 25°C down to current routinely drillable depth (conservatively taken herein to be 7 km) or the depth at which the critical temperature of water (374°C) is reached, whichever is less.* This definition is modified somewhat from that of the US Geological Survey, here taking 25°C (rather than mean annual surface temperature of 15°C) as the reference temperature, and 7 km (instead of 6 km) as the drillable depth. The accessible resource base is meant to be a more "realistic" gross measure of the resource than is the resource base. However, note that because of the depth limit specification, Q_A is technology dependent and hence, indirectly, also economics dependent, which ultimately results in its being a time-variable quantity.

Potentially Useful Resource Base, Q_U —*that part of the accessible resource base that could potentially be used for either electricity generation or direct heat applications, assuming a minimum process rejection temperature of 40°C.* This quantity, Q_U , is peculiar to this report and is intended to give a still more realistic measure of the fraction of the resource base that might be commercially exploitable under appropriate economic circumstances. Q_U is divided into useful resource with potential for electricity generation (PEG), Q_{UE} , and useful resource for direct applications of thermal energy (DATE), Q_{UD} . The latter is, in turn, subdivided into process heat potential, Q_{UP} , and space heating potential, Q_{US} .

Thus

$$\begin{aligned} Q_U &\equiv Q_{UE} + Q_{UD} \\ &= Q_{UE} + Q_{UP} + Q_{US} . \end{aligned} \tag{1}$$

The temperature regimes associated with these components of Q_U are taken, somewhat arbitrarily, to be

PEG: 150 to 370°C

DATE: 60 to 150°C, of which

PROCESS HEAT: 100 to 150°C

SPACE HEAT: 60 to 100°C.

Like Q_A , Q_U is dependent upon then-current drilling and energy conversion technology and its associated economics.

3.2. Units

In keeping with current practice, the resource base data are computed and reported herein in the SI (Système International d'Unités) energy units of *exajoules*. For readers familiar with previously published values in *quads*, the conversion is

$$1 \text{ exajoule} = 10^{18} \text{ joules} = 9.479 \times 10^{14} \text{ Btu} = 0.9479 \text{ quad}$$

or, roughly speaking, 1 exajoule is about equal to 1 quad. Because most persons do not have a "feel" for exajoules (or quads)—an uncommon measure of energy in industrial parlance—approximate equivalents are given where appropriate in crude oil equivalent (COE) and/or coal equivalent, on the basis of their industry-specified nominal energy content:

$$\begin{aligned} 1 \text{ exajoule} &\approx 176 \text{ million barrels, COE} \\ &\approx 44.36 \text{ million (short) tons, coal equivalent.} \end{aligned}$$

In addition to these direct energy conversion factors, which are most appropriate for the DATE part of Q_{UE} , we cite the electricity generation capability in gigawatt-years, using the US Department of Commerce (1991) standard factor for geothermal generation of electricity, 2.1096×10^3 Btu/kW-h. This present electricity generation conversion factor, which implies a 16.2% overall conversion efficiency (and is also therefore technology dependent), is then

$$1 \text{ exajoule} \xRightarrow{\text{yields}} 44.93 \text{ billion kilowatt-hour} = 5.129 \text{ gigawatt-year.}$$

These equivalents are especially helpful in comparing the HDR resource with other energy resources.

3.3. Analytical Approach

Each of the resource measures reported was calculated, on a state-by-state basis, with an equation of the form

$$Q = \sum_i \Delta A_i \int_{z_{min,i}}^{z_{max,i}} \overline{\rho C_{p_i}}(z) [(T_0 + \nabla T_i z) - T_{ref}] dz, \quad (2)$$

where

- Q represents any of the resource measures defined;
- ΔA_i is the total area of region(s) within the state over which the average geothermal gradient is assumed constant at ∇T_i ;
- $\overline{\rho C_{p_i}}(z)$ is the average volumetric-specific heat of the rock under the i th region, as a function of depth;
- T_0 is the mean annual surface temperature, herein taken, in all cases, to be 15°C;
- ∇T_i is the average geothermal gradient, $\frac{\partial T}{\partial z}$, assumed constant over the depth range of interest for the i th region;
- T_{ref} is the assumed "reference" temperature, representing the minimum temperature of interest, or minimum process rejection temperature, for that resource measure; and
- z is depth, measured from the surface, integrated over the range $z_{min,i}$ to $z_{max,i}$ for the i th region.

Values for the demographic "divisions," the conterminous 48 states, and the entire United States were then computed by summation of the values for the applicable states. The mathematical details are discussed in Appendix B.

