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METHODS FOR REGIONAL ASSESSMENT OF GEOTHERMAL RESOURCES

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Abstract—A consistent, agreed-upon terminology is prerequisite for geothermal resource assessment. Accordingly, we propose a logical, sequential subdivision of the "geothermal resource base", accepting its definition as all the thermal energy in the earth's crust under a given area, measured from mean annual temperature. That part of the resource base which is shallow enough to be tapped by production drilling is termed the "accessible resource base", and it in turn is divided into "useful" and "residual" components. The useful component (i.e. the thermal energy that could reasonably be extracted at costs competitive with other forms of energy at some specified future time) is termed the "geothermal resource". This in turn is divided into "economic" and "subeconomic" components, based on conditions existing at the time of assessment.

In the format of a McKelvey diagram, this logic defines the vertical axis (degree of economic feasibility). The horizontal axis (degree of geologic assurance) contains "identified" and "undiscovered" components. "Reserve" is then designated as the identified economic resource. All categories should be expressed in units of thermal energy, with resource and reserve figures calculated at wellhead, prior to the inevitable large losses inherent in any practical thermal use or in conversion to electricity.

Methods for assessing geothermal resources can be grouped into 4 classes: (a) surface thermal flux, (b) volume, (c) planar fracture and (d) magmatic heat budget. The volume method appears to be most useful because (1) it is applicable to virtually any geologic environment, (2) the required parameters can in principle be measured or estimated, (3) the inevitable errors are in part compensated and (4) the major uncertainties (recoverability and resupply) are amenable to resolution in the foreseeable future.

The major weakness in all the methods rests in the estimation of how much of the accessible resource base can be extracted at some time in the future. In a manner similar to mineral and fuel assessment, this recoverability is expressed as a "recovery factor". For an ideally permeable hot-water system, the recovery factor may be as much as 50% and seems to be independent of temperature. It must decrease as effective porosity (ϕ_e) decreases, but the relation between the two is little more than a guess. On the other hand, for favorable systems like Larderello that produce steam by a mechanism of intergranular vaporization, the recovery factor is probably around 15–20%, decreasing to zero at an effective porosity of zero. According to the anlysis of Bodvarsson (1974), it increases with decreasing reservoir temperature, and as pointed out by Nathenson (1975*a*) is limited at low temperatures by the need to have sufficient reservoir pressure for extraction and use.

The extent to which a geothermal reservoir can be resupplied with heat during "industrial" times of 10–100 yr can be evaluated using simple analytical models. The results, combined with gravity and levelling data of Hunt (1977) for Wairakei and Isherwood (1977) for The Geysers, confirm earlier conclusions by Ramey (1970) and Nathenson (1975*a*) that resupply to reservoirs producing only steam can be neglected, and the conclusion of Nathenson (1975*a*) that it may be significant for hot-water systems of high natural discharge.

Major subjects that demand continuing investigation include:

1. Determination of recovery factors as functions of temperature and effective porosity, particularly for hot-water systems.
2. Evaluation of fluid recharge and heat resupply by repetitive gravity, levelling and underground temperature surveys in producing geothermal fields.
3. Analysis of the extent to which a recovery factor can be enhanced by stimulation and by use of confined circulation loops.

INTRODUCTION

The critical dependence of modern society on minerals and fuels has fostered an increasing awareness of the need to estimate not only the quantities that could be produced under present economic conditions, but also the quantities not yet discovered or that might be produced with improved technology or under different economic conditions. This broad-based estimation of future supplies of minerals and fuels has come to be termed "resource appraisal" or "resource assessment".

During the past few years it has become obvious that the more commonly used sources of energy (oil, natural gas, coal and hydro-power) are indeed limited, and furthermore that they are

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not distributed uniformly throughout the world. The resultant dependence of many countries on imported fuels in short supply has impelled both governments and industry to diversify existing energy sources and to develop new sources, including geothermal energy.

The potential role that geothermal energy might play in helping to meet the world's energy needs, however, remains difficult to evaluate. There exist only a few documented attempts to estimate geothermal resources in broad regions, and these efforts have proceeded independently, often using widely divergent methodologies, assumptions and terminology. Hence, it is nearly impossible to compare one estimate with another (even for the same area), much less with estimates of other types of energy.

Both Italy and the United States have recently attempted to evaluate geothermal resources in their respective countries. In Italy, the Geothermal Research Center of the National Electric Agency of Italy (ENEL) has prepared an appraisal of the pre-Apennine belt from Pisa to Naples (Barelli *et al.*, 1975*a* and 1975*b*), and in the United States, an assessment of geothermal resources was prepared by the U.S. Geological Survey (White and Williams, 1975).

There is a continuing need, however, to revise geothermal resource assessments, owing to the rapidly changing state of geothermal knowledge, the increasing data base (particularly drill holes), the improving technology, and the changing economics with respect to other sources of energy. These factors enable, and indeed make obligatory, the periodic updating of geothermal resource appraisals.

During the past few years, various organizations and individuals in Italy and in the United States have intensified efforts aimed at sharing geothermal experience between the two countries. In June 1975, these scattered efforts were merged in a formal agreement of geothermal cooperation between ENEL and the U.S. Energy Research and Development Administration (ERDA), now the Department of Energy. The major objectives of this agreement are the development of the technology for the electric power applications of geothermal energy and the development of improved techniques for assessing geothermal resources.

Inasmuch as both ERDA and ENEL recognized the pressing need to clear up the confusion surrounding geothermal resource assessment, a joint effort aimed at devising improved assessment techniques was set up in June 1976 under the ERDA–ENEL Agreement (EEA). The results of this effort, termed task 1 of Project 3 and abbreviated EEA-3/1, are presented in this report. An application of the methodology developed in EEA-3/1 is given in the report for task 3/2 (Assessment of the Geothermal Potential of Central and Southern Tuscany; Cataldi *et al.*, 1978). Both reports were presented at the Larderello Workshop on Geothermal Resource Assessment and Reservoir Engineering (12–16 September 1978), and preliminary versions were released in an issue of the ENEl Studi e Richerche.

The goals of EEA-3/1 and this report can be stated as follows:

— to provide a comprehensive evaluation of geothermal resource assessment techniques in a report that can serve as a basis for future discussion and refinement of assessment methodology;

— to propose geothermal resource terminology that is compatible with established usage in the mining and petroleum industries, yet takes into account the particular characteristics of geothermal energy;

— to propose a methodology for forthcoming refinements and revisions of geothermal resource assessment in the United States and Italy;

— to stimulate the careful attention of geothermal resource specialists to questions of geothermal resource methodology, particularly with respect to terminology, assumptions, limitations and documentation.

GEOTHERMAL TERMINOLOGY

Historical evolution of general resource terminology

Most of the concepts used today in describing the amounts of valuable materials in the earth have their origins in the mining industry (Schanz, 1975 pp. 1–2). In pre-industrial times the miner was concerned primarily with visible ore and productive capacity. The industrial age, however, brought increasingly larger scales of activity and investment, requiring that the mine owner quantify his estimates of known ore and also make estimates of the possible extent of his deposit. Furthermore, large companies and industries dependent on minerals and fuels needed educated guesses of amounts yet to be discovered, of deposits of a grade not yet commercial, and of possible substitutes for scarce commodities. Finally, the past 50 yr have seen the increasing role of governments in defining minerals and energy policies to maximize social well-being and national security, thus focussing attention on the ultimate quantities of a given substance likely to become available.

This evolution of needs and concepts has been accompanied by a parallel evolution of terminology. The simple, practical, and often informal terms of earlier days tended to be nouns (e.g. ore, reserve, deposit, resource, etc.). Over the years these nouns came to be used with various meanings, and have been modified by a bewildering number of adjectives (e.g. proven, probable, prospective, possible, identified, measured, indicated, inferred, undiscovered, hypothetical, speculative, submarginal, paramarginal, subeconomic, etc.) which in turn are used with different meaning by different workers. Finally, various combinations of these adjectives with the above-mentioned nouns have resulted in numerous classifications that differ from commodity to commodity, from industry to government, and from country to country.

Efforts by industry groups and governmental bodies to bring some consistency to this chaos have recently been summarized by Schanz (1975). There appears to be a general consensus, at least in North America, that minerals and fossil fuels can be classified according to degree of economic feasibility and degree of geologic assurance, following the scheme advocated by McKelvey (1972). There also has emerged the need to specify two general categories: (1) the amount of a given material that can be produced at a profit at the time of classification and (2) the amount that might be produced at a profit at some future time. The former is commonly termed *reserve*; the latter, *resource*. Reserve figures are normally used in short-term investment decisions and marketing tactics, whereas resource figures are needed for long-term investment strategy and public policy.

Status of geothermal terminology

There is an understandable tendency to apply existing mineral resource terminology to geothermal energy. In doing this, however, one must keep in mind several special characteristics of geothermal energy:

- the commodity to be extracted is thermal energy (expressed as joules, calories, Btu, etc.) rather than a substance only subsequently to be converted to thermal energy (e.g. barrels of oil, cubic meters of gas, tons of coal, kilograms of U_3O_8, etc.);
- this thermal energy is contained in rock (itself a multicomponent mixture) and in fluids (water, steam and noncondensable gases) contained in pores and fractures of the rock;
- even at depths reachable by drilling, only part of the thermal energy is recoverable;
- some of the thermal energy may be replaced or renewed from greater depths, and this replacement possible is accelerated by the extraction process itself;
- geothermal energy is used both for electrical generation and for "direct" uses (e.g. space heating, agricultural heating, product processing, cooling, bathing, etc.);
- natural geothermal fluids commonly contain dissolved solids that may be potentially usable by-products.

Attempts to estimate the amounts of geothermal energy that might be used by man have utilized varying assumptions and diverse terminology, resulting in the present situation of confusion on many aspects. Among these aspects are:
— thermal energy in place vs thermal energy extracted vs thermal energy used;
— various uses of extracted thermal energy;
— assumed depths of extraction;
— assumed recovery factor;
— assumed importance of renewability;
— measurement units, particularly concerning thermal energy vs electrical capacity.

Accordingly, before proceeding to methods of geothermal resource assessment, we must fix on a simple and usable terminology. In attempting this, firstly we shall develop a logical classification of geothermal energy using only general descriptive adjectives. Secondly, we shall identify the geothermal resource and the geothermal reserve within this logical framework. Thirdly, we shall consider the additional terminology and assumptions required when the various uses of geothermal energy are considered.

Logic of proposed classification

In building a classification of geothermal energy, we begin from the unambiguous, general definition of "resource base" given by Schurr and Netschert (1960, p. 297): "Resource base is all of a given material in the earth's crust, whether its existence is known or unknown and regardless of cost considerations." Resource base thus provides an upper limit to any estimates of valuable materials in the earth and is obviously far greater than the amounts extractable and usable at any future time (Schanz, 1975, p. 11). Explicitly excluded from resource base are materials in the mantle.

An extension of this definition to geothermal energy leads us to define "geothermal resource base" as all the thermal energy in the earth's crust beneath a specific area, measured from local mean annual temperature. This definition does not restrict the geothermal resource base to the upper few kilometers of the crust as in White and Williams (1975), Renner *et al.* (1975) and Nathenson and Muffler (1975), but involves the whole crust as in the original definition given by Muffler (1973) and accepted by Barelli *et al.* (1975*a*, *b*), Catadli (1977), and Leardini (1977).

We have chosen to follow this original definition for the following reasons:

1. "Resource base" is a term derived from the general literature on mineral and energy resources, and accordingly should not be redefined unilaterally for one specific type of resource, such as geothermal energy.
2. Schanz (1975) correctly points out that it is necessary to recognize the existence of materials beyond those which can be reasonably expected to be used in the foreseeable future. Schanz states (1975, p. 11): "Since we can not say categorically that [these materials] will never have any value at some point in the future, there must be a place for them in our terminology, and we must make every effort to relegate them to where they properly belong".

Although the concept of geothermal resource base is precise and unambiguous, its uncritical application can grossly exaggerate the practical significance of geothermal energy, since in fact only a small part of the geothermal resource base is likely ever to be used by man. Hence, the logic of the following paragraphs is directed towards conceptually isolating that part of the geothermal resource base that might be used under certain reasonable assumptions.

It is commonly recognized that drilling costs per meter increase rapidly with depth (Altseimer, 1976, Fig. 5), and that accordingly only thermal energy in the shallower part of the crust is likely to be extracted economically in the foreseeable future. Hence it is reasonable to divide the geothermal resource base (Fig. 1) into a shallow part likely to be tapped by production drilling (the "accessible resource base") and a deeper part unlikely to be tapped by production drilling in

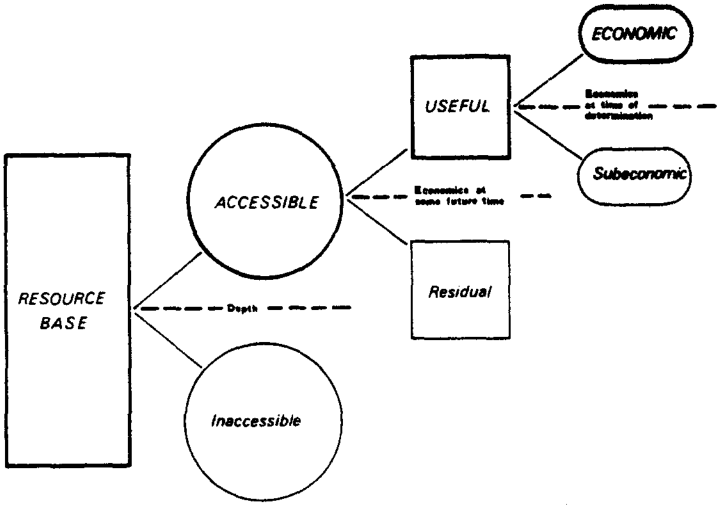

Fig. 1. Diagram illustrating logical subdivision of the geothermal resource base.

the foreseeable future (the "inaccessible resource base"). The depth separating the two categories obviously is a function of the drilling technology and economics predicted for the future, and thus must be specified in each case. Our use of "accessible resource base" corresponds to the "potential resource" of Barelli *et al.* (1975*a*) and Cataldi (1977), and is similar but not identical to the "resource base" used in USGS Circular 726 (White and Williams, 1975). For hydrothermal convection systems, the latter authors use "resource base" to refer to thermal energy in the ground (measured from 15°C) between two specified depths, rather than from the earth's surface to a specified depth.

