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CLASSIFICATION OF GEOTHERMAL RESOURCES - AN ENGINEERING APPROACH

K. C. Lee

Geothermal Institute
The University of Auckland, Private Bag 92019
Auckland, New Zealand

ABSTRACT

Geothermal resources have been classified into low, intermediate and high enthalpy resources by their reservoir temperatures. The temperature ranges used are arbitrary and there is not a general agreement.

Geothermal resources should be classified by two independent thermodynamic properties of their fluids at the wellhead. They should reflect the fluids availability to do work. By setting the triple point of water as the sink condition, and normalising the fluids specific exergies by the maximum specific exergy of dry saturated steam, geothermal resources can be classified into high, medium, and low category resources by their specific exergy indices (SEI) of greater than 0.5, between 0.05 and 0.5, and less than 0.05. These correspond to geothermal fluids having exergies greater than that of dry saturated steam at 1 bar absolute, between saturated water and dry saturated steam at 1 bar absolute, and less than saturated water at 1 bar absolute respectively.

INTRODUCTION

A geothermal energy resource has been termed in many ways: earth power, earth heat, geothermal reserve, geothermal reservoir, geothermal field, geothermal area, geothermal aquifer, geothermal system, geothermal source, hydrothermal systems, etc (Armstead 1983, Edward et al 1982, Grant et al 1982, Hochstein 1990, Kenward 1976, Kestin et al 1980).

Geothermal resources have been classified into low, intermediate and high enthalpy resources by their reservoir temperatures (see Table 1). The temperature ranges used are arbitrary and there is not a general agreement. Temperature is used as the classification parameter because it is considered as one of the simplest parameters. However, the temperature used is the average reservoir temperature measured in exploration wells or estimated by geothermometers or other means (Hochstein, 1990).

	(a)	(b)	(c)	(d)
Low enthalpy	<90 °C	<125 °C	<100 °C	≤150 °C
Intermediate	90-150	125-225	100-200	---
High enthalpy	>150	>225	>200	>150

Source: (a) Muffler and Cataldi, 1978.
(b) Hochstein, 1990.
(c) Benderitter and Cormy, 1990.
(d) Haenel, Rybach and Stegena, 1988.

Table 1: Classification of geothermal resources by temperature. (Dickson and Fanelli, 1990).

Armstead (1983) classified the earth's surface into non-thermal and thermal areas. Thermal areas are those with temperature gradients greater than 40 °C/km depth. Armstead made a distinction between thermal areas and thermal fields. Thermal fields are thermal areas with sub-surface permeability which allows the containment of a fluid that can convey deep-seated heat to the surface. Geothermal fields are classified into semithermal fields producing hot water up to 100 °C at the surface, hyperthermal wet fields producing hot water and steam at the surface, and hyperthermal dry fields producing dry saturated or superheated steam at the surface.

Temperature is acceptable as a classification parameter only for its simplicity and being a measured quantity. However, temperature alone is not a good classification parameter. For example, two geothermal resources both at 200 °C but one is saturated water and one saturated steam. Both are classified as intermediate enthalpy resources by Hochstein whereas high enthalpy by the others, but the specific enthalpy of saturated steam is 3 times that of saturated water! Indeed, the steam is 5 times 'better' than the water on their ability to do work! That is, the steam can produce 5 times more power than the water per unit mass.

It is also inappropriate to define or classify the resources by enthalpy, h, alone. For example, one fluid at p=40 bar abs (T=250 °C) and h=1087 kJ/kg, and another at p=5 bar abs (T=152 °C) and h=2749 kJ/kg. The lower enthalpy one is classified as a high enthalpy resource by its temperature and the higher one as an intermediate resource! Indeed, it is difficult to tell which is the 'better' resource of the two from the given p, T, and h information alone. However, it can be easily shown later that the lower temperature and higher enthalpy one is nearly 3 times 'better' than the higher temperature and lower enthalpy one. Neither is a higher enthalpy resource necessary always better than a lower one. For example, a resource of T=180 °C and h=2500 kJ/kg is 'better' than one of T=120 °C and h=2700 kJ/kg.

So, it can be seen that classification of geothermal resources by their temperatures or enthalpies alone is inconsistent and confusing. The purpose of this paper is, therefore, to find a better way to classify geothermal resources.

POSSIBLE CLASSIFICATION PARAMETERS

It is apparent that one thermodynamic property alone cannot define or classify geothermal resources completely. At least two independent thermodynamic properties are needed to define the state of the fluids of a geothermal resource, assuming the fluids are inherently steam and/or water, and that dissolved chemicals and gases present do not significantly affect the properties of the dominant fluid.