3.4. The Geothermal Gradient Map

In computing the measures of the HDR resource, one of the key variables—probably the single most important variable—is the rock temperature. In actuality, this temperature varies continuously with location (i.e., latitude and longitude) as well as with depth. An impractical infinitude of measurements would be required to accurately define this temperature field. The vector that characterizes the rate of change of rock temperature with distance is the *geothermal gradient*, ∇T . Because the rock temperature at a given depth does not normally change very rapidly with small variations in location (latitude and/or longitude), those components of the gradient are usually assumed negligible and the gradient's magnitude, ∇T , is then essentially the rate of increase of rock temperature with depth, $\frac{\partial T}{\partial z}$. The magnitude of the gradient itself changes with both location and depth and, at any given location, the temperature at a depth z_1 would be computed as

$$T(z_1) = T_0 + \int_0^{z_1} \nabla T dz,$$

assuming that ∇T were known as a function of z for that location. An accurate specification of ∇T everywhere in a geographic area to some prescribed depth would likewise require an impractically large set of measurements. Fortunately, unless local peculiarities in the rock strata cause abrupt changes in their bulk thermal conductivity, the temperature profiles to depths of interest are approximately linear, and the magnitude of the gradient can be treated as having an approximately constant value, $\overline{\nabla T}$, over a finite geographic area. The temperature at any depth, z_1 , within the limits of applicability of such a constant $\overline{\nabla T}$, is then simply $T(z_1) \approx T_0 + \overline{\nabla T} z_1$. Geologists and geophysicists can determine average gradients from downhole thermal measurements, exploiting existing O&G well or deep-water-well data where possible and drilling occasional ad hoc test wells when necessary. The resulting data can be usefully presented in the form of a geothermal gradient contour map.

Since the upsurge of interest during the 1970s in geothermal energy as an alternative energy source, US gradient data have been systematically compiled and several gradient maps have been published, notably those of Kron and Stix (1982) and of Nathenson and Guffanti (1988) for the conterminous 48 states and—most recently—that of Kron, Wohletz, and Tubb (1991) for the entire US. The latter is herein reproduced in miniature as Fig. 2 and also presented as a full-sized map in the pocket inside the back cover of this report. The gradients, in units of kelvins per kilometer (K/km) or, equivalently, celsius degrees per kilometer (C°/km), are shown in five colored contour intervals. The contours on this map represent the aggregation and smoothing of some 1800 data points and served as the basis for the present resource estimates.

3.5. Resource Calculations

The areal integration of the contoured regions in Fig. 2 for each state was performed graphically. The detailed calculations for each state and for the Bureau of Census demographic divisions, the conterminous 48-state area, and the entire US were then done with a Lotus 1-2-3TM spreadsheet. Data for a “Pacific Subdivision,” comprising the Pacific Division without Alaska and Hawaii, were also tabulated to facilitate computations for the conterminous 48 states.

To use the contour-derived data, it was necessary to assign a single representative gradient value to each of the contour intervals. As the cumulative frequency-vs-log gradient histogram of Fig. 3 shows, the areal distribution of the gradients is approximately log-normal over the actual range of gradients encountered. Consequently, the geometric mean gradient was used to represent each contour interval in the calculations. Because of the wide logarithmic bandwidth of the first contour interval, “zero” to 14 K/km (there are no actual 0 K/km data points!), and the unspecified upper limit of the fifth contour interval, “60+” K/km, these two ranges were examined in more detail. As a result of the overall geographic pattern of gradient distribution, it was found to be more appropriate to assign slightly different mean values to the 0–14 K/km

interval for the eastern and western US. The interval-mean values used in the calculations are listed in Table I. These contour intervals also lend themselves conveniently to the resource classification scheme of Tester and Herzog (1990).

The resource base data computed via Eq. (2), under the assumptions of Appendix B, are listed in Table II. The accessible resource base data, as defined in Section 3.1, are listed in Table III. Here, in addition to the standard unit of exajoules, the approximate COE and coal equivalents, in trillions ($\times 10^{12}$) of barrels and short tons respectively, are given.

Finally, Table IV presents the potentially useful resource base. The "potential for electricity generation" component and those for direct applications of thermal energy are cited separately, as well as the total. For the PEG component, the approximate quantity of electric energy that could be *produced* therefrom, allowing for conversion efficiencies, is given in thousands of gigawatt-years ($\text{GW}_e\text{-yr}$). The DATE component is presented under "process heat" and "space heat" headings. These classifications assume that all of the heat available at high enough temperature would be assigned to electricity generation (it could, of course, be used for DATE) and of the remainder, that in the intermediate temperature range would indeed all be used for process heat, with the low-grade residuum then relegated to space heating. For subsequent comparisons, the grand total Q_U is also converted to its COE and coal equivalent.

In principle, in computing Q_B , Q_A , and Q_U , the US Geological Survey's estimated hydrothermal and geopressured resource bases (Muffler [1979b]) should have been subtracted out. They are, however, so small in comparison with the HDR resource that, within the accuracy of these calculations, this minor correction can reasonably be ignored.