It is also commonly recognized that not all the thermal energy accessible by drilling can be collected and extracted, even under the most optimistic assumptions of technology and economics. For various physical reasons, as well as legal and environmental considerations, a fraction will always be left in the ground. Hence we split the accessible resource base into "useful" and "residual" components (Fig. 1). The criterion for discrimination is a subjective aggregate of predicted technology and economics at some reasonable and specified future time (e.g. 25 yr, 50 yr, or perhaps as much as 100 yr). This criterion is logically rigorous, but obviously is impossible to express with accuracy because it depends on subjective prediction of future events. Our intent is that "useful accessible resource base" represent that thermal energy which could reasonably be extracted at costs competitive with other forms of energy at a specified time, under the general assumptions of progressively improving technology and of increasingly favorable economic situation.

Finally, we split the useful accessible resource base into "economic" and "subeconomic" categories (Fig. 1). The "economic" category refers to the geothermal energy that can be extracted legally at a cost competitive with other commercial energy sources at the time of determination. The "subeconomic" category refers to the geothermal energy that cannot be extracted legally at a cost competitive with other commercial energy sources at the time of determination, but could be extracted competitively under the technology and economics at some reasonable and specified future time (i.e. is still "useful" in the sense of the previous paragraph and Fig. 1).

We follow the recommendation of Schanz (1975, pp. 25, 26 and 34) in not splitting subeconomic into paramarginal and submarginal, for the following reasons:

— the general criterion for such a subdivision is not logically different from the criterion that discriminates "useful" from "residual" (i.e. the subjective aggregate prediction of economics and technology at some specified future time);
— prior attempts to apply these subdivisions to geothermal heat were forced to fall back on arbitrary criteria (Nathenson and Muffler, 1975, p. 115) and met with very limited success;
— we observe that the original Greek and Latin meaning of prefixes are often distorted, and that consequently the meanings of resultant compound terms are prone to misinterpretation and misuse.

McKelvey diagram

The logic outlined in the previous section essentially determines the vertical axis (degree of economic feasibility) of a "McKelvey diagram" (McKelvey, 1972; U.S. Geol. Survey, 1976). Along the horizontal axis (degree of geologic assurance) we follow McKelvey (1972) and Schanz (1975) in using the categories "identified" and "undiscovered" (Fig. 2). Adapting the general definitions of U.S. Geol. Survey (1976, p. A3), "identified" refers to specific concentrations of geothermal energy known and characterized by drilling or by geochemical, geophysical, and geological evidence. Undiscovered refers to unspecified concentrations of geothermal energy surmised to exist on the basis of broad geologic knowledge and theory. It should be noted that this distinction is meaningful only when applied to the accessible resource base.*

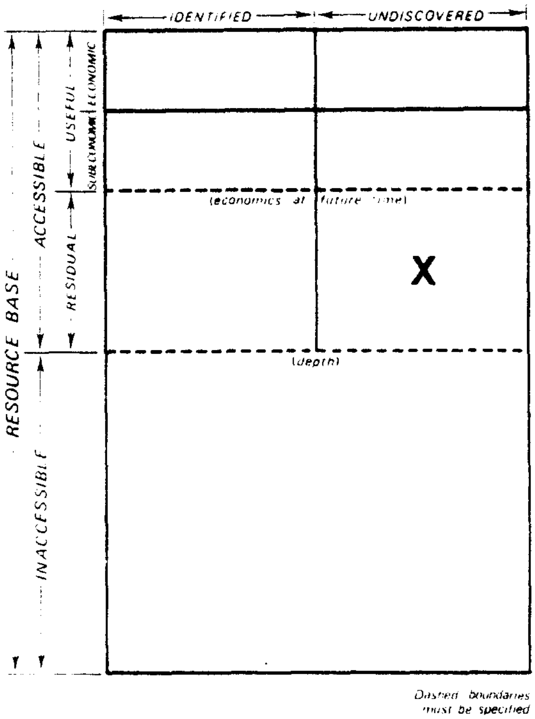

Fig. 2. McKelvey diagram illustrating proposed logical subdivision of geothermal resource base according to degree of economic feasibility (vertical axis) and degree of geologic assurance (horizontal axis). Scales are arbitrary and thus the relative sizes of the rectangles have no necessary relation to the relative magnitudes of the categories.

Each box on the resultant McKelvey diagram can be specified unambiguously by the appropriate combination of adjectives and adjectival phrases. For example, the box labeled "X"

*In certain circumstances it may be possible and appropriate to further subdivide the "identified" and "undiscovered" categories of Fig. 2. For examples of such subdivisions, see Appendix I.

in Fig. 2 is the "undiscovered residual accessible resource base". Obviously such a designation, although rigorous, is overwhelmingly cumbersome. Hence, we specify two collective terms (Fig. 3):

resource = useful accessible resource base (both identified and undiscovered),
reserve = that part of the resource that is identified and economic.

A synthesis of the geothermal definitions and of their attributes and corollaries is given in Table 1.

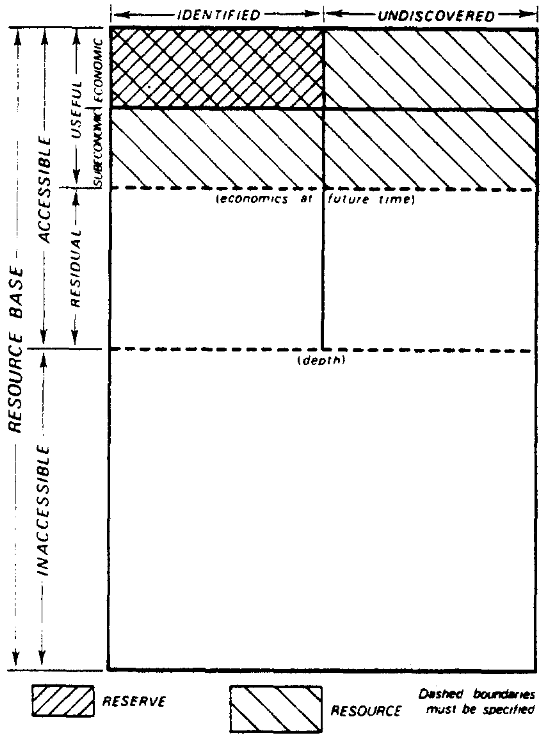

Fig. 3. McKelvey diagram for geothermal energy showing derivation of the terms *resource* and *reserve*. Scales are aribrary and thus the relative sizes of the rectangles have no necessary relation to the relative magnitudes of the categories.

Electrical generation vs *other uses*

In estimating either resource or reserve, one should specify the assumed economic conditions and technology, which in turn depend on the use for which the geothermal heat is intended. Deferring for the moment any detailed discussion of uses, we note that the production of electrical energy under foreseeable technology and economics requires high reservoir temperature (>130°C?), whereas most other uses of geothermal energy can utilize reservoirs of lower temperature. Although it is physically possible to use high-temperature geothermal resources or reserves for a variety of purposes, electrical generation generally is considered the most valuable use and is implemented where possible. Hence, in considering terminology, it is normally sufficient to divide resource (or reserve) into resource (or reserve) *for electrical production* and resource (or reserve) *for other uses*. It should be emphasized that these two categories are additive, not cumulative; that is, reserve = (reserve for electrical production) + (reserve for other uses). Because the abundance of geothermal systems decreases markedly with increasing reservoir temperature, the reserve (or resource) for electrical production will be only a small fraction of the total reserve (or resource).

Table 1. Geothermal definitions

Name	Definition	Attributes and corollaries
Resource base	All of the geothermal energy in the earth's crust beneath a specified area, referenced to local mean annual temperature	Refers to an instant in time Neglects transfer of heat from mantle Takes no regard of whether or not it would ever be technically or economically feasible to recover the geothermal energy
Inaccessible resource base	All of the geothermal energy stored between the base of the crust and a specified depth in the crust, beneath a specified area and referenced to local mean annual temperature	Refers to an instant in time Neglects transfer of heat from mantle Depth chosen for the upper limit is a matter of convenience, but must be specified in each case Implies that geothermal energy beneath the specified depth is unlikely to be tapped by production drilling at a reasonable time in the future
Accessible resource base	All of the geothermal energy between the earth's surface and a specified depth in the crust, beneath a specified area and referenced to local mean annual temperature	Refers to an instant in time Neglects transfer of heat from deeper levels Depth chosen for the lower limit is a matter of convenience, but must be specified in each case Implies that geothermal energy within the specified depth might be tapped by production drilling at some reasonable time in the future
Residual accessible resource base	That part of the accessible resource base unlikely to be extracted economically and legally at some specified time in the future	Criterion for subdivision of accessible resource base is a subjective aggregate of predicted technology and economics at some reasonable and specified future time
Useful accessible resource base (= RESOURCE)	That part of the accessible resource base that could be extracted economically and legally at some specified time in the future	Criterion for subdivision of accessible resource base is a subjective aggregate of predicted technology and economics at some reasonable and specified future time ($\leqslant 100$ years)
Subeconomic resource	That part of the resource of a given area that cannot be extracted legally at a cost competitive with other commercial energy sources at the time of determination, but might be extracted economically and legally at some specified time in the future	
Economic resource	That part of the resource of a given area that can be extracted legally at a cost competitive with other commercial energy sources at the time of determination	
Undiscovered economic resource	That part of the economic resource in unexplored parts of regions known to contain geothermal resources, or in regions where geothermal resources are suspected but not yet discovered	
Identified economic resource (= RESERVE)	That part of the economic resource known and characterized by drilling or by geochemical, geophysical and geological evidence	

We emphasize here that all geothermal resource and reserve figures are calculated as heat producible or potentially producible at the wellhead, prior to any transportation, conversion, or utilization. Accordingly, geothermal resource and reserve figures do not take into account the inevitable large losses inherent in any practical application. This procedure is directly analogous to the procedure followed in estimating fossil fuels where, for example, oil is tabulated in barrels rather than in kwh of electricity that might be generated from the oil.

This procedure allows for a variety of uses, each with its own utilization factor. In space heating, for example, only part of the available geothermal energy (calculated from mean annual temperature) is actually used in the building; the remainder is wasted (Nathenson and Muffler, 1975, p. 116). Accordingly one can speak of a resource or reserve used for space heating by an expression such as "a reserve of x calories, which give y calories of beneficial heat at a utilization efficiency of z".

For use in generating electricity, the situation is more complicated, because the ultimate product is electricity, not thermal energy. Only a small fraction of the produced geothermal energy can be converted to electricity (perhaps around 10%, the exact value depending on the specific reservoir conditions); the remaining 90% is discarded. Hence, in specifying the geothermal resource or reserve used for generating electricity one should use an expression such as "a reserve of x calories which give y kilowatt-hours at a conversion efficiency of z". If the discarded heat is itself used, two products (electricity and thermal energy) and two efficiencies (conversion and heat utilization) must be specified.

Units of measurement

Comparison among various geothermal resource assessments has been plagued by the use of a variety of measurement units, particularly in the United States. However, with the metric conversion act of 1975 (United States Public Law 94–168), the United States is committed to join the vast majority of other nations in the use of the metric system of measurement. Accordingly, it is clear that all geothermal measurements and calculations should follow the International System of Units (SI) as established by the General Conference on Weights and Measures in 1960. SI units for quantities most frequently encountered in geothermal investigations are given in Table 2 (from Page and Vigoureux, 1972).

Table 2. SI units for quantities commonly encountered in geothermal investigations

Quantity	SI name	Symbol	Expression in terms of other units
length	metre	m	100 centimetres
mass	kilogram	kg	1000 grams
time	second	s	
temperature	kelvin	K	
force	newton	N	
pressure	pascal	Pa	N/m^2
energy	joule	J	N·m
power	watt	W	J/s

Although there have been and are considerable practical and engineering problems in converting to SI units, there has been little conceptual resistance within the geothermal community except for the units for temperature (the kelvin), pressure (the pascal) and energy (the joule). Temperature is commonly expressed in degree Celsius (°C), where 0°C = 273·5 Kelvin. For pressure, there is a strong inclination to retain either the bar (= 10^5 Pa) or the atmosphere ($1{\cdot}01325 \times 10^5$ Pa). For energy, there is a persistent inclination to retain the calorie (= 4·186 J).

Given human and institutional lethargy, it is likely that units other than SI will persist for years to come. Accordingly, we present in Table 3 various multiplication factors to allow quick conversion between units of thermal energy. It should be noted that GWy or similar units of thermal energy should be specified as *thermal* by using the subscript "t", in order to avoid confusion with the electrical units of similar designation.