If we use the two commonly measured parameters of p and T, for example, one resource at 30 bar absolute and 300 °C, and another at 35 bar absolute at 270 °C; it is difficult to tell which is the 'better' resource. Indeed, the same problem will exist for any two properties which cannot be reduced to a single parameter or index. So, we really need a parameter that can state, unambiguously, the thermodynamic state of the geothermal fluids.

Lets first look at how some other energy resources are classified. Fossil fuels such as hydrocarbons and coals can be classified by their calorific values (CVs) or their chemical structures (Goodger, 1975). Similarly, geothermal resources can be classified by their energy contents or their reservoir structures. The energy contents can be related to the thermodynamic properties of the geothermal fluids and/or reservoir rocks, such as, pressure, temperature, enthalpy, entropy, specific heat, etc. The structure can be related to transport or physical properties, such as, viscosity, conductivity, permeability, porosity, volume, density, etc. However, these properties are difficult to measure because they are underground. Moreover, the geothermal energy, like fossil fuels, is of little use if left underground. Fluids (natural or artificial for hot-dry rock) must be present to bring the heat to aboveground level to be useful. So, it is more logical to classify geothermal resources based on the properties of the fluids at the surface.

Since fossil fuels can be classified by their CVs, the maximum heat contents, geothermal energy can be classified by the maximum work available. Geothermal energy is already in the form of heat, and from thermodynamic point of view, work is more useful than heat because not all heat can be converted to work (2nd Law of thermodynamics). In thermodynamic term, the maximum work available is the availability or exergy of the fluid media (natural or artificial). So, we should classify a geothermal resource by its ability to do work, i.e. its exergy which is a function of enthalpy and entropy. Exergy is a better criterion than energy because water at 20 °C contains a lot of energy but it has little ability to do work (ignoring kinetic and potential energy).

METHODOLOGY OF CLASSIFICATION BY EXERGY

We need to decide on the criteria for the classification of geothermal resources by their exergies:

1. Where is the fluid definition point?
2. What should the sink condition be?
3. What values of exergy are considered high or low?
4. Do we consider the total quantity of the resource or the quality of the resource per unit mass?

As discussed earlier, if a geothermal fluid is to do any useful work, it would have to do it at the surface. So it is appropriate to have the fluid definition point at the wellhead because this is the first point where the geothermal fluid can do useful work.

If we use the wellhead condition, should we use the static fluid condition with the master valve totally shut or dynamic flowing condition with the master valve fully open? Static fluid cannot do work and moreover, some wells require stimulation to discharge and would indicate zero condition if the valves are fully shut. Typical well output characteristics shows that mass flow rate is maximum with wellhead pressure (WHP) minimum when the master valve is fully open, and mass flow rate minimum with WHP maximum when master valve nearly fully shut (Figure 1). The enthalpy varies little with WHP, especially for 'dry' fields and two-phase wells with single dominant feed zone. This would normally give a maximum power output somewhere in between these two extremes. For most high 'category' fields,

the optimum WHP is between the range of 5 to 10 bar gauge. So fluid at what WHP should be used? As will be clarified later, the proposed method of classification is robust and insensitive to the pressure range of a geothermal resource with relatively constant enthalpy. So, any WHP condition can be used.

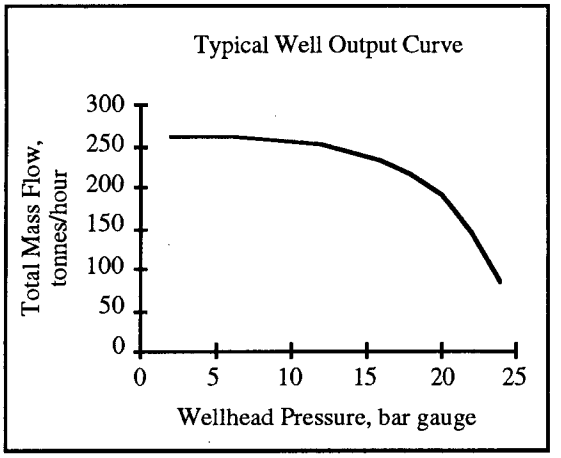

Figure 1: Typical well output curve.

Ambient temperature condition is commonly used as the sink condition for exergy calculation (Kestin et al 1980, Wahl 1976). However, it will also be shown later that the proposed method is also robust and insensitive to the sink condition.