Table I.
Mean Values for Geothermal Gradient Contour Intervals in Figure 2 (K/km)

<u>Contour Interval</u>	<u>Mean Value</u>		<u>Resource Classification</u>
	<u>Eastern US</u>	<u>Western US</u>	
0-14	10.2	10.7	Marginal
15-29	21.2	21.2	Low-Grade
30-44	36.5	36.5	Low-Grade
45-59	51.6	51.6	Mid-Grade
60+	—	81.5	High-Grade

Fig. 2. Geothermal gradient contour map of the United States.

Fig. 3. Areal distribution of geothermal gradients in the United States.

Table II.
Hot Dry Rock Geothermal Energy Resource Base
(thousands of exajoules)

	<u>US</u>	<u>Division</u>	<u>State</u>
Maine			118
New Hampshire			49
Vermont			35
Massachusetts			32
Rhode Island			3
Connecticut			15
New England Division		252	
New York			277
New Jersey			57
Pennsylvania			256
Middle Atlantic Division		590	
Ohio			244
Indiana			209
Illinois			344
Michigan			275
Wisconsin			354
East North Central Division		1426	
Minnesota			535
Iowa			295
Missouri			449
North Dakota			831
South Dakota			968
Nebraska			1126
Kansas			816
West North Central Division		5021	
Delaware			20
Maryland and DC			75
Virginia			190
West Virginia			152
North Carolina			263
South Carolina			183
Georgia			360
Florida			347
South Atlantic Division		1589	
Kentucky			273
Tennessee			215
Alabama			217
Mississippi			329
East South Central Division		1034	
Arkansas			426
Louisiana			430
Oklahoma			582
Texas			2435
West South Central Division		3873	
Montana			1332
Idaho			1171
Wyoming			1002
Colorado			1164
New Mexico			1176
Arizona			1028
Utah			891
Nevada			1624
Mountain Division		9389	
Washington			545
Oregon			1507
California			1510
Alaska			4615
Hawaii			27
Pacific Subdivision (w/o AK & HI)		3562	
Pacific Division		8204	
Conterminous 48 States	26,738		
United States	31,379		

Table III.
HDR Energy Accessible Resource Base^a

	Thousands of <u>Exajoules</u>	Trillions of Barrels, <u>Oil Equivalent^b</u>	Trillions of Tons, <u>Coal Equivalent^c</u>
Maine	45	7.9	2.0
New Hampshire	20	3.5	0.9
Vermont	13	2.3	0.6
Massachusetts	12	2.2	0.5
Rhode Island	1	0.2	0.05
Connecticut	5	1.0	0.2
New England Division	97	17.1	4.3
New York	113	19.9	5.0
New Jersey	24	4.2	1.1
Pennsylvania	104	18.3	4.6
Middle Atlantic Division	241	42.3	10.7
Ohio	100	17.6	4.4
Indiana	85	15.0	3.8
Illinois	141	24.9	6.3
Michigan	110	19.3	4.8
Wisconsin	146	25.7	6.5
East North Central Division	582	102.5	25.8
Minnesota	222	39.1	9.8
Iowa	119	20.9	5.3
Missouri	186	32.7	8.2
North Dakota	357	62.8	15.8
South Dakota	417	73.3	18.5
Nebraska	484	85.2	21.5
Kansas	348	61.2	15.4
West North Central Division	2132	375.2	94.5
Delaware	9	1.5	0.4
Maryland and DC	31	5.5	1.4
Virginia	75	13.2	3.3
West Virginia	63	11.0	2.8
North Carolina	106	18.7	4.7
South Carolina	75	13.2	3.3
Georgia	148	26.0	6.6
Florida	143	25.2	6.3
South Atlantic Division	650	114.3	28.8
Kentucky	113	20.0	5.0
Tennessee	86	15.2	3.8
Alabama	85	14.9	3.7
Mississippi	137	24.0	6.1
East South Central Division	421	74.1	18.7
Arkansas	179	31.6	8.0
Louisiana	183	32.2	8.1
Oklahoma	245	43.2	10.9
Texas	1033	181.8	45.8
West South Central Division	1640	288.8	72.8
Montana	565	99.4	25.0
Idaho	503	88.5	22.3
Wyoming	428	75.3	19.0
Colorado	498	87.7	22.1
New Mexico	499	87.8	22.1
Arizona	435	76.6	19.3
Utah	381	67.0	16.9
Nevada	695	122.4	30.8
Mountain Division	4004	704.7	177.6
Washington	229	40.3	10.2
Oregon	646	113.7	28.6
California	639	112.5	28.4
Alaska	1940	341.4	86.0
Hawaii	10	1.8	0.5
Pacific Subdivision (w/o AK & HI)	1514	266.5	67.2
Pacific Division	3464	609.7	153.7
Conterminous 48 States	11,281	1,985.5	500.4
United States	13,231	2,328.7	587.0

^a Division and continental totals may not agree exactly, because of rounding.