Table 3. Multiplication factors for units of thermal energy

from \ to	cal	Cal	joule	GWy$_t$ ‖	MWc$_t$ §	Btu	Quad	Q	PET* ‡	Bbl †
1 cal	1	10^{-3}	4·186	$1{\cdot}32 \times 10^{-16}$	$1{\cdot}32 \times 10^{-15}$	$3{\cdot}97 \times 10^{-3}$	$3{\cdot}97 \times 10^{-18}$	$3{\cdot}97 \times 10^{-21}$	10^{-10}	$7{\cdot}3 \times 10^{-10}$
1 Cal	10^3	1	4186	$1{\cdot}32 \times 10^{-13}$	$1{\cdot}32 \times 10^{-12}$	3·97	$3{\cdot}97 \times 10^{-15}$	$3{\cdot}97 \times 10^{-18}$	10^{-7}	$7{\cdot}3 \times 10^{-7}$
1 joule	0·239	$2{\cdot}39 \times 10^{-4}$	1	$3{\cdot}17 \times 10^{-17}$	$3{\cdot}17 \times 10^{-16}$	$9{\cdot}48 \times 10^{-4}$	$9{\cdot}48 \times 10^{-19}$	$9{\cdot}48 \times 10^{-22}$	$2{\cdot}4 \times 10^{-11}$	$1{\cdot}8 \times 10^{-10}$
1 GWy$_t$ ‖	$7{\cdot}56 \times 10^{15}$	$7{\cdot}56 \times 10^{12}$	$3{\cdot}15 \times 10^{16}$	1	10	$2{\cdot}98 \times 10^{13}$	$2{\cdot}98 \times 10^{-2}$	$2{\cdot}98 \times 10^{-5}$	$7{\cdot}5 \times 10^5$	$5{\cdot}5 \times 10^6$
1 MWc$_t$ §	$7{\cdot}56 \times 10^{14}$	$7{\cdot}56 \times 10^{11}$	$3{\cdot}15 \times 10^{15}$	0·1	1	$2{\cdot}98 \times 10^{12}$	$2{\cdot}98 \times 10^{-3}$	$2{\cdot}98 \times 10^{-6}$	$7{\cdot}5 \times 10^4$	$5{\cdot}5 \times 10^5$
1 Btu	252	0·252	1055	$3{\cdot}36 \times 10^{-14}$	$3{\cdot}36 \times 10^{-13}$	1	10^{-15}	10^{-18}	$2{\cdot}5 \times 10^{-8}$	$1{\cdot}9 \times 10^{-7}$
1 Quad	$2{\cdot}52 \times 10^{17}$	$2{\cdot}52 \times 10^{14}$	$1{\cdot}06 \times 10^{18}$	33·6	336	10^{15}	1	10^{-3}	$2{\cdot}5 \times 10^7$	$1{\cdot}9 \times 10^8$
1 Q	$2{\cdot}52 \times 10^{20}$	$2{\cdot}52 \times 10^{17}$	$1{\cdot}06 \times 10^{21}$	$3{\cdot}36 \times 10^4$	$3{\cdot}36 \times 10^5$	10^{18}	10^3	1	$2{\cdot}5 \times 10^{10}$	$1{\cdot}9 \times 10^{11}$
1 PET *‡	10^{10}	10^7	$4{\cdot}2 \times 10^{10}$	$1{\cdot}3 \times 10^{-6}$	$1{\cdot}3 \times 10^{-5}$	$4{\cdot}0 \times 10^7$	$4{\cdot}0 \times 10^{-8}$	$4{\cdot}0 \times 10^{-11}$	1	7·33
1 Bbl †*	$1{\cdot}4 \times 10^9$	$1{\cdot}4 \times 10^6$	$5{\cdot}7 \times 10^9$	$1{\cdot}8 \times 10^{-7}$	$1{\cdot}8 \times 10^{-6}$	$5{\cdot}4 \times 10^6$	$5{\cdot}4 \times 10^{-9}$	$5{\cdot}4 \times 10^{-12}$	0·136	1

* Approximate values obtained using for crude oil a specific gravity of 0·858 g/cm^3 and a combustion energy of 10^4 cal/g
† Barrel of crude oil (= 159 l = 42 gal)
‡ Petroleum equivalent ton
§ Megawatt-century thermal
‖ Gigawatt-year thermal

Electrical energy, in contrast to thermal energy, is commonly expressed not in joules (the accepted SI Unit) but in kilowatt-hours (1 kWh = 3·60 × 10^6 watt-second = 3·60 × 10^6 joules). Multiplication factors for this unit and other common units of electrical energy are given in Table 4.

Table 4. Multiplication factors for common units of electrical energy

from \ to	kWh	MWy_e	GWy_e	MWc_e
1 kilowatt-hour = kWh	1	$1{\cdot}14 \times 10^{-7}$	$1{\cdot}14 \times 10^{-10}$	$1{\cdot}14 \times 10^{-9}$
1 megawatt-year electrical = MWy_e	$8{\cdot}77 \times 10^6$	1	10^{-3}	10^{-2}
1 gigawatt-year electrical = GWy_e	$8{\cdot}77 \times 10^9$	10^3	1	10
1 megawatt-century electrical = MWc_e	$8{\cdot}77 \times 10^8$	10^2	0·1	1

Electrical capacity (or power) is somewhat more straightforward than energy, being conventionally expressed throughout the world in watts or derivatives thereof (kW = 10^3 W; MW = 10^6 W; GW = 10^9 W).

REVIEW OF METHODS FOR ASSESSING GEOTHERMAL RESOURCE POTENTIAL

General remarks

As noted above, the estimation of resources and reserves of minerals and fuels has been common practice for centuries, and accordingly, techniques for evaluation have improved with increasing experience, particularly in the past 75 yr.

On the other hand, the estimation of geothermal potential is a young field of investigation, which only recently has attracted serious attention from scientists and engineers. Furthermore, as might be expected in such a young subdiscipline, the various evaluation methods put forward thus far do not follow a standard approach. In addition, more times than not the various authors have addressed the problem of geothermal evaluation only with reference to the particular area of interest rather than comparing their results with those from other areas or with estimates of other forms of energy.

Assessment of geothermal resources is not simply the estimation of the resource base in a given area, but requires evaluation of that part of the resource base that can be recovered under specified economic conditions. Accordingly, geothermal resource assessment depends on a variety of factors that can be grouped as follows:

— *geological and physical factors*, including: the distribution of temperature and specific heat of the rock; the total and the effective porosity; the permeability; the pattern of fluid circulation; the fluid phase (steam or water); the reservoir depth; etc.

— *technological factors*, such as: the drilling technology; the extraction of geothermal energy by means of natural fluids or by thermohydraulic loops; the conversion factors of the thermal energy into electric energy; the plant and utilization factors; possible multipurpose use of the fluid extracted; the disposal of residual gases or water; etc.

— *economic factors*, such as: the value of the geothermal energy (which may be used directly or for electricity production); the costs of the different elements of the utilization plant; the economic convenience of multipurpose projects; the costs of the substitute source of energy; the capital costs; etc.

— *general factors*, including: legal regulations; opportunity of developing other local sources; national energy policy; social constraints; ecological limitations; etc.

In approaching a resource estimation task for a given area, most of the geological and physical factors, as well as some of the technological and economic ones, can be more or less objectively established on the basis of surface research and exploratory drilling data, factual situations and reasonable working hypotheses. Other factors, on the contrary, such as those related to the future technological development or to the medium- to long-period economical situation, or even more those depending upon political orientation, social issues and environmental and legal constraints, are very difficult to establish and often represent subjective assumptions.

The estimation of geothermal potential becomes progressively more difficult as one proceeds from a continental scale to the regional and local scales. This situation results from three main, interconnected considerations:

— on a regional or local scale, it is necessary to provide rather specific estimates that can serve as a basis for investment decisions and governmental strategy;

— accordingly it is necessary to provide rather precise geological information on subsurface conditions, information that *a priori* is commonly lacking;

— geothermal energy is "dynamic" in both space and time. For example, consider the temperature variations (both horizontal and vertical) with time, the variation in fluid state, the presence in varying proportion of incondensable gases, the existence of complex saline and hypesaline solutions, the changes in formation permeability due to precipitation and solution, and the possibility of resupply of thermal energy from outside a given reservoir.

Until just a few years ago, the attempts to evaluate the potential of a geothermal field in the initial phases of exploration were based essentially on analogy with previously explored areas, comparing known or inferred elements of the new area with the same elements in a geothermal field already in an advanced stage of development. Although this qualitative approach can give a first approximation to the potential of a new field having similarities to an already developed field, it can not be applied with much confidence to areas geologically different from the reference field. The crudeness of this analogical approach and the resultant danger of erroneous development decisions has led investigators in the past 10 yr to seek more reliable and quantitative means of estimating geothermal resources.

In order to provide a basis for improvement of methods of geothermal resource estimation, we have grouped the diverse methods appearing in the literature into four categories.

1. Method of surface heat flux
2. Volume methods
3. Planar fracture method
4. Methods of magmatic head budget.

We shall describe each of these categories in turn, deferring evaluation of their respective advantages and limitations to the following section.

Description of methods

Method of surface thermal flux. This method is conceptually the most simple. It is based on the calculation of thermal energy that, in a given unit of time, is transferred from the soil to the atmosphere and surface waters by means of conductive heat flow and thermal effluents from springs, fumaroles, etc. The value thus obtained is termed the "natural thermal power" (P) of the area (A) considered. That is,

$$P = P_1 + P_2 \tag{1}$$

where the conductive heat flow is

$$P_1 = (A)\,(q) \tag{2}$$

and the thermal energy contained in the fluid effluent is

$$P_2 = (Q)\,(C_w)\,(T_w - T_o). \tag{3}$$

In these equations q is the conductive heat flow, Q, C_w and T_w respectively the mass flow, heat capacity, and temperature of the effluent, and T_o the ambient temperature. From the natural thermal power (P) one can calculate the total energy (H) stored underground, assuming that all this energy dissipates itself to the surface, without contemporaneous resupply from subcrustal regions, in a fixed geological time (e.g. $t = 10^4, 10^5, \ldots$ etc. years). One thus obtains

$$H = Pt = (P_1 + P_2)\,t \tag{4}$$

Once having calculated H, it is possible to estimate the recoverable fraction thereof using the concept of recoverability as in the volume method (p. 65).

As an alternative to estimating (guessing?) the duration of natural hydrothermal discharge, one can apply the technique of analogy with other areas. For example, White (1965, p. 13) stated that "Experience at some localities indicates that heat can be withdrawn at rates of 4 to more than 10 times the natural heat flow for at least 10 yr without serious effect". Similarly, K. Baba (on p. 73 of Suyama *et al.*, 1975) states that geothermal areas can be exploited at 10 to more than 100 times the natural heat output.

The methods of surface thermal flux have been employed primarily in areas of abundant thermal manifestations, for example Wairakei in New Zealand (Banwell, 1963), Tatunshan in Taiwan (Chen, 1970), and Takinoue in Japan (K. Baba on p. 74 of Suyama *et al.*, 1975).

Volume method. This method of estimation is probably most noted and most commonly used, being designated also as the method of "volumetric heat" (White and Williams, 1975) or "stored heat" (Bolton, 1973) because it is based on the calculation of energy contained in a certain volume of rock.

The first step in applying the method is the calculation of the accessible resource base: that is, the thermal energy "in place" to a specified depth referring all calculations to mean annual temperature (T_o) (see p. 57). In practice one can approach the calculation by dividing the upper crust beneath a given area into a series of depth intervals, usually corresponding to geohydrologic units, and then estimating the average temperature of each volume. One can then proceed in two modes:

(a) to estimate a volumetric specific heat (C_{v_i}) and to calculate the total thermal energy contained in the rock and water using the formula

$$H = (C_{v_i})\,(V_i)\,(T_i - T_o) \tag{5}$$

where the subscript "i" refers to the specific volume of rock and water under consideration.

(b) to establish a value for total porosity (Φ_t) and then to calculate separately the energy contained in the solid phases (H_{i_r}) and energy contained in the pore fluids (H_{i_w}), such that

$$H_i = H_{i_r} + H_{i_w} = (1-\Phi_{ti})\,(C_{r_i})\,(\rho_{ri})\,(V_i)\,(T_i - T_o) + (\Phi_{ti})\,(C_{wi})\,(\rho_{wi})\,(V_i)\,(T_i - T_o) \tag{6}$$

where C_{r_i} and C_w represent the (mass) specific heats of the rock and water respectively, and ρ_{ri} and ρ_w represent the densities of the rock and water respectively.

The results obtained by the two modes in general do not differ by more than 5% as long as the total porosity is less than 20% and the pore fluid is liquid water rather than steam or gas. Mode (b), however, serve to emphasize that, in nearly all reservoirs roughly 90% of the geothermal energy is contained in the rock and only 10% in the water.

Regardless of the calculation mode chosen, this method lends itself optimally to assessing geothermal resources by the finite element concept. In fact, it is always possible to subdivide the region under examination into many different areas (the number of which will be determined by geologic conditions) and, along the vertical, into geologic complexes more or less homogeneous, each having a different lithology, mean temperature, porosity, and thickness. One can thus analyze the various areas one by one and evaluate the accessible resource base in detail appropriate to the degree of knowledge of underground conditions to the depth considered.

In areas where subsurface drillhole, thermal and geologic information is inadequate, one can often estimate the minimum subsurface reservoir temperature from chemical analyses of surface thermal manifestations, using various chemical geothermometers (Truesdell, 1976; Truesdell and Fournier, 1976; Fournier and Truesdell, 1974; Fournier, 1977). The SiO_2 and Na–K–Ca geothermometers were used by Renner *et al.* (1975) to estimate reservoir temperatures of hydrothermal convection systems in the U.S.A. Their approach required the estimation of a top and a bottom of the reservoir, assumed that the waters last equilibrated in the reservoir and thus reflected the reservoir temperature, considered only those reservoirs over 90°C, and neglected the geothermal energy in rocks overlying and underlying the reservoir.

As is emphasized elsewhere in this report, only a small fraction of the accessible resource base can be brought to the surface and thus constitute the geothermal resource (H_R). To evaluate the latter one should know the value of the *effective* porosity of the geologic formations constituting a given subsurface volume. Furthermore, one must assume a particular model by which the energy is brought to the surface by means of transport in water, steam, or a mixture of the two. The models that have been considered for transport of geothermal energy to the surface are reducible to the following two principal types:

— intergranular vaporization (boiling in place)
— intergranular flow of water (sweep process): whether this model produces water or a mixture of steam and water at the surface depends on the reservoir temperature and well conditions.

The amount of geothermal energy extractable from a given volume of rock and water (V_i) will depend on a series of geological and physical factors, and can be expressed by a general relation of the type

$$H_R = f\,(H_i,\ M_p,\ \phi_e,\ T_i,\ P_i,\ T_{wh},\ P_{wh},\ \text{etc.})$$

where M_p is a function of the production model adopted and T_{wh} and P_{wh} equal, respectively, the wellhead temperature and pressure. It is clear that a sophisticated evaluation of this relation requires the knowledge of many parameters, and thus approaches a reservoir engineering calculation not applicable to an *a priori* evaluation of extractable energy in new areas without extensive production data.

In this situation, many authors have resorted to the so-called "recovery factor" (Rg) that allows one to express recoverable geothermal energy as a percentage of the thermal energy contained in a given subsurface volume (V_i), such that

$$H_R = (Rg)\ (H_i) \tag{7}$$

Rg ranges from 0 to 100%, and obviously depends on the hypothesized production mechanism, on the effective porosity of the formations that constitute the volume V_i, and on the temperature difference between the volume V_i and the wellhead. We defer detailed discussion of recovery factor to the section of this report entitled *Recoverability of hydrothermal convection systems*, in which we suggest that Rg can range up to $\sim$ 25% for hot-water reservoirs.

Although with diverse articulation of logic, numerous authors have followed the volume method. Among these we note Banwell (1963, 1967, 1974) for Wairakei and Broadlands, Macdonald (1976) for Broadlands, Macdonald and Muffler (1972) for Kawerau, Bolton (1976) for various fields in New Zealand, Bodvarsson and Bolton (1971) and Cataldi (1974) for the Ahuachapàn field in El Salvador, Sugrobov (1970) for Pauzhetsk in Kamchatka, Barelli *et al.* (1975*a*) for the Preappennine belt of Italy, White and Williams (1975) for hydrothermal convection systems in the United States, and Baba (on p. 74 of Suyama *et al.*, 1975) for the Takinoue area in Japan. This method has also been adopted, in obviously schematic form, in numerous studies for the estimation of geothermal potential on the continental or planetary scale (e.g. White, 1965 and 1973; Banwell, 1967; Muffler and White, 1972; Rex, 1972*a* and 1972*b*).