The dividing lines between high and low 'category' resources are, of course, arbitrary. However, based on Lindal diagram (Lindal, 1973), it is logical and common to categorise resources that can be used for the generation of electricity using conventional steam turbines as high category, and that those suitable only for direct uses for heating purposes as low. There is no good reason to depart from this common understanding. Armstead (1983) categorised 140 °C as the lowest temperature suitable for conventional power production in Lindal diagram. However, 100 °C LP (low pressure) steam at Wairakei has been used for the direct generation of electricity. The source of the LP steam could be from 100 °C dry steam LP wells or flashed from 140 °C (3.6 bar abs) IP (intermediate pressure) saturated water. So, do we say 100 °C steam or 140 °C water as suitable for convention power production? The answer has to be both but that does not mean 140 °C water should be classified as a high category geothermal resource. If it was, 100 °C steam would be a 'very' high category resource as its exergy is 5 times that of 140 °C water but it is not classified as a high enthalpy resource by the classification approaches based on temperature. Therefore, 140 °C water cannot be classified as a high category resource. Thence, 100 °C saturated steam is more appropriate to be defined as the threshold for a high category resource based on its exergy. It then follows that 100 °C saturated water would be the appropriate threshold for a low category resource.

When we compare two geothermal resources to see which is the 'better' resource, we can compare them quantitatively by their total capacity, or qualitatively by their ability to perform a 'task'. As with using temperature or enthalpy, total mass flow does not affect qualitatively a resource's exergy to perform. Hence, specific exergy of the fluid should be used instead of the total fluid exergy to 'quantify' a geothermal resource ability to do work. That is, the ability of a geothermal resource to do work is determined by the specific exergy of fluid irrespective of the total amount of fluid in the reservoir. After all, the total capacity of a geothermal resource is difficult to predict with reasonable accuracy.

SPECIFIC FLUID EXERGY AND SPECIFIC EXERGY INDEX (SEI)

To start with, specific exergies of saturated water and steam are calculated because the area of most interest is the two-phase zone. The equation for specific exergy, e, is

$$e = h - h_o - T_o(s - s_o)$$

where h is specific enthalpy, kJ/kg,
s is specific entropy, kJ/kgK,
T is absolute temperature, K,
and subscript o denotes sink condition.

The specific exergies of saturated water and steam for sink conditions of triple point (0.01 °C), 10 °C and 20 °C are shown in Table 2. The exergies range from (-)180 kJ/kg for saturated steam at triple point with 20 °C sink to 1192 kJ/kg for saturated steam at 90 bar absolute with triple point sink. From Table 2, it is clear that the specific exergies values are quite sensitive to sink conditions which vary with locations as well as seasons and altitudes. Specific exergy values alone do not appear to be a good parameter for the classification of geothermal resources although we could draw arbitrary lines, at say, exergies over 500 kJ/kg for high exergy resources and exergies below 100 kJ/kg for low exergy resources.

From Table 2, the maximum exergy of saturated steam occurs between 90 and 100 bar abs. Although higher exergy is possible for superheated steam it would still likely to be less than that of 90 bar abs saturated steam. Hence, the exergies values in Table 2 can be 'normalised' by the maximum exergy of the corresponding sink condition. The 'normalised' exergy values, henceforth known as SEI for 'specific

exergy index', can still exceed 1.0 but unlikely. As can be seen from Table 2, the SEI values are quite robust as they are almost independent of the sink conditions. For example, the SEI values of saturated water at 10 bar abs range from 0.13 to 0.15 for 20 °C to triple point sink conditions respectively, and the range for saturated steam is 0.79 to 0.82. Therefore, the choice of sink condition between the ambient temperature and the triple point becomes a less contentious issue and more of a personal preference. However, it is more convenient to use the triple point (0.01 °C) because enthalpy and entropy are zero at this condition in tables of thermodynamic properties (Reynolds 1979, Rogers and Mayhew 1995). If the triple point is the sink condition, the specific exergy equation simplifies to

$$e = h - T_0 s.$$

We are now left with the hard decision of drawing lines between high and low performance resources.

As can be seen from Table 2, the SEI range for saturated water is 0 to 0.74 from the triple point to the maximum at the critical point of 221.2 bar abs. The SEI range for saturated steam is 0 to 1.0 from the triple point to the critical pressure with the maximum SEI at 90 bar abs (303.3 °C).

It is possible to have bottomhole pressure and temperature of 150 bar abs and 340 °C. However, shut-in WHP and temperature seldom exceed 100 bar abs and 300 °C. Therefore, it is possible to have SEI of close to 1.0 at the wellhead. So where do we draw the lower limit of SEI for the high performance wells? If we accept the lowest exergy of steam which can be used for the direct generation of electricity to be at atmospheric pressure as in Wairakei, then the lower limit for high performance well or resource is of SEI=0.5 approximately. Therefore, high exergy resources can be defined as having SEI values not less than 0.5 (50% of the maximum specific exergy of dry saturated steam). This appears to be reasonable as it is a half of the maximum SEI, and high enthalpy two-phase wells can be flashed to produce steam for the direct generation of electricity.

Now what is the upper limit of SEI for low performance wells? If we take it to be the upper limit at which it is good only for direct uses, then it is

	Pressure p, ba	Temp. ts, C	Entropy s, J/gK	Enthalpy h, J/g	Exergy e, J/g	Triple