^b 42-gallon (159-liter) barrel; 1 trillion (American) = 10¹².

^c Short ton (2000 lb_m = 907.2 kg).

Table IV.
Potentially Useful Hot Dry Rock Geothermal Energy Resource Base^a

	Potential Electricity Generation		Direct Applications of Thermal Energy		Grand Total		
	Thousands of Exajoules	Thousands of GWe-yr Equivalent ^b	Process Heat (Thousands of Exajoules)	Space Heat (Thousands of Exajoules)	Thousands of Exajoules	Trillions of Barrels Oil Equivalent ^c	Trillions of Tons Coal Equivalent ^d
Maine	3	17	9	15	27	5	1
New Hampshire	3	15	8	4	15	3	~0.7
Vermont	1	5	2	4	8	1	~0.4
Massachusetts	1	6	3	4	8	1	~0.3
Rhode Island	—	—	—	~0.5	~0.5	~0.1	~0.02
Connecticut	~0.1	~0.4	~0.2	2	3	~0.5	~0.1
New England Division	8	43	22	30	61	11	3
New York	31	157	34	21	85	15	4
New Jersey	12	59	5	3	19	3	1
Pennsylvania	23	117	35	20	78	14	3
Middle Atlantic Division	65	333	74	44	182	32	8
Ohio	16	80	42	18	76	13	3
Indiana	15	78	33	16	64	11	3
Illinois	32	65	52	24	108	19	5
Michigan	14	70	36	26	77	13	3
Wisconsin	25	126	66	24	114	20	5
East North Central Division	101	519	229	109	439	77	19
Minnesota	46	233	94	34	174	31	8
Iowa	19	98	40	27	86	15	4
Missouri	33	167	82	30	145	25	6
North Dakota	243	1246	51	19	313	55	14
South Dakota	293	1502	52	19	363	64	16
Nebraska	319	1638	53	20	392	69	17
Kansas	198	1015	73	26	297	52	13
West North Central Division	1150	5900	445	176	1771	312	78
Delaware	5	25	2	~0.6	7	1	~0.3
Maryland & DC	12	64	9	4	25	4	1
Virginia	14	71	20	18	52	9	2
West Virginia	10	53	27	11	48	9	2
North Carolina	20	101	36	22	78	14	3
South Carolina	13	66	31	13	57	10	3
Georgia	28	144	60	26	114	20	5
Florida	24	122	64	24	111	20	5
South Atlantic Division	126	647	248	118	492	87	22
Kentucky	26	134	478	17	90	16	4
Tennessee	14	72	29	19	62	11	3
Alabama	9	44	23	24	55	10	2
Mississippi	38	195	51	20	109	19	5
East South Central Division	87	445	150	80	316	56	14
Arkansas	74	378	54	20	148	26	5
Louisiana	102	521	40	14	156	27	7
Oklahoma	107	547	71	26	204	36	9
Texas	534	2737	246	92	872	153	39
West South Central Division	816	4183	411	152	1379	243	61
Montana	283	1451	140	51	475	84	21
Idaho	310	1587	58	21	388	68	17
Wyoming	253	1298	83	31	367	65	16
Colorado	311	1595	85	31	428	75	19
New Mexico	263	1349	112	43	417	73	19
Arizona	208	1067	113	41	362	64	16
Utah	228	1170	69	26	323	57	14
Nevada	350	1794	79	30	459	81	20
Mountain Division	2205	11312	739	274	3219	567	143
Washington	88	453	71	26	185	33	8
Oregon	332	1703	69	25	426	75	19
California	291	1495	143	56	491	86	22
Alaska	749	3844	612	223	1584	279	70
Hawaii	2	9	~0.8	3	6	1	~0.3
Pacific Subdivision (w/o AK & HI)	712	3650	282	108	1102	194	49
Pacific Division	1453	7503	895	334	2692	474	119
Conterminous 48 States	5270	27032	2601	1091	8963	1577	398
United States	6022	30886	3214	1317	10553	1857	468

^a Division, continent, and application totals may not agree exactly because of rounding.

^b Converted with US Dept. of Commerce standard factor for geothermal energy:

1 exajoule = 0.9749 quad (trillion Btu) will produce 44.93 billion kWe-h = 5.129 GWe-yr.

^c 42 gallon (159 liter) barrel; 1 trillion (American) = 10^{12} .

^d Short ton (2000 lb_m = 907.2 kg).

4. DISCUSSION OF RESULTS

Before the resource bases were computed, several areal average geothermal gradients were calculated as a “sanity check” on the fundamental data. Specifically the average gradients were determined for the Eastern US, Western US (with and without Alaska and Hawaii), the conterminous 48 states, and the entire country. The results were as follows:

Eastern US:	$\nabla T \approx 20 \text{ K/km}$
Western US: (w/o AK & HI)	$\nabla T \approx 33 \text{ K/km}$
Western US: (with AK & HI)	$\nabla T \approx 31 \text{ K/km}$
Conterminous 48 States:	$\nabla T \approx 27.7 \text{ K/km}$
US:	$\nabla T \approx 27.3 \text{ K/km}$

These values are comparable with, if not exactly the same as, those estimated earlier by the USGS, LANL, and others, which cluster around 25 K/km for the conterminous 48 states and which Nathenson and Guffanti (1988) report as 25 K/km and 34 K/km, respectively, for the Eastern and Western US.