Planar fracture method. This method was developed by Bodvarsson (1951, 1962, 1970) primarily for use in the flat-lying, late Cenozoic basalts of Iceland. The method is presented systematically as the "single fracture method" in Bodvarsson (1974), with additional computational details being found in Bodvarsson (1970, 1972).

The model used in the planar fracture method consists of a planar fracture in otherwise impermeable rock. Heat is transferred to the fracture by conduction and thence along the fracture by means of flowing water. Using a synthesis of Bodvarsson's symbology, T_0 is the initial temperature of the rock and T_r is the temperature of recharge water entering the fracture. The temperature of the outflow water will decrease from T_0 at the beginning of fluid extraction to a minimum temperature (T_m) after a production period (t_0). Using classical heat-conduction theory, Bodvarsson (1974, Fig. 9, b and d) calculates the heat theoretically extractable per unit fracture area, as a function of T_0 and of the "end temperature ratio"

$$r = \frac{T_m - T_r}{T_0 - T_r} \tag{8}$$

for production periods of 25 and 50 yr. Bodvarsson emphasizes that his Figs. 9 (b and d) give *theoretical* values for extractable thermal energy, and that these values must be reduced substantially in real field situations.

The planar fracture model can of course be extended to multiple fractures (Fig. 4) as long as the distance (d) between individual fractures is large enough to preclude thermal interaction. According to Nathenson's (1975*a*, pp. 17–18) modification of Bodvarsson (1974, p. 85), interaction between parallel fractures will be negligible when

$$d/2 > 3\sqrt{a\,t_0} \tag{9}$$

where a is the thermal diffusivity.

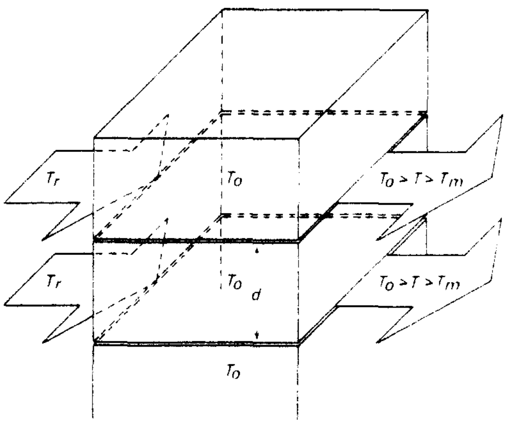

Fig. 4. Schematic diagram illustrating the planar fracture model of Bodvarsson (1974). T_0 = original rock temperature; T_r = recharge fluid temperature; T_m = minimum outlet temperature after production time t_0; d = minimum distance between fractures so that thermal interaction between fractures will be negligible.

The planar fracture method, and in particular its multiple-fracture variant, can readily be applied to a sequence of gently dipping basalt flows, where the subsurface fracture geometry is simple and predictable with confidence. Application to more complex volcanic terranes (e.g. Ahuachapán, El Salvador; Bodvarsson and Bolton, 1971) or even to microfractured intrusive rock (Bodvarsson, 1974, p. 83) is theoretically possible, but in these cases the assumed fracture spacing and orientation become progressively less certain and the results of the method increasingly subjective. subjective.

Methods of magmatic heat budget. This group of methods is based on the fact that, in volcanic areas, magma is being supplied intermittently to the upper crust. Much of this magma passes through the upper crust and is erupted on the surface as volcanic rocks. A fraction of the magma, however, lodges in the upper crust as igneous intrusions, which either act as heat sources for overlying geothermal systems or are themselves targets for exploration and development. Accordingly, an estimate of the number, size, position and age of young igneous intrusions, combined with an analysis of the cooling history, provides a means of estimating the geothermal potential of a region or even of a specific restricted area. By its very nature, this method does not provide a precise categorization of resources, but gives a broad overview of the accessible resource base; inherently, the method gives little quantitative insight into the fraction of this resource base that might be recoverable.

Noguchi (1970) has estimated the geothermal resources of Japan using a variant of the magma thermal budget method. He assumes that in Japan on the average one volcano develops every 500 yr, and that each volcano has an associated cylindrical intrusion 5 km thick and of 5 km radius located at 10 km depth. He assumes each intrusion is emplaced at 1200°C and cools to 900°C in 61,500 yr by conduction, eruption of magma, and loss of volatiles. Thus, in Japan now there are (under this model) 124 intrusions of temperature ranging linearly from 1200°C for the youngest to 900°C for the one emplaced 61,500 yr ago. Noguchi further assumes that in cooling from 1200° to 900°C a given intrusion will liberate 5% by weight of steam, with this steam loss being distributed uniformly over the 300°C temperature interval. Summing all the 124 intrusions (of age 0, 500, 1000, . . . 61,500 yr) with respect to present temperature and fraction of steam lost, he calculates that the geothermal energy still remaining to be lost by steam escape is $2{\cdot}5 \times 10^{21}$ cal, throughout Japan.

Smith and Shaw (1975) have analyzed the resource base associated with young intrusive rocks in the United States. They consider that basic magmas usually rise directly to the earth's surface without forming magma chambers at high levels in the crust, but that more silicic magmas do form storage chambers in the upper 10 km of the crust. Hence, their approach is to estimate the volumes of these silicic magma chambers, to estimate their age of emplacement, and to calculate the amount of geothermal energy still remaining in the intrusion and adjacent country rock using conventional calculations of conductive heat loss. The size of the intrusion is determined primarily by inference from the volume of associated volcanic rock, supplemented by geophysical information where available. The age of the intrusion is approximated by the age of the youngest silicic volcanic rock. Cooling by hydrothermal convection is assumed to be offset by the effects of magmatic pre-heating and additions of magma after the assumed time of emplacement.

Observations on methods of estimation

In this section we attempt to evaluate the circumstances under which the various methods can be applied to field problems, or, stated conversely, to analyze the practical limitations of each method. As we have seen, all the methods are defective in one way or another. Each calculation in fact is based on parameters only in part known or knowable *a priori*, and involves assumptions and hypotheses that are in great degree subjective. Hence, different methods may be appropriate for different field problems, depending on the geological situation, the amount of subsurface information, the scope of the investigation, and the purposes for which it is intended.

Methods of surface thermal flux. We have seen in the preceding section that this method is based on the measurement of the combined conductive heat flow and specific thermal flux of hydrothermal manifestations. Despite the fact that these both can be measured elegantly (e.g. K. Yuhara on pp. 80–89 of Suyama *et al.*, 1975), the method gives little more than a qualitative affirmation that areas of high natural hydrothermal discharge are attractive targets for geothermal exploration and development. Areas of low natural discharge (such as Mt. Amiata and Alfina in

Italy, Roosevelt, The Geysers, and the Salton Sea area in the United States) are likely to be grossly underestimated, and "blind" geothermal reservoirs of no natural fluid discharge at the surface (such as East Mesa and Heber in the United States and Cesano in Italy) are likely to be neglected completely, particularly if gradient surveys to significant depth are not available.

Furthermore, even in areas of high natural discharge of thermal fluid, this method is at best semiquantitative, in that it requires one either to guess the duration of steady natural heat discharge or to make a subjective comparison with an already developed area whose characteristics are assumed to be identical.

In summary, the method of surface thermal flux can give the minimum potential of a geothermal area, but the true geothermal potential will usually be substantially higher, particularly for areas of low natural discharge. Furthermore this true potential cannot be determined quantitatively by the method of surface thermal flux.

Volume method. This method uses estimates of subsurface temperature, volume, specific heat and density to calculate the accessible resource base, multiplying the resultant value by a recovery factor to get the recoverable thermal energy. Its common usage results from (1) the fact that it is based on a series of geological and physical parameters that, at least in principle, can be determined for a specific area and (2) the fact that it is similar to methods used commonly in petroleum and mineral resource estimation. Accordingly, of all the methods described above, the volume method lends itself best to the assessment of individual hydrothermal convection systems. However, currently there are two principal weaknesses in the method.

The more important weakness, in our opinion, concerns the estimation of the recovery factor. The value chosen depends first of all on the assumed fluid production model, and then on an evaluation of how the recovery factor for the particular model varies with temperature, effective porosity, and depth. As discussed in more detail in the section entitled "Recoverability of hydrothermal convection systems", there are theoretical formulations and some field examples that allow evaluation of the recovery factor for steam-producing systems. But the estimation of a recovery factor for a hot-water system, and the manner in which the recovery factor varies with effective porosity, are little more than educated guesses.

The second weakness is that the volume method considers only the *status quo* underground, without taking into account the resupply of heat that certainly comes, even in relatively short geologic times, from greater depths. Most authors using the volume method (e.g. Armstead *et al.*, 1974) have avoided augmenting their estimates to take into account resupply, deeming it prudent and conservative to present the accessible resource base calculated (from storage alone) as a minimum value. However, as discussed in more detail in our section entitled "Heat resupply to geothermal systems", one can evaluate possible heat resupply as a percentage of the heat extractable from storage alone, for a given industrial time. The results of various approaches indicate that resupply of heat during some tens of years of exploitation is unlikely to exceed 10–20% of the heat extracted from storage alone.

We consider that neither of these weaknesses are fatal and indeed, are optimistic that further research and field histories will refine and calibrate the various models for recoverability and resupply. Hence, we favor the volume method above the others as giving the most complete and reliable depiction of the accessible resource base and as showing promise of rapid improvement in evaluation of recoverability and resupply.

Planar fracture method. As noted above, this method involves extraction of heat through flow of water along extensive, planar fractures, with heat being transferred to the fractures only by conduction. This elegant method is appealing in that it enables the direct calculation of recoverable thermal energy from a minimum number of physical parameters (primarily rock temperature, recharge temperature, minimum outflow temperature, and production period) without going through the intermediate step of calculating the accessible resource base.

The major uncertainty in the method, however, is the degree to which the model can be applied to real field situations. Natural situations comparable to the model exist only in a few geologic environments (e.g. flat-lying flood basalts), and even there only in areas of limited extent, perhaps less than several square kilometers. For extensive areas, particularly in non-basaltic terranes, it is difficult to imagine the regular, schematic situation required by the model. Moreover, geothermal fields almost always occur in tectonically active areas in which there are numerous, open tectonic fractures, the net result of which is to create essentially a single, three-dimensional reservoir of fractures in all orientations.

In summary, one can conclude that the planar fracture method can be very useful in calculating the heat extractable from geothermal areas in flood basalt terranes but is not reliably applicable to large regions or to most common geologic situations characterized by folding and faulting.

Method of magmatic heat budget. This method combines the calculation of energy in a magma chamber at the time of emplacement with an estimate of the heat lost to the earth's surface since that time, thus giving an indirect estimate of the thermal energy in the intrusion and the country rock.

This method is inherently limited in that any particular crustal igneous anomaly can give rise to three types of geothermal system (magma, hot dry rock, and hydrothermal convection). The estimate of heat recoverable from the total crustal igneous anomaly obviously requires an estimate of the accessible resource base in each type at the present time, plus an analysis of the corresponding recovery factors. Hence, the method of magmatic heat budget is capable of giving only a broad indication of the accessible resource base, and then only in volcanic regions.

The specific procedures used, both by Noguchi (1970) and by Smith and Shaw (1975) unavoidably involve major, unverified (unverifiable?) assumptions. Noguchi assumes (a) a rate of magma emplacement, (b) an identical size, geometry and depth of emplacement for each pluton, (c) a specific cooling mechanism, (d) liberation of 5% by weight of the magma as steam and (e) loss of this steam uniformly over the 1200–900°C range of cooling and crystallization. major assumptions made by Smith and Shaw (1975) include (a) the age of the intrusion as approximated by the age of the youngest associated silicic volcanic rock, (b) the size of the magma chamber as inferred from the volume of extrusive products or from geophysics and (c) use of conduction cooling models under the premise that cooling by hydrothermal convection is offset by magmatic pre-heating and additions of magma after the assumed time of emplacement. This last assumption appears particularly tenuous in view of the abundant isotopic evidence (e.g. Taylor, 1971) that meteoric water does circulate into the margins of intrusions and considering the recent modeling of Norton (1977).

It should be noted here, however, that Smith and Shaw (1975, p. 73) are careful to emphasize that their method was conceived and developed as a guide for exploration rather than a rigorous method for quantitative estimation of the accessible resource base. They consider the estimates in their Table 7 as "first and incomplete approximations of igneous-related resource about which little is known with any degree of certainty".

Conclusion

As already noted, none of the methods described in this report appears completely satisfactory. In fact, each method requires the knowledge of specific physical factors and geologic conditions, which knowledge is almost always lacking during the *a priori* evaluation of a given area prior to the establishment of a production history.

In general, the available literature on geothermal resource assessment seems to favor the volume method, not because it is inherently more rigorous, but because it allows the discrimination and compensation of the inevitable errors introduced by the geological and physical approximations and by the subjective assumptions. Also, we feel that the major uncertainties in the volume method (recoverability and resupply) are amenable to resolution in the foreseeable future, either by means of focussed research or through the development of case histories in type geothermal areas.

Finally, we note that the volume method is applicable to virtually any geologic environment, whereas each of the other methods is limited to specific situations. Accordingly, we recommend that the volume method be adopted as the common base of comparison among different areas and regions. The other methods are best suited for supplementary roles in those areas where the geologic situation approximates the theoretical model.

RECOVERABILITY OF HYDROTHERMAL CONVECTION SYSTEMS

General considerations

It is important to make a careful distinction between the total amount of a given mineral deposit underground prior to mining and that part of the deposit that might be extracted under foreseeable economics and technology. This distinction is normally expressed as "recoverability", with the recoverable part being the total deposit multiplied by a "recovery factor".

For some metallic ore deposits, the recovery factor is nearly one and recoverability need not be considered in estimating resources or reserves (Schanz, 1975, p. 28). For most ore deposits and fossil fuels, however, a significant part of the deposit can never be recovered. For example, the recoverability of coal depends on depth and on thickness of the coal bed, and is currently about 50% for deep-mined coal in the United States (Schanz, 1975, p. 28). For oil, Miller *et al.* (1975) use a 32% factor at present, but estimate that ultimately the recoverability factor could be as high as 60%.