The overall US resource base figure, $Q_B \approx 31.4$ million exajoules, given in Table II, is of the same order of magnitude as earlier estimates: 33 ± 4 million EJ (Diment et al. [1975]); 13.7 million EJ above 50°C (LASL HDR Project Staff [1978]); 36.5 million EJ (Electrical Power Research Institute [1978]); 6.3 million EJ regional resource base at gradients $\geq 30 \text{ K/km}$ (Heiken et al. [1982]); 16.9 million EJ to 7 km (Muffler [1979b]); and 10.5 million EJ above 150°C (Tester et al. [1989]). The value of Q_B is, from a practical standpoint, unimportant, except as a gross figure of merit to roughly characterize the magnitude of a given energy resource. For HDR energy, Q_B is—by anyone’s computation and even under the most conservative assumptions—enormous. This realization is what prompted the US Department of Energy and other alternative energy developers worldwide to explore the potential of HDR energy extraction systems.

The accessible resource base, Q_A , is a more conservative, and somewhat more meaningful, figure of merit for the resource in that it recognizes limitations in physical accessibility—in this case drillable depth—and rejection temperature. The “routinely drillable” depth is here assumed to be 7 km or the depth at which the critical temperature of water (648 K or 374°C) prevails, whichever is less. Both of these are conservative limitations because several boreholes in recent years have been drilled to depths greater than 7 km (23,000 ft) and the temperature limit applies only to the present superheated-liquid extraction loop technique being developed by LANL and in related projects elsewhere. Need-driven technology developments could greatly mitigate these restrictions. The 25°C reference temperature is somewhat more realistic than the 15°C mean annual surface temperature reference used for Q_B but is optimistic as a commercial process rejection temperature, even for low-grade space heating applications. However, the depth conservatism dominates the reference temperature optimism, making Q_A still a useful single figure of merit for a given geographic region with an eye toward future technology developments. The Q_A value of 13.2 million EJ for the US reported in Table III is comparable with the 14 million EJ between 3 and 7 km estimated by Muffler (1979). Table III includes the Q_A value’s COE and coal equivalents to facilitate inter-resource comparisons.

The resource base information that is probably the most useful to the resource development planner, however, is what we have herein termed the potentially useful resource base, Q_U , and its components, as identified in Table IV. These values in EJ represent the same conservative depth assumptions as used for Q_A but, in addition, embody a still more conservative assumed reference temperature of 40°C . As noted previously, the PEG and DATE components assume that all of the energy available at high enough temperatures *would* indeed be earmarked for electricity generation. The electricity generation “equivalent,” which was calculated using the present factor for generation from hydrothermal systems, does not assume any improvement in conversion efficiency in future HDR applications. Even so, if it were all available, the

30.9-million $\text{GW}_e\text{-yr}$ equivalent would supply the electricity demands of the entire US at the present rate of demand (2.7 trillion $\text{kW}_e\text{-h/yr}$) for many thousands of years!

The DATE components of Q_U cited in Table IV are likewise very large. Specifically, a process heat potential Q_{UP} of some 3.2 million EJ and a space heat potential Q_{US} of about 1.3 million EJ are available for the US as a whole.

The last three columns of Table IV give the total value of Q_U —PEG plus DATE components—and its crude oil and coal equivalents. The reader can acquire some “feel” for significance of these numbers by referring to Fig. 4. The left half of this figure compares the US crude oil equivalent of Q_U (from Table IV) with the current *world* reserve oil and gas COE (note logarithmic scale!) and shows that the former is more than 1000 times greater than the latter. The present US oil and gas reserve (Energy Information Administration [1990]) is only 61.9 billion barrels COE, with Q_U 30,000 times as large.

Of course a major fraction of the O&G reserve, most of which is petroleum, is needed for transportation and, to a lesser degree, petrochemical feedstocks. These uses, currently about two thirds of the total annual O&G consumption, cannot easily be replaced by alternatives in the near future. However, the remaining one-third, which is devoted to DATE uses, could be provided by HDR energy instead, extending the life of the O&G reserve by 50%. New technology developments in the first half of the 21st century, such as possible electrification of the roads and derivation of current petrochemicals from other organic starting materials, might then allow HDR energy and other alternatives to supplant an even larger part of the O&G demand.