The extension of the term "recovery factor" to geothermal resources leads one to define *geothermal recovery factor* as "the ratio of extracted thermal energy (measured at the wellhead) to the total geothermal energy contained originally in a given subsurface volume of rock and water".* Implicit in this definition is the necessity that recovery takes place in an industrial time frame (10–100 yr) rather than in a geological time frame ($> 10^3$ yr).

The geothermal recovery factor under natural conditions of porosity and permeability ranges up to perhaps 25% in some hydrothermal convection systems, but in most natural systems is substantially lower, approaching zero in unfractured, impermeable rock. The geothermal recovery factor in most cases is poorly known, and usually can only be estimated subjectively. It depends on many items, the most important of which seem to be (1) the type of geothermal system (hydrothermal convection, geopressured, conduction-dominated, magma), (2) porosity, (3) nature of fluid in pores, (4) reservoir temperature and (5) extraction technology.

Most attempts to estimate recoverability of hydrothermal convection systems have dealt with an idealized permeable reservoir, with little attention paid to the less permeable, non-ideal situations that characterize most of the earth's crust. This emphasis on the recoverability of ideal reservoirs has led in more than a few instances to the uncritical extrapolation of high recovery

*The term "recovery factor" has been used with a variety of meanings in the geothermal literature. Among these usages are the following:
Ratio of the actually recoverable energy to the "total theoretical resource energy" (i.e. that energy calculated to be recoverable using a specific given process; Bodvarsson, 1974, p. 90).
Ratio (expressed as percentage) of fluid mass extracted at the earth's surface to the fluid mass originally in place (Cataldi, 1974).
Ratio (expressed as percentage) of the recoverable energy to the energy contained in water and rock (Barelli *et al.*, 1975*a*, p. 18).
Ratio of electricity generated to geothermal energy originally in a volume of rock and water at depth (i.e. incorporating conversion efficiency; Nathenson and Muffler, 1975, Table 15).
Ratio of "beneficial heat" (= thermal energy that can be applied directly to its intended non-electric use) to geothermal energy originally in a volume of rock and water at depth (i.e. incorporating process efficiency; Nathenson and Muffler, 1975).

factors to large tracts of unfavorable terrain, and thus to exaggeration of the true regional geothermal potential.

Favorable permeable reservoirs

Examples of recovery factors based on arbitrary assumptions. One of the first attempts to estimate how much thermal energy could be recovered from a high-temperature permeable hydrothermal convection system was that of Banwell (1963). In his Fig. 4 are given a set of curves showing 25% of stored energy (in megawatt-years) as a function of depth and surface area, for a hydrothermal convection system everywhere at the boiling point. Porosity is assumed to be 40%. Unfortunately, the figure and the accompanying text (p. 63) are ambiguous, but reconstruction of the calculations shows that the curves represent thermal energy rather than electricity. However, Fig. 4 of Banwell (1963) has been used uncritically to estimate electrical energy (Armstead *et al.*, 1974).

Another use of an arbitrary recovery factor is given in Cataldi (1974) for Ahuachapán. With a reservoir temperature of 240°C, a porosity of 20%, and no resupply, he assumes that 15 to 18% of the mass of water originally in place in the central part of the productive structure could be recovered. However, if 240°C water is supplied from the surroundings at a rate half the extraction rate, the recoverability will be augmented to 23–28% of the fluid mass originally contained in the central part of the productive structure. From this mass recovery factor one can calculate a geothermal recovery factor of 6·7–8·2% of the thermal energy originally in rock and water.

Several authors have estimated the energy recoverable by assuming that the reservoir decreases in temperature during exploitation to an average temperature below which extraction of heat is no longer economic. For Kawerau in New Zealand, Macdonald and Muffler (1972) calculated the recoverable heat for a drop in temperature from 250 to 200°C under the assumption that 50% of the reservoir would be accessible to drillholes. Muffler and Williams (1976) used the same method for Long Valley, California, under two assumptions of initial temperature (250 and 220°C) and assuming a temperature drop to 180°C. Macdonald (1976) at Broadlands, New Zealand, calculated the thermal energy extractable from rock and pore water with a temperature drop from 172 to 200°C. In contrast to Macdonald and Muffler (1972) and Muffler and Williams (1976), Macdonald (1976) assumes 100% of this thermal energy is accessible to drillholes.

Recovery factors based on theoretical models. Other authors, primarily Bodvarsson (1974) and Nathenson (1975*a*), have calculated recoverable thermal energy based on various theoretical models for extraction. These models fall into four main categories.

Intergranular flow of water.
Planar flow of water.
Intergranular vaporization (= *in situ* boiling) from a waterfilled reservoir.
Boiling from a vapor-dominated reservoir.

Intergranular flow of water. Intergranular flow of water through a reservoir of substantial thickness (greater than several hundred meters) is considered by both Bodvarsson (1974) and Nathenson (1975*a*). Bodvarsson assumes an ideal, porous reservoir where "the fluid has a very large contact area with the rock mass and the thermal contact can therefore be almost perfect" (p. 86), and he concludes (p. 87) that "the exchange of heat between the rock and the fluid can be practically complete". The recoverability is independent of temperature drop and approaches 100% in this idealized situation. However, for actual field cases, the recovery factor will be much lower; in fact, Bodvarsson (1974, pp. 90–91) suggests using a "first rough estimate" of 10%.

Nathenson (1975*a*, pp. 10–16) discusses essentially the same intergranular flow model, expanded to consider a five-spot drive pattern (four reinjection wells surrounding a producing well) and gravity segregation of colder water. He concludes (p. 16) that "on the average, perhaps 0·5 of the energy stored in a porous and permeable reservoir may be recovered through the use of a sweep process". This factor is further reduced to 0·25 by Nathenson and Muffler (1975, p. 106 and lower part of Table 15), who consider that only one half of a given "heat reservoir" is likely to be porous and permeable (i.e. accessible to drillholes).

Planar flow of water. Bodvarsson (1974) also considers the case of a volume of impermeable rock penetrated by a planar fracture along which water flows to a well. As described above, he presents his results (his Fig. 9, b and d) as "specific theoretical resource energy" (in megawatts of heat per square meter) as a function of original rock temperature (T_o) and the "end temperature ratio" (r), where $r = (T_m - T_r)/(T_o - T_r)$. T_m is the minimum outflow temperature from the crack, and T_r is the recharge temperature. To convert this "specific theoretical resource energy" into a geothermal recovery factor, one must specify the thickness ($d/2$) of rock from which heat is conducted to the fracture in time t_o. Using Nathenson's (1975*a*, pp. 17–18) modification of equation (9) of Bodvarsson (1974), and assuming t_o = 100 y and $a = 10^{-6}$ m^2/s, the interaction between parallel horizontal fractures is negligible when d is greater than 338 m. Accepting this value as the thickness from which thermal energy is extracted (i.e. 169 m above and below the fracture), we have calculated geothermal recovery factors for times of 100, 50 and 25 yr as a function of rock temperature (Fig. 5). It must be emphasized that since these geothermal recovery factors are derived from *theoretical* curves of Bodvarsson (1974, Fig. 9, b and d), they are undoubtedly greater than recovery factors under real field conditions.

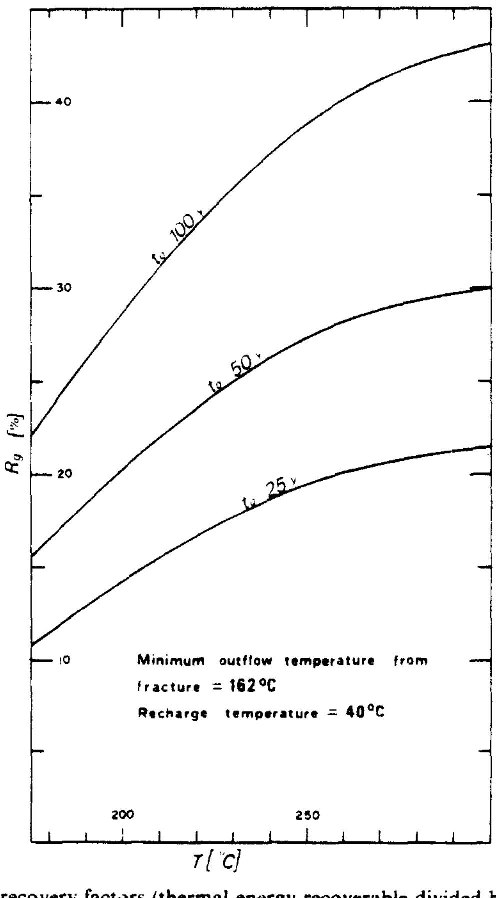

Fig. 5. Theoretical geothermal recovery factors (thermal energy recoverable divided by geothermal energy originally in rock) in % relative to 40°C as a function of original rock temperature and time, for the planar fracture model of Bodvarsson (1974). Calculated from Fig. 9 (b and d) of Bodvarsson (1974), assuming a distance of 338 m between adjacent fractures. Actual field values of recovery factor will be somewhat lower than the theoretical values shown on this figure.

Intergranular vaporization. Intergranular vaporization of a reservoir initially filled with water has been discussed by Bodvarsson (1974, pp. 87 and 88), Nathenson (1975*a*, pp. 6–9), and Barelli *et al.* (1975*a*). Bodvarsson (1974, Fig. 12) presents a set of curves relating "specific resource energy" in kWh-thermal per m^3 to reservoir temperature and porosity (note the erroneous designation of this energy as electrical in the caption of his Fig. 12). Using this Fig. 12 and the "HEAT" curve of his Fig. 11 (which curve represents thermal energy referenced to 40°C), we have calculated the geothermal recovery factor (thermal energy extracted divided by geothermal energy originally in the reservoir) as a function of porosity and temperature. The results (our Fig. 6) are for an "ideal" reservoir, and we agree with Bodvarsson (1974, pp. 90–91) that they must be decreased by an uncertain but large amount (2/3–3/4?) to reflect real field conditions.

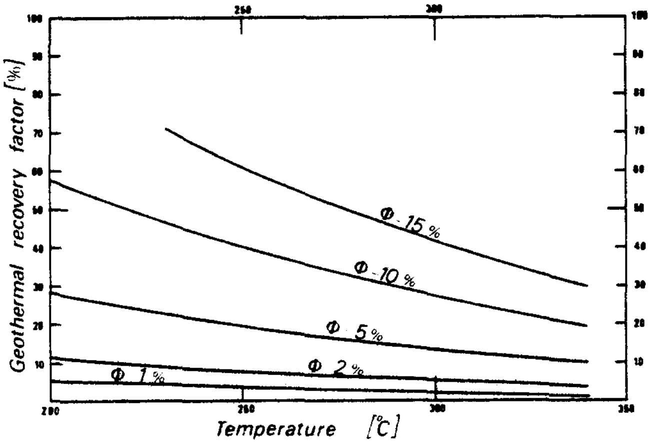

Fig. 6. Theoretical geothermal recovery factors (thermal energy recovered divided by geothermal energy originally in reservoir) in % relative to 40°C as a function of reservoir temperature and porosity. Calculated from Fig. 12 and the HEAT curve of Fig. 11 of Bodvarsson (1974). Actual field values of recovery factor will be substantially lower than the theoretical values shown on this figure.

Nathenson (1975*a*, Fig. 4) presents similar curves relative to 15°C, reproduced here as Fig. 7. Nathenson (1975*a*, p. 8) notes that a reservoir produced under this intergranular vaporization model would have to be abandoned at a finite pressure, thus giving an upward limit of recoverability for any given porosity. Nathenson (1975*a*, p. 8) suggests an abandonment pressure

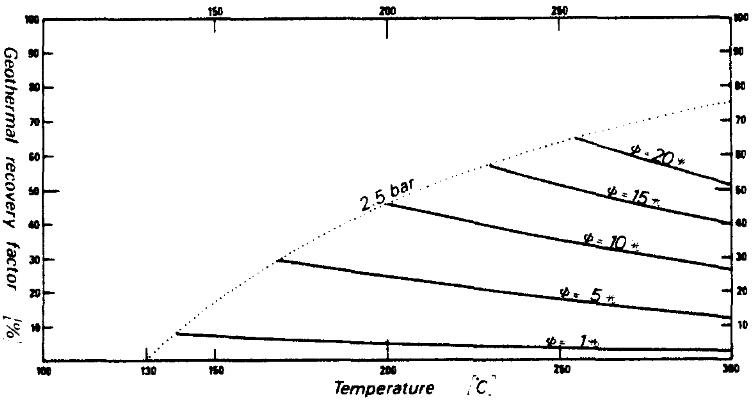

Fig. 7. Theoretical geothermal recovery factor (thermal energy recovered divided by geothermal energy originally in reservoir) in % relative to 15°C as a function of reservoir temperature and porosity. Adapted from Fig. 4 of Nathenson (1975*a*), with addition of the final pressure limitation of 2·5 bar. Actual field values of recovery factor will be substantially lower than the ideal values shown on this figure.

of 8 bar, but this seems much too high, given that steam is today being economically exploited at reservoir pressures of below 5 bar in some parts of the Italian geothermal fields. Considering only use for generating electricity, using a turbine of intake pressure 0·7 bar, and assuming a difference between wellhead and bottom-hole pressure of ~1·2 bar (Nathenson, 1975*b*, Fig. 3), a reservoir abandonment pressure of 2·5 bar is perhaps appropriate. The limiting curve for this abandonment pressure, shown by the dotted line of Fig. 7, indicates that production by intergranular vaporization of steam suitable for electrical generation is not feasible at reservoir temperatures less than 130°C.

Barelli *et al.* (1975*a*) derived a volume recovery factor for an intergranular vaporization model using specific data from the Larderello–Travale region of Italy. The volume of water extracted was calculated from the mass of steam produced from 1900 to 1974, using a density of 1 g/cm^3. The volume of water initially in the reservoir was calculated assuming that the water table in the reservoir decreased from 1900 to 1974 by an average value of 400 m over a production area of 115 km^2. A *total* porosity of 15% was used for the upper part of the reservoir (carbonate and anhydrite formation) and 4% for the underlying terrigenous rocks (Barelli *et al.*, 1975*a*, footnote to p. 18, supplemented by notes used in preparation of the report). The ratio of the volume of water extracted to the volume of water initially in the Larderello–Travale reservoir is 18%, and is designated in Table 6a of Barelli *et al.* (1975*a*) as the "recovery factor for water" for the reservoir complex of the Larderello–Travale productive area. The corresponding volume recovery factors for water given in Table 6a for other areas and complexes in the Preappennine belt of Italy were scaled from this factor, taking into account porosity, depth and temperature.

Factors for recovery of thermal energy separately from rock and water of the reservoir complex of the Larderello–Travale productive area (12·5% and 15% in Table 5a of Barelli *et al.*, 1975*a*) were derived from the volume recovery factor of Table 6a under the assumption of intergranular vaporization. Again these factors were scaled to other complexes and areas in the Preappennine belt of Italy, taking into account porosity, depth and temperature. Although Barelli *et al.* (1975*a*) did not present any values of geothermal recovery factor (ratio of thermal energy extracted to geothermal energy originally in rock and water of the reservoir), this factor can be calculated from their data, and for the reservoir complex of the Larderello–Travale productive area is 13·3%.

The mass of steam produced since 1900 from the reservoir complex of the Larderello–Travale productive area is approximately $1{\cdot}1 \times 10^{15}$ g. On the other hand, we calculate using the model and data of Barelli *et al.* (1975) that $4{\cdot}2 \times 10^{15}$ g of liquid water still remain in the reservoir complex (i.e. the volume partly depleted of water originally in interconnected pores). If we suppose that in this volume there exist some interconnected pores still containing liquid water, then part of the present steam production could be coming from this residual water. In this case, the ultimate recovery factors for the reservoir volume will be somewhat (a few percent?) greater than the 18% volume recovery factor and the 13·3% geothermal recovery factors noted above.

Boiling from a vapor-dominated reservoir. Nathenson (1975*a*) has presented an estimate of recoverability based on the vapor-dominated reservoir model of White *et al.* (1971) and Truesdell and White (1973). This model considers the reservoir of a steam-producing system such as Larderello or The Geysers to be filled initially with a *mixture* of water and steam, with steam being volumetrically dominant and the pressure-controlling phase. Nathenson (1975*a*) states that the curves for the intergranular vaporization model (Fig. 7) can be used for a vapor-dominated situation if ϕ is not the porosity but is the volume percentage of water in the reservoir (i.e. porosity multiplied by the volume fraction of water in the pores). Nathenson and Muffler (1975) applied this model to The Geysers, assuming 5% for the volume percentage of water in the 240°C reservoir, thus estimating an ideal recovery factor of 19·4% (Fig. 7). They further assumed porous, permeable rock to make up only one-half of The Geysers "heat reservoir", thus giving a geothermal recovery factor of 9·7% (Nathenson and Muffler, 1975, top part of Table 15).

Less favorable reservoirs. Virtually all the literature dealing with geothermal recoverability deals solely with favorable, highly permeable "reservoirs". Even the horizontal fracture method of Bodvarsson (1974), although based on classical heat-conduction theory, requires that several permeable horizontal fractures extend throughout the impermeable rock. However, most volumes of rock (or rock and water) in the earth's crust are far from ideal permeable reservoirs, and the geothermal recovery factor must be reduced accordingly.

Barelli *et al.* (1975*a*) have explicitly considered this problem, and have scaled the recovery factors for heat from water and rock (Table 5a) were scaled to zero at 20 C, and the volume areas of the Preappennine belt of Italy. Although detailed methodology was not presented, in general the recovery factor was considered to decrease linearly with decreasing temperature, decreasing porosity, and increasing depth (Barelli *et al.*, 1975*a*, p. 19). In particular, the recovery factors for heat from water and rock (Table 5a were scaled to zero at 20°C, and the volume recovery factors used to calculate electrical production (Table 6) were scaled to zero at a resevoir temperature allowing production of 130°C fluid at the surface.

In order to scale recovery factors downward from ideal reservoirs, one must specify whether the reservoirs are likely to be produced as steam or as a mixture of steam and water. In the steam situation, the geothermal recovery factor is a function of porosity, depth, and temperature. In the water-dominated situation, however, the models of Bodvarsson (1974) and Nathenson (1975*a*) both suggest that the geothermal recovery factor is essentially independent of temperature.

Reservoirs producing only steam. For a reservoir producing only steam, the formulations of Bodvarsson (1974, Fig. 12) and Nathenson (1975*a*, Fig. 4) suggest that recoverability decreases linearly with porosity towards a geothermal recovery factor of zero at zero porosity. In the ideal situations assumed by both authors, all of the pores are assumed to be interconnected (i.e. "effective" porosity = "total" porosity). But in real situations, effective porosity is only a fraction of total porosity. For example, the reservoir complex of Larderello has an average total porosity of approximately 12%, whereas the effective porosity is only 4–5%. For the overlying cover of shale etc. the discrepancy is even more striking; the total porosity is very high (20–30%), but the effective porosity quite low, perhaps 0·5–5%. Only the effective porosity has any bearing on recoverability (under conditions of "natural" or "unstimulated" production), and hence recoverability must be scaled to *effective* porosity, not total porosity.

The variation of recovery factor with the temperature of a steam-producing reservoir is equally complex. Nathenson (1975*a*) and Bodvarsson (1974) indicate that the geothermal recovery factor *increases* with decreasing temperature, and Fig. 4 of Nathenson (1975*a*) and our Fig. 7 show that this trend is reversed as curves for a given porosity are constrained by the final pressure limitation.

The geothermal recovery factor is a function of depth, independent of porosity and temperature, in that a fluid flowing to the earth's surface loses enthalpy by four processes: (1) loss to potential energy, (2) loss to kinetic energy, (3) loss by thermal conduction and (4) friction loss. Nathenson (1975*b*) gives measured wellhead conditions for well VC 10 in the Larderello region, as well as calculated conditions at 1088 m. At wellhead pressures of 15–20 bar, the loss in enthalpy from well bottom to the surface is ~5 cal/g, over a depth of approximately 1 km. Kinetic energy of VC 10 is ~0·03 cal/g and accordingly can be neglected. Inasmuch as loss to potential energy, loss by thermal conduction, and friction loss are likely to increase linearly with increasing depth, we can apply the VC 10 factor of 5 cal/g/km to a reservoir at any depth. Since the specific heat of water is about 1 cal/g°C, the reservoir temperature required to give fluid of a given enthalpy at the surface would increase linearly at approximately 5°C per km of depth. Accordingly, the loss in enthalpy as the fluid flows to the surface can be taken into account by subtracting from the reservoir temperature 5°C for each km of depth, before applying a recovery factor.

Hot-water reservoirs. We know of no specific studies that relate the recovery factor to porosity for a reservoir producing water or a water–steam mixture by means of intergranular flow. It seems reasonable, however, to assume that the recovery factor is a direct linear function of effective porosity, at least as a conservative approximation.

If we follow Bodvarsson (1974) and Nathenson (1975a) in assuming the geothermal recovery factor (*Rg*) to be independent of reservoir temperature (T_1) under an intergranular flow model, we can prepare a simple graph (Fig. 8) relating *Rg* to effective porosity (Φ_e). This curve is likely to be conservative, with the true relation falling more towards the upper left of Fig. 8. Ideally, one should calibrate this graph to a favorable reference reservoir. However, we have been unable to find the necessary data or theoretical models for such a calibration, and accordingly must resort to interpolation from the conclusion of Nathenson (1975*a*) that an ideally permeable hot-water reservoir (possibly with $\phi_t = \phi_e = 20\%$) would have a recovery factor of 50%. This situation, admittedly unsatisfactory, points up the immediate need of field and model studies of recoverability of heat from thermal energy from hot-water systems.

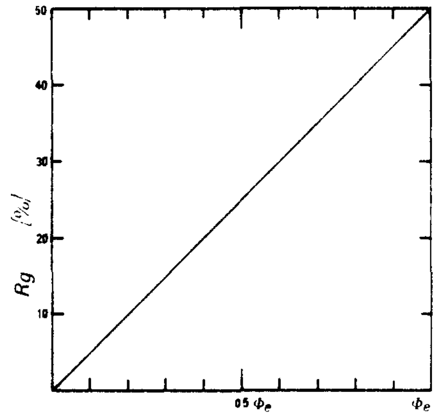

Fig. 8. Graph showing possible variation of geothermal recovery factor in % as a function of effective porosity for reservoirs producing by a mechanism of intergranular flow. *Rg* is taken to be 50% for an ideally permeable reservoir (Nathenson, 1975*a*) in which total porosity = effective porosity = ϕ_e. In the ideal situation ϕ_e perhaps can be assumed to be 20%.

Figure 8 does not take into account loss in enthalpy as the fluid flows to the earth's surface, but this can be incorporated easily by subtracting 5°C from the measured reservoir temperature for each kilometer of depth.

Consensus (?)

Bodvarsson (1974, p. 90) concludes his analysis of various models of production by stating that "... accurate computations of recovery factors are generally not feasible, and one will invariably have to resort to estimates based on little solid evidence". And indeed, this statement was borne out in the 1975 assessment of geothermal resources in the United States (White and Williams, 1975), where Nathenson and Muffler (1975) had to resort to subjective judgement in estimating recovery factors for both steam-producing and hot-water systems.

Admitting that the assignment of a recovery factor is subjective, there does, however, appear to be a general consensus that values around, or less than, 25% are appropriate for hot-water systems, and that even lower values are appropriate for steam-producing systems. For the latter, the specific case of the Larderello–Travale reservoir complex is illustrative. At an assumed average reservoir temperature of 215°C, one can calculate the following geothermal recovery factors by different models:

— $>13{\cdot}3\%$ from intergranular vaporization based on the model and data of Barelli *et al.* (1975*a*), assuming $\Phi_t = 15\%$;
— 19% by intergranular vaporization, assuming $\Phi_e = 4\%$;
— $11{\cdot}5\%$ by the vapor-dominated model assuming a total porosity of 15%, only 1/3 of the pores filled initially with water, and only 1/2 of the heat reservoir to be porous and permeable.

Thus, for production of steam from a favorable geothermal reservoir comparable to Larderello–Travale, the recovery factor seems to be between 11 and 19%; we favor 15% as a conservative first approximation.

At our present state of understanding of hydrothermal convection systems, it appears that recovery factors can be summarized as follows:

— *Hot-water systems:* the recovery factor (Rg) theoretically could be as much as 50% for an ideally permeable reservoir $\Phi_t = \Phi_e = \sim 20\%$, and as a conservative approximation it appears to decrease linearly with decreasing Φ_e to zero at $\Phi_e = 0$. In real field situations, Rg probably never exceeds 25%.
— *Steam-producing systems:* the recovery factor (Rg) may exceed 15% for a favorable reservoir such as Larderello–Travale. As a first approximation it appears to decrease linearly with decreasing Φ_e to zero at $\Phi_e = 0$ but it *increases* with decreasing temperature until constrained by the abandonment pressure limitation (Fig. 7).

Resources and reserves

It should be noted that the above discussion takes no explicit account of economics, and accordingly the values of recoverable thermal energy calculated are *not* resources as defined on p. 59 and in Table 1. They do, however, represent an upper limit for resources, but the actual calculation of resources must involve some further, subjective estimate of economics.

White and Williams (1975, p. 1) addressed this problem by defining the geothermal resource as that heat recoverable using current or near current technology, regardless of cost. They maintained that technology for extracting and using heat had been demonstrated in the United States only for the hydrothermal convection systems and the geopressured systems, thus ruling out any geothermal resources in regional conductive environments or in "hot dry rock". With respect to hydrothermal convection systems, the overall methodology of White and Williams had already eliminated geothermal energy (a) at depths greater than 3 km, (b) shallower than the reservoir top, (c) outside the reservoir area and (d) in reservoirs less than 90°C. Thus, the identified resource of hydrothermal convection systems was calculated only from the most favorable volumes of rock, and thus (when augmented by an estimate of undiscovered resources) represented a subjective, indirect estimate of future economic feasibility.

Cataldi *et al.* (1978) use a different approach for calculating the geothermal resources of central and southern Tuscany, in excluding those volumes at temperatures below 60°C from the resource calculations. Thus, the resource of these authors is the recoverable thermal energy from all volumes of $T > 60$°C, still referred to 15°C. The "resource for electrical generation" is restricted to that thermal energy recoverable from reservoirs of temperature greater than 130°C.

The calculation of reserves from the accessible resource base data is even more arbitrary. Nathenson and Muffler (1975) in estimating reserves of high-temperature (>150°C) hydrothermal convection systems resorted to a subjective judgement, based primarily on estimated reservoir temperature. They concluded (p. 115) that reservoirs at $T > 200$°C were most likely to contain reserves. No such split was even attempted for intermediate temperature (90–150°C) hydrothermal convection systems or for geopressured systems.

Cataldi *et al.* in the accompanying paper note that depth is the main factor bearing on the cost of extracting geothermal resources. Accordingly, they reduce the resource recovery factor (Rg) by a "depth factor" (F_D) that ranges from 1 at the land surface to 0 at 3 km. The resultant "reserve recovery factor" ($\bar{R}g = Rg \times F_D$) in effect penalizes the deep volumes that become less and less favorable as depth increases. However, it gives a systematic, albeit subjective, estimate of the geothermal reserves in a broad region. In a manner parallel to the resources, the reserves are restricted to those reservoirs at $T > 60°C$, and the "reserves for electrical production" to reservoirs at $T > 130°C$.

HEAT RESUPPLY TO GEOTHERMAL SYSTEMS

Introduction

Neither mineral deposits nor fossil fuels are significantly renewable in a human or industrial time scale. Although they clearly are replenishable over geologic time, for practical extraction and use they must be considered to be fixed quantities. On the other hand, there are indeed perpetual sources of energy that depend on the sun's energy (solar, wind, hydropower, biological) or on the relative motion of the earth and moon (tidal).

Geothermal energy consists of heat being transferred continuously from depth by conduction, by penetrative movement of magma, or by convection of water. Accordingly, geothermal energy is renewable when considered over geologic time, but it is moot whether renewal over human or industrial times (< 100 yr) is significant in the estimation of geothermal resources.

As defined on p. 56 and in Table 1, the accessible resource base refers to geothermal energy stored in rock and water at an instant in time, and takes no account of resupply. Any geothermal reservoir, however, is subject to continuous albeit areally variable flux of heat from deeper levels, and the movement of water may concentrate this flux from an area significantly greater than the reservoir itself. Furthermore, the actual exploitation of a reservoir could conceivably accelerate the flow of fluid (and thus heat) from neighboring volumes of hot rock. Accordingly, we must attempt to evaluate whether resupply of heat to the reservoir is likely to augment significantly the geothermal resource as calculated from storage of geothermal energy alone.