The right half of Fig. 4 similarly shows that the US coal equivalent of Q_U is over 300 times greater than the world reserve of coal. US coal consumption is now at a record high of about 893 million short tons per year, most of which is consumed for electricity generation and process and space heating and of which a significant fraction could be replaced by HDR energy, given the necessary development. Of particular interest in this regard is the low-temperature (i.e., low-grade) DATE consumption of the US. Presently (1990 data), about 31 of the 85+ exajoules consumed annually in the US are used at temperatures of 250°C and less. Figure 5 shows the cumulative distribution function for this energy and indicates the temperature ranges of some of the applications. Note particularly the large component for space and water heating.

The question remains as to how much of Q_U really can be exploited for the designated uses. In other words, how much of Q_U is actually the HDR energy *reserve*? This is a question whose answer involves both technology and economics issues and the answer, at the moment, is *none*. The technology issues revolve primarily around the creation of the subterranean HDR reservoir and, to a lesser extent, the conversion and/or distribution process(es) in the accompanying surface facility. It has been clearly demonstrated, in both O&G exploration and in LANL's and others' HDR experiments, that present-day O&G drilling technology is more than capable of reaching depths to the 7 km assumed in computing Q_U , and existing hydrofracturing techniques are demonstrably applicable to creating downhole permeability. Yet, these are experimental applications, and expensive, insofar as HDR reservoir formation is concerned. Hence further ad hoc development and refinement of these technologies is needed. The surface facility, for electricity generation, would probably use a binary fluid Rankine cycle, although a double-flash system has also been discussed. Exchange of heat with a secondary fluid, most probably also water, would in most cases be necessary for DATE uses. Any improvements in the types and achievable efficiencies of these surface systems would enhance the potential for use of HDR energy.

Ultimately, the development decision boils down to economics, and at a very local level. HDR energy sources will be developed and exploited only where the energy produced would be at least price competitive with, if not cheaper than, that from alternative (most likely more conventional) sources. It is not the intention of this report to develop again the theoretical economics of HDR energy. That has been done admirably and extensively by others, including Milora and Tester (1976), Cummings and Morris (1979), Murphy et al. (1982), Shock (1986), Hori et al. (1986), Armstead and Tester (1987), Entingh (1987), Bechtel (1988),

Fig. 4. Comparison of potentially useful HDR energy resource base of the US with projected⁴ WORLD reserves of fossil fuels.

⁴Energy Information Administration (1990).

Tester et al. (1989), and, of particular note, the comprehensive review and analysis of these predecessors and revised economic modeling by Tester and Herzog (1990). However, the author feels that a few additional comments about the economics of HDR are in order:

- (1) Although all of the aforementioned economic models assume that drilling cost is an exponential function of depth, Nunz and Murphy (1985) have shown, through analysis of Joint Association Survey data (1984) on some 200,000 onshore O&G wells, that drilling cost is actually a more slowly increasing polynomial function of depth.⁵ They have also shown a continuous improvement in HDR-related drilling costs with time, apparently trending toward convergence with O&G drilling costs. These trends lend some optimism that the drilling component of HDR energy can approach that of conventional O&G drilling. Further, future economics-motivated ad hoc improvements in HDR drilling technology and/or technique may significantly reduce this cost.
- (2) The question of how much of the thermal energy in rock underlying a given area can actually be put to use must be technically, economically, and environmentally analyzed in detail for each local situation. However, we may obtain an optimistic upper bound by considering technical limitations, irrespective of cost. If we assume that the fractured regions created are roughly spherical and placed as close to each other as possible, about 52% of a given volume will be thermally accessed. For electricity generation, we might also assume that the surface process permits up to 20% temperature drawdown and involves a 20% average conversion cycle efficiency. Thus, about 2% of the local Q_{UE} could be produced as baseload electricity if the economics justified it. For the DATE component, the conversion (i.e., transfer) efficiency could be considerably higher, but the value of the lower-grade heat energy might not justify the volumetrically intensive drilling/fracturing campaign implicit in maximizing thermal accessibility to a given rock volume, making 2% not an unreasonable upper-limit estimate of the deliverable fraction of Q_{UD} as well. The degrees of exploitation ultimately realized, driven by local need and time-variant economics, will probably still be well below, perhaps by an order of magnitude or more, this 2% "soft" upper bound. Qualitatively speaking, one might expect that as time passes, a larger fraction of the high-grade resource base, a smaller fraction of the moderate- and lower-grade resource bases, and very little to none of the marginal resource base will be economically producible.
- (3) HDR energy is a *quasi-renewable* resource. All of the aforementioned economic studies clearly indicate that if HDR energy is to be produced profitably, thermal energy must be extracted from the reservoir rock much more rapidly than it can be replaced by heat flowing up from the still hotter regions below. This limitation is a natural consequence of the low thermal conductivity of rock. However, over a sufficiently long time period and depending upon the degree of drawdown, the original temperature levels in the reservoir will be re-established and the reservoir could be used again. Hence, HDR energy development on a large scale might see some fraction of the individual reservoir units in a production complex "lying fallow" at any given time as they are being thermally recharged. Because the resource is so large and so widely distributed, this could become a very feasible mode for its exploitation.

Some states are blessed with a larger percentage of the higher-grade resource than others, as indicated by Table IV and on the Fig. 6 map showing each state's average areal density of the potentially useful resources, $(Q_U/A)_{avg}$. Development of the PEG component in the high-grade regions would not only produce baseload electricity at competitive prices in the near future, but the experience gained in creating these high-grade electricity generation systems in different parts of the country and in varying geological milieus would help to reduce the cost of subsequently developing the lower-grade DATE systems. Then, somewhat further in the future, as fossil fuel prices and the concomitant costs of environmental abatement inexorably increase, development of the lower-grade HDR resources would become profitable. In the meanwhile, engineering

⁵ Recently reconfirmed by the author by analysis of the JAS 1991 *Drilling Costs* data for onshore wells.

Fig. 5. Low-temperature energy use in the US and some typical applications.

development of the HDR reservoir creation and production technologies must continue under broad and adequate sponsorship to achieve commercial readiness as soon as possible.

Fig. 6 State average areal densities of potentially useful HDR resource base.

5. CONCLUSIONS AND RECOMMENDATIONS

The data presented herein confirm previous assessments showing the enormity and ubiquity of the HDR energy resource. They strengthen the conclusion that the geographical distribution and quality of the resource are now known well enough for most of the United States to make reasonable assertions concerning the resource's applicability in specific locales.

As the world's political climate is currently developing, it is possible that a large part of the US petroleum supply could suddenly be cut off. In the interest of national security, it therefore behooves us to accelerate development of at least the capability to exploit major alternative energy sources if need d. In the case of the HDR resource, scientific feasibility has been well demonstrated and comprehensive economic analyses have been performed, but these have employed several somewhat speculative assumptions. To foster commercial interest in, and exploitation of, this resource in the context of the American industrial culture, *engineering* development must be completed under governmental (federal and/or state and/or local) sponsorship. Specifically, and as a minimum

- (1) the now-dormant Fenton Hill Project should be completed with a truly *long-term* flow test to provide needed data and/or verify predictions on reservoir drawdown rate, thermal stress cracking, impedance variation, scaling, and so on.
- (2) at least one additional "pilot-plant-sized" engineering prototype HDR energy extraction system should be established in a geographically separate and geologically disparate high-grade region to validate the predicted economics, using the lessons learned from the experimental Fenton Hill system.

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Appendix A. Glossary

BTU	British thermal unit (of energy) = 1055 joules
coal equivalent	the quantity of "standard" coal equivalent to a given amount of energy; 44.36 million short tons/EJ
COE	crude oil equivalent, the quantity of "standard" crude oil equivalent to a given amount of energy; 176 million barrels/EJ
conterminous US	the "lower" 48 states, i.e., the US without Alaska and Hawaii
DATE	direct applications of thermal energy, i.e., process heat and space heat
division	a demographic region within the US, defined by the Bureau of Census and comprising a cluster of contiguous states
DOE	the US Department of Energy
drawdown	the reduction in temperature of an HDR rock unit due to extraction of its heat energy at a rate greater than its natural reheating
EIA	the Energy Information Administration (of the DOE)
EPRI	the Electric Power Research Institute
ERDA	the Energy Research and Development Administration (predecessor organization to the DOE)
exajoule (EJ)	an energy unit of one quintillion (10^{18}) joules, sometimes also called one "Q"
gigawatt-year ($\text{GW}_e\text{-yr}$)	a unit of electrical energy equal to 8.76 billion kilowatt-hours
geofluid	the fluid used to extract geothermal energy, either naturally occurring as in hydrothermal systems or artificially introduced as in HDR; an aqueous solution varying from mildly mineralized to heavy brine
gradient (geothermal), ∇T	the vertical scalar component of the gradient vector of rock temperature, i.e., the rate of increase of temperature with depth (K/km or $^{\circ}\text{C}/\text{km}$)
HDR	hot dry rock (geothermal energy source)
high-grade resource	that portion of the HDR resource (base) having an average gradient of 60 K/km or more
JAS	Joint Association Survey (of the American Petroleum Institute)
LANL	Los Alamos National Laboratory
LASL	Los Alamos Scientific Laboratory (former name of LANL)
low(er)-grade resource	that portion of the HDR resource (base) having an average gradient between 15 and 44 K/km
marginal resource	that portion of the HDR resource (base) having an average gradient of 14 K/km or less
mid-grade resource	that portion of the HDR resource (base) having an average gradient between 45 and 59 K/km
NPC	National Petroleum Council
NRC	National Research Council
O&G	oil and gas (industry)
OPEC	the Organization of Petroleum Exporting Countries
PEG	potential (for) electricity generation
quad	an energy unit of one quadrillion (10^{15}) Btu's (≈ 0.95 EJ)
SI	Système International d'Unités, the international system of scientific units
UKDOE	the Department of Energy of the United Kingdom (Great Britain)
USGS	the United States Geological Survey (of the US Dept. of the Interior)
xerolithic	(geothermal source) characterized by lack of a spontaneously producible geofluid