In the discussion that follows, the word "resupply" refers only to heat (thermal energy), whereas the word "recharge" refers only to water influx, which may be either hot or cold. Resupply (of thermal energy), of course, can occur by means of either thermal conduction or recharge of hot water.

Resupply models

We can address the question of renewability of heat using some simple analytical models, chosen to represent three possible mechanisms by which heat could be resupplied to a hydrothermal reservoir: (1) transfer of regional heat flow to the reservoir by horizontal flow of water, (2) conduction of heat from a subjacent intrusion and (3) concentration of heat by flow of water from rock surrounding the reservoir.

In developing these models, we assume a permeable geothermal reservoir of area A_1, thickness Z_1, uniform volumetric specific heat c_{v_1}, and average reservoir temperature T_1. Accordingly, the geothermal energy (H_1) in the reservoir is

$$H_1 = (c_{v_1})\,(T_1 - T_o)\,(A_1)\,(Z_1) \tag{10}$$

where T_o is the reference temperature. This geothermal energy is then multiplied by the geothermal recovery factor (Rg) to obtain the recoverable thermal energy (H_R). Thus,

$$H_R = (Rg)\,(H_1) = (Rg)\,(c_{v_1})\,(T_1 - T_o)\,(A_1)\,(Z_1) \tag{11}$$

In the most of the calculations to follow we assume $c_{v_1} = 0{\cdot}6$ cal/cm^3°C, $T_1 = 215°C$, $T_o = 15°C$, and $Rg = 15\%$, thus giving (in cgs units)

$$H_R = (0{\cdot}15)\,(0{\cdot}6)\,(215 - 15)\,(A_1)\,(Z_1) = 18\ A_1 Z_1 \tag{11a}$$

Resupply from regional heat flow

Consider the conductive heat flow q (in cal/cm^{2}s) to an area A_2 beneath the reservoir, with $A_2 \geqslant A_1$. Assume that all this heat conducted from deeper layers in the earth is transferred to the reservoir by water flowing along surface A_2 (see Fig. 9). The heat transferred in time t (in seconds) is

$$H_2 = (q)\ (A_2)\ (t) \tag{12}$$

In order to compare this resupply with the thermal energy recoverable from a geothermal reservoir having the characteristics A_1, Z^1, c_{v1} and T_1 described above, we take the ratio of equation (12) to equation (11a)

$$\frac{H_2}{H_R} = \frac{(q)\ (A_2)\ (t)}{18\ (A_1)\ (Z_1)} \tag{13}$$

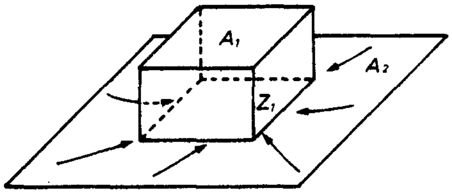

Fig. 9. Schematic diagram illustrating the concentration of conductive heat flow from area A_2 to the reservoir of area A_1 and thickness Z_1, by means of water flowing horizontally along plane A_2.

Now let us assume that the heat resupply (H_2) is of practical significance only when it is greater than 10% of the recoverable thermal energy calculated by equation (11a). Under this condition, we can depict the relations between Z_1, t, A_2 and A_1 by setting $H_2/H_R = 0{\cdot}1$ and rearranging equation (13) to get

$$\frac{A_2}{A_1} = \frac{1{\cdot}8\ Z_1}{qt} \tag{14}$$

For the limiting condition $H_2/H_R = 0{\cdot}1$, A_2/A_1 as a function of q and t is plotted on Fig. 10 for two values of Z_1 (1 km on the right, and 0·5 km on the left). We see, for example, that for a time of 50 yr, a regional heat flow of 5×10^{-6} cal/cm^{2}s, and a reservoir thickness of 1 km, A_2/A_1 must be at least 23 in order for H_2 to be 10% of H_R. Such a ratio is perhaps reasonable for a reservoir of small area (e.g. 1 km^2). But if the reservoir has a large area (e.g. 200 km^2), the size of A_2 (4600 km^2) required by the model seems excessive.

Resupply under this model becomes more significant the longer the assumed time and the thinner the assumed reservoir. For example, at a time of 100 yr, a regional heat flow of 5, and a reservoir thickness of 0·5 km, A_2/A_1 must be only 5 in order for H_2 to be 10% of H_R. This ratio does not seem excessive, even for large reservoirs.

In summary, this model suggests that resupply to small reservoirs from anomalously high regional heat flow over a period of 100 yr can be significant. On the other hand, resupply to large reservoirs for short periods in regions of near-normal heat flow is unlikely to augment significantly the recoverable thermal energy calculated from storage alone.

One can independently assess the importance of resupply from regional heat flow using data from the Larderello–Travale region. Barelli *et al.* (1975*a*, Table 5) estimate the total thermal energy recoverable from the main reservoir in the productive area of Larderello–Travale to be $557{\cdot}2 \times 10^{15}$ cal $+ 252 \times 10^{15}$ cal $= 809{\cdot}2 \times 10^{15}$ cal. On the other hand, the conductive heat

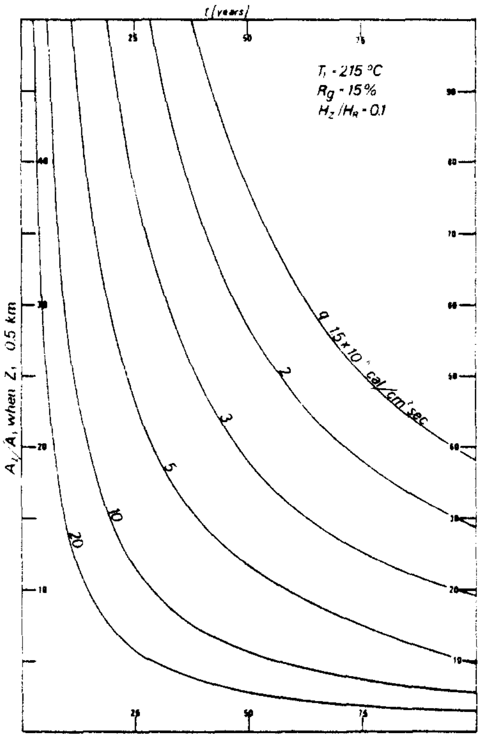

Fig. 10. Graph showing the ratio A_2/A_1 (see Fig. 9) as a function of time (t) and conductive heat flow (q) to area A_2, for two values of reservoir thickness (Z_1). The graph represents the relations when the heat resupplied to the reservoir is 10% of the thermal energy recoverable from storage alone.

flow measured throughout the region (Calamai *et al.*, 1977) allows us to calculate that $42{\cdot}3 \times 10^{15}$ calories are supplied by conduction over 300 km^2 in 100 yr. This potential resupply, were it somehow concentrated and introduced to the reservoir, would thus be only 5% of the thermal energy recoverable from the reservoir.

Resupply from a subjacent intrusion

Consider that at distance Z_{600} beneath the reservoir there is an igneous intrusion at 600°C having area A_i (see Fig. 11). Assume heat is transported by conduction alone to level A_2 and then is transported to the base of the reservoir (having an area A_1) by water flowing horizontally.

Neglecting edge effects, the heat conducted upwards from the intrusion in time t is

$$H_i = (q)\,(A_i)\,(t) \tag{15}$$

where q is heat flow. Since heat flow is the product of thermal gradient (G) and thermal conductivity (K),

$$H_i = (G)\,(K)\,(A_i)\,(t) \tag{15a}$$

The mean thermal gradient between the top of the intrusion and the base of the reservoir is

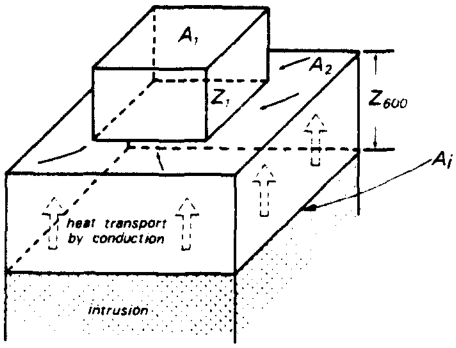

Fig. 11. Schematic diagram illustrating the relationship of a geothermal reservoir (of area A_1 and thickness Z_1) to a 600°C intrusion of area A_i located at a distance Z_{600} beneath the reservoir. Conductive heat flow from the intrusion is concentrated from area A_2 ($= A_i$) to the reservoir by water flowing horizontally.

$$G = \frac{600°\text{C} - T_1}{Z_{600}} \tag{16}$$

Accordingly,

$$H_i = \frac{(600 - T_1)\,(K)\,(A_i)\,(t)}{Z_{600}}$$

since

$$H_R = (Rg)\,(c_{v1})\,(T_1 - T_o)\,(A_1)\,(Z_1) \tag{11}$$

$$\frac{H_i}{H_R} = \frac{(600 - T_1)(K)A_i)(t)}{(Z_{600})(Rg)(c_{v1})(T_1 - T_o)(A_1)(Z_1)} \tag{17}$$

As in the preceding model, we assume that heat supply is of practical significance when it is greater than 10% of H_R. Setting $H_i/H_R = 0{\cdot}1$, assuming $c_{v1} = 0{\cdot}6$ cal/cm^3°C and K $= 7 \times 10^{-3}$ cal/cm °C s (Diment *et al.*, 1975), and rearranging equation (17), we obtain

$$Z_{600} = \frac{(600 - T_1)\,(7 \times 10^{-3})\,(t)}{(0{\cdot}1)\,(Rg)\,(0{\cdot}6)\,(T_1 - T_o)\,(Z_1)} \cdot \frac{A_i}{A_1} = 0{\cdot}117\,\frac{(600 - T_1)\,(t)}{(Rg)\,(T_1 - T_o)\,(Z_1)} \cdot \frac{A_i}{A_1} \tag{18}$$

For the standard reservoir conditions of $T_1 = 215$°C, $T_o = 15$°C and $Rg = 0{\cdot}15$

$$Z_{600} = \frac{(0{\cdot}117)\,(600 - 215)\,(t)}{(0{\cdot}15)\,(215 - 15)\,(Z_1)} \cdot \frac{A_i}{A_1} = 1{\cdot}5\,\frac{t}{Z_1} \cdot \frac{A_i}{A_1} \tag{18a}$$

For the limiting condition $H_i/H_R = 0{\cdot}1$, Z_{600} is plotted on Fig. 12 as a function of t and A_i/A_1, for two values of reservoir thickness (Z_1). For $Z_1 = 1$ km, $t = 100$ yr, and $A_i/A_1 = 1$, for example, we see that $Z_{600} = 475$ m. In other words, a 600°C igneous intrusion having an area equal to that of an overlying reservoir will have to be closer than 475 m to the reservoir before resupply by conduction could significantly augment thermal energy recoverable from storage. An intrusion of area $A_i = 5\,A_1$, however, could be as far as 2·4 km from a reservoir of 1 km thickness and still resupply significant heat in 100 yr. This distance is geologically reasonable, and accordingly in some cases resupply of heat from a large subjacent intrusion could significantly augment recoverable thermal energy calculated from storage alone.

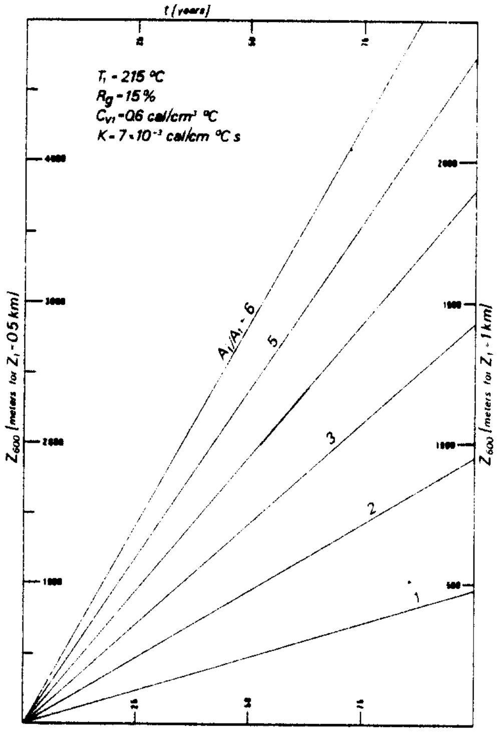

Fig. 12. Graph showing the distance (Z_{600}) between a reservoir of area A_1 and a subjacent intrusion of area A_i as a function of time (t) and the ratio A_i/A_1, for two values of the reservoir thickness Z_1. The graph represents the relations when the heat resupplied to the reservoir is 10% of the thermal energy recoverable from storage alone.

The possible influence of resupply by conduction from an underlying intrusion at The Geysers, California can be evaluated using published data. Renner *et al.* (1975, pp. 8–9) assign The Geysers reservoir the following parameters: area = 70 km^2; depth to reservoir top = 1 km; depth to reservoir bottom = 3 km; temperature = 240°C. On the other hand, Isherwood (1976) calculates that the large gravity anomaly centered northeast of The Geysers could be caused by a silicic intrusion of radius 6·9 km and with its top more than 6·55 km below the earth's surface (i.e. > 3·55 km below the bottom of the reservoir). Assuming t = 100 yr = 3·16 × 10^9 s and RG = 0·15, from equation (18) we obtain

$$Z_{600} = \frac{(0{\cdot}117)\,(600-240)\,(3{\cdot}16\times10^9)}{(0{\cdot}15)\,(240-15)\,(2\times10^5)}\cdot\frac{\pi(6{\cdot}9\ \text{km})^2}{70\ \text{km}^2} = 418\ \text{m} \tag{19}$$

We thus see that the intrusion deduced by Isherwood to be > 3·55 km below the reservoir bottom is far too deep to significantly augment the recoverable thermal energy calculated from geothermal energy in the reservoir at The Geysers.

Concentration of heat by fluid transport from surrounding rocks

We can envisage a mechanism by which a porous and permeable reservoir is resupplied with heat by means of fluid transport from surrounding rocks of lower porosity and permeability (Fig. 13). The significance of this process can be evaluated by assigning a recovery factor R_2 to the surrounding rocks, with R_2 being substantially less than the recovery factor (Rg) of the reservoir. For a given resupply, the lower the value of R_2 the higher must be the volume (V_2) of surrounding rocks from which heat is concentrated.