Appendix B. Resource Base Computation Algorithms

The quantity of heat energy, dQ , stored in an element of rock volume, dV , at a temperature, T , above a reference temperature, T_{ref} , is

$$dQ = \rho C_p (T - T_{ref}) dV \quad , \quad (B1)$$

where ρ is the mass density and C_p is the specific heat of the rock element. The total energy contained within a part of a spherical shell, in earth-centered latitude/longitude coordinates, is given by the integral of equation (B1)

$$Q = - \int_r \int_\theta \int_\lambda \rho C_p (T - T_{ref}) r^2 \cos \lambda d\lambda d\theta dr \quad , \quad (B2)$$

in which r is the radius variable; λ and θ are latitude and longitude variables, respectively, which define the surface boundaries of the region in question; and the negative sign accommodates the integration from the surface to smaller radii. As in previous calculations of this nature, and specifically for use of geothermal gradient map of Fig. 2, equation (B2) is reduced to a simplified computational algorithm via several approximations:

1. The shell segments are thin (relative to earth radii); hence we may revert to surface-based Cartesian coordinates with the positive z -axis (depth) downward.
2. A constant average gradient ∇T_i , invariant within the i th contour interval on the geothermal gradient map to the depth limits of the resource bases, is assumed, as well as a fixed mean annual surface temperature, T_0 . These assumptions result in a linear relationship between temperature and depth, z , within the i th contour interval, as noted in Section 3.3.

$$T_i(z) = T_0 + \nabla T_i z \quad (^\circ\text{C}) \quad , \quad (B3)$$

with $T_0 = 15^\circ\text{C}$, for ∇T in (K or $^\circ\text{C}/\text{km}$) and z in kilometers.

3. Within each state, the incremental area

$$\Delta A_i = \iint_{S_i} dA \quad (\text{km}^2) \quad (B4)$$

contained in the contour interval S_i is determined by graphical integration.

4. The volumetric-specific heat of rock, represented by the product ρC_p , varies with the rock's mineralogic composition, porosity, fluid content, temperature, and confining pressure. Because it is assumed that we are dealing largely with relatively impermeable and dry granitic crystalline rock, the porosity and fluid effects may be neglected. Further, to a depth of 10 km or less, the compressibility effect is also second-order and can be ignored. Review of the assumptions and recommendations from the literature (Perry [1984], Stacey [1969], Lindroth and Kranza [1971], *Military Engineering* [1976], Ho et al. [1988]) used in prior resource calculations indicates that we may take as a constant representative average rock density over the range of compositions and conditions of interest

$$\bar{\rho} \approx 2600 (\text{kg}/\text{m}^3) = 2.60 \times 10^{12} (\text{kg}/\text{km}^3)$$

and a temperature-dependent average specific heat

$$C_p(T) \approx 807. + 0.690T \quad (\text{J}/\text{kg}\cdot\text{K}) \quad .$$

Combining the temperature/depth equation (B3) with this average C_p relation and multiplying by $\bar{\rho}$ yields an expression for depth-dependent average volumetric-specific heat in the i th contour interval region

$$\overline{\rho C_p}(z)_i \approx 2.12 \times 10^{-3} + 1.79 \times 10^{-6} \nabla T_i z \text{ (EJ/km}^3\text{-K)} . \quad (\text{B5})$$

With the approximations (1) through (4), using equations (B3), (B4), and (B5), the computational form of equation (B2) becomes

$$Q = \sum_{i=1}^5 \Delta A_i \int_{z_{min}}^{z_{max}} \overline{\rho C_p}(z)_i [(15. + \nabla T_i z) - T_{ref}] dz . \quad (\text{B6})$$

To calculate Q_B , Q_A and the components of Q_U , as indicated in Section 3.3, the values of T_{ref} and of the limits of integration, z_{min} and z_{max} , used with equation (B6) were as follows:

<u>Resource Base Calculated</u>	<u>T_{ref} (°C)</u>	<u>z_{min} (km)</u>	<u>z_{max}</u>
total, Q_B	15.	0.	10.
accessible, Q_A	25.	$z(25^\circ\text{C})$	7.
potentially useful PEG, Q_{UE}	40.	$z(150^\circ\text{C})$	$\min[7., z(374^\circ\text{C})]$
process heat, Q_{UP}	40.	$z(100^\circ\text{C})$	$\min[7., z(150^\circ\text{C})]$
space heat, Q_{US}	40.	$z(60^\circ\text{C})$	$\min[7., z(100^\circ\text{C})]$

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