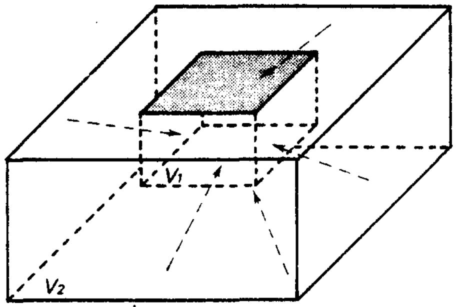

Fig. 13. Schematic diagram illustrating the concentration of heat from a volume (V_2) of low permeability rock surrounding a hydrothermal reservoir of volume V_1.

Again assuming standard reservoir conditions ($T_1 = 215°C$, $c_{v_1} = 0{\cdot}6$ cal/cm³ °C, and $Rg = 15\%$),

$$H_R = 18\,(A_1)\,(Z_1) = 18\ V_1 \tag{11a}$$

Heat supplied from the surrounding rocks is

$$H_s = (R_2)\,(H_2) = (R_2)\,(V_2)\,(c_{v2})\,(T_2 - T_o) \tag{20}$$

equation (18) we obtain

Assume $c_{v_2} = 0{\cdot}6$ cal/cm³°C and $T_2 = 215°C$,

$$H_s = (V_2)(0{\cdot}6)(215-15)(R_2) \tag{20a}$$

and

$$\frac{H_s}{H_R} = \frac{120\ (V_2)\,(R_2)}{18\ (V_1)} = 6{\cdot}7\ R_2\ \frac{V_2}{V_1} \tag{21}$$

As in the preceding sections, we assume that heat resupply is of practical significance when it is greater than 10% of H_R. Setting $H_s/H_R = 0{\cdot}1$ and rearranging, equation (21) becomes

$$\frac{V_2}{V_1} = \frac{0{\cdot}1}{6{\cdot}7\ R_2} = \frac{0{\cdot}015}{R_2} \tag{21a}$$

This function is plotted on Fig. 14.

A reasonable value for the recovery factor (R_2) of the rocks surrounding the reservoir is perhaps 1·5%, that is, one-tenth of Rg. Thus, for the limiting condition $H_s/H_R = 0{\cdot}1$, we see from Fig. 14 that V_2/V_1 is only 1·0, a value that by no means seems geologically unreasonable. Even reducing R_2 by another order of magnitude, to 0·15%, the ratio V_2/V_1 need be only 10 for H_s to be $0{\cdot}1\ H_R$ and thus be considered significant. Accordingly, this model suggests that resupply from hot, low permeability rocks surrounding a reservoir can indeed be significant at reasonable values of R_2.

Reservoirs producing only steam vs hot-water reservoirs

Nathenson (1975*a*, pp 1–4) addressed the question of heat resupply by comparing natural heat discharge at the earth's surface above various types of geothermal reservoirs with expected production rates. For reservoirs such as Larderello or The Geysers that produce only vapor, he concludes that natural heat discharge (and presumably natural resupply to the reservoir) is much

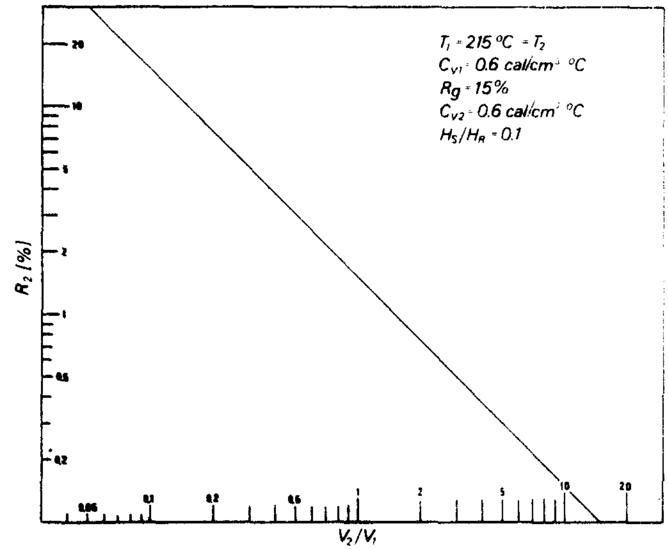

Fig. 14. Graph showing how the volume (V_2) of low-permeability rock surrounding a reservoir of volume V_1 varies with the recovery factor of the low-permeability rock, assuming heat concentrated from V_2 to V_1 as illustrated in Fig. 13. The graph represents the relations when the heat resupplied to the reservoir is 10% of the thermal energy recoverable from storage alone.

smaller than reasonable rates of exploitation, and that accordingly heat resupply may be neglected in resource calculations. A similar conclusion was reached by Ramey (1970) for The Geysers, based on reservoir engineering considerations.

Nathenson (1975*a*) also infers little heat resupply for hot-water systems such as East Mesa (Imperial Valley, California) that have little natural discharge and appear to be isolated convection cells. But for hot-water systems of high natural discharge, such as Wairakei (New Zealand), he concludes that heat resupply is indeed significant.

Repetitive gravity and levelling surveys at Wairakei have allowed Hunt (1977) to calculate the changes in subsurface fluid mass as a function of time. Fluid recharge (expressed as a percentage of the mass withdrawal in a given year) decreased from 50% in 1958 to less than 10% in 1961 and 1962, but subsequently rose to 90% from 1966 to 1974 (Hunt, 1977, Fig. 7). These figures indicate clearly that *fluid* recharge is extremely important in a highly permeable hot-water system such as Wairakei, but unfortunately do not allow any conclusions with respect to *heat* resupply, since Hunt's curves for reservoir temperature (his Fig. 2, taken from data of Bolton, 1970) extend only up to 1968. Pertinent data to evaluate the relative importance of hot and cold recharge at Wairakei almost certainly exist, but to our knowledge have not yet been published.

Isherwood (1977) has carried out similar repetitive gravity and levelling surveys at The Geysers, California. Since most modern wells at The Geysers are cased to at least 1000 m, mass loss must be concentrated at greater depths. On the other hand, if the observed gravity decrease of up to 120 μgal were caused by removal of mass from depths greater than 2000 m, required fluid loss would greatly exceed the quantity of fluid actually produced. Thus restricting mass loss (by intergranular vaporization) to depths of 1000–2000 m, Isherwood uses mass balance equations to conclude that fluid recharge to the reservoir is negligible. This conclusion was predicted by the vapor-dominated model of White *et al.* (1971), and is compatible with the conclusions of Nathenson (1975*a*, p. 2).

Conclusions

The simple models discussed above suggest that resupply of heat to hot-water systems of high natural discharge should not be neglected (i.e. that resupply heat can be greater than 10% of the recoverable thermal energy calculated from storage alone). Not only can a large, young intrusion supply significant heat to a nearby, overlying reservoir in 100 yr, but under reasonable parameters, a reservoir could be significantly resupplied with heat either by extraction from surrounding rock or even by water flowing horizontally to the reservoir in a region of elevated heat flow. In all cases, resupply appears potentially more significant for small reservoirs than for large ones. For the latter, the areas (A_2) or volumes (V_2) from which the heat must be derived are so large that in practice they exceed the regional hydrologic limits.

For hot-water systems of low natural fluid discharge, the importance of fluid recharge and resultant heat resupply will depend on the extent to which such recharge is enhanced by the extraction process itself. On the other hand, it appears from data of Isherwood (1977) that fluid recharge to a steam-producing reservoir is low, and that accordingly any resupply of heat is limited to that which can be conducted to the reservoir without appealing to concentration of heat by flowing water. Accordingly, resupply from regional heat flow is thus limited to $A_2/A_1 = 1$ on Fig. 1C, and is small enough to be neglected. Similarly, resupply from a subjacent intrusion will be significant for a reservoir 1 km thick only if the intrusion (at 600°C) is less than 475 m from the reservoir (curve $A_i/A_1 = 1$ of Fig. 12).

It is clear that the question of heat resupply to hydrothermal convection systems deserves far more careful and systematic attention than it has received to date. The repetitive gravity and levelling studies are powerful tools for evaluating fluid recharge and thus constraining the amount of heat that can be supplied by flowing water (e.g. Isherwood, 1977). In hot-water systems where fluid recharge seems to be important, systematic data on reservoir temperature, particularly in peripheral wells, should resolve the question of whether the fluid recharge is hot or cold.

CONCLUSIONS AND RECOMMENDATIONS

This report does not pretend to have exhausted the subject of geothermal resource assessment methodology. However, we submit that our review of the major approaches used to date can serve as a basis for further discussion and refinement. In addition, we hope that our identification of the more important problems and limitations will stimulate new investigations by earth scientists, engineers, and resource economists.

We see an urgent need to reach an international consensus on geothermal terminology, and accordingly we recommend that an appropriate organization (the International Energy Agency?) take the lead in convening a multinational panel to develop this consensus. We submit that the geothermal terminology proposed by us could serve as a starting point in negotiating a multinational agreement.

Our review of geothermal resource assessment methodology leads us to the conclusion that the volume method is the most useful means of estimating geothermal resources and making comparisons among different areas and geological situations. We recommend that it be accepted as a common basis of comparison, with other methods providing supplementary control in particular geological situations or for unusual purposes.

It is clear to us that intensive research should be directed toward the questions of recoverability of hydrothermal reservoirs under conditions of natural permeability. Particular attention should be paid to the recoverability of hot-water reservoirs, because these are much more common than steam-producing reservoirs and because their recovery factors are little more than guesses. This research should include theoretical analysis, laboratory experimentation and field verification through case histories. All aspects of the proposed research should make a careful distinction between total porosity (ϕ_t) and effective porosity (ϕ_e).

Resources that might be producible from rocks of low or very low permeability cannot be assessed until two conditions are met: (1) evaluation of the extent to which ϕ_e can be increased by fracturing and associated phenomena (e.g. thermal cracking) in real field situations and (2) demonstration of a technology for extracing heat by closed hydraulic loops.

It appears that hydrothermal reservoirs can be partly resupplied with heat under some geologically reasonable circumstances. However, the question of heat resupply needs further study, particularly by field experiments using repetitive gravity, levelling, and subsurface temperature surveys.

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APPENDIX I

In certain circumstances it may be possible and appropriate to further subdivide the *identified* category of Figs. 2 and 3. For example, if one follows the general terminology of U.S. Geol. Survey (1976), one could define the following terms (Fig. A–1):

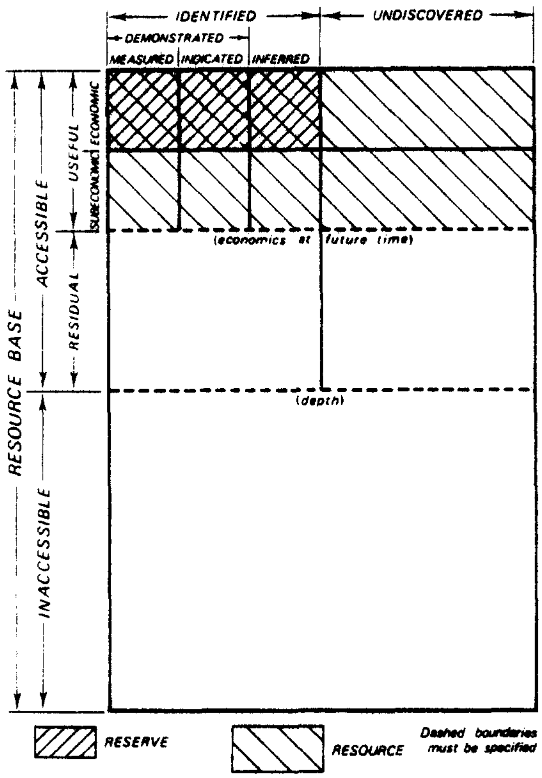

Fig. A–1. McKelvey diagram for geothermal energy showing possible subdivision of *identified* category into *measured*, *indicated*, *demonstrated* and *inferred* (cf. *U.S. Geol. Survey*, 1976).

measured—referring to that part of the accessible resource base, resource, or reserve whose size can be computed from drillhole data and reservoir engineering measurements
indicated—referring to that part of the accessible resource base, resource, or reserve whose size can be estimated by a combination of drilling data and extrapolation using geochemical, geophysical, or geological data
demonstrated = measured + indicated
inferred—referring to that part of the identified accessible resource base, resource, or reserve whose size can be inferred from geochemical, geophysical, or geological evidence but for which there is little if any corroborating drillhole data.

Alternatively, it may be useful to divide the *identified* category into *under development* and *under exploration* (Fig. A–2). The former refers to geothermal energy in areas where production wells and utilization facilities either exist or are under construction. The latter refers to geothermal energy identified only by exploratory drilling supplemented by geophysics, chemical geothermometers, etc.

Similarly, if necessary, the *undiscovered* category can be divided into *in known regions* and *in new regions* (Fig. A–2). The former refers to regions where useful geothermal energy is known to exist. The latter refers to regions where useful geothermal energy is likely to exist but has not yet been positively identified. Although these categories correspond respectively to "hypothetical" and "speculative" of U.S. Geol. Survey (1976), we suggest these words be avoided as being insufficiently descriptive of the categories and thus prone to confusion and misunderstanding.

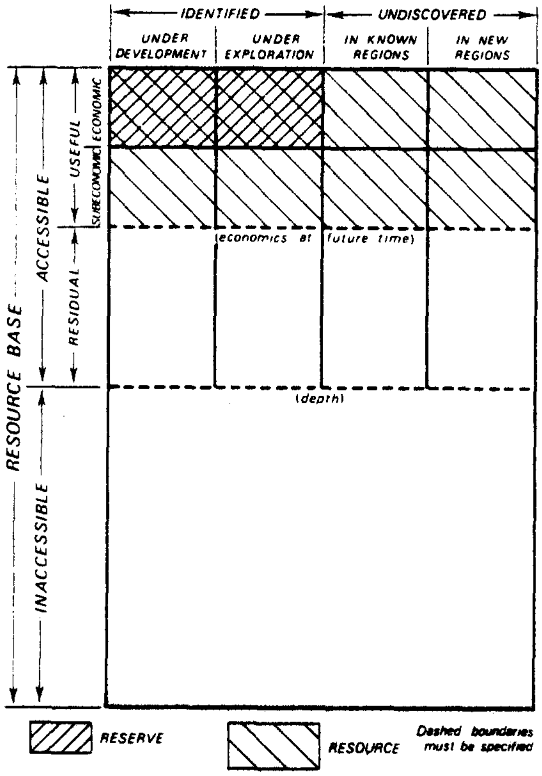

Fig. A-2 McKelvey diagram for geothermal energy showing possible subdivision of *identified* category into *under development* and *under exploration*, and *undiscovered* category into *in known regions* and *in new regions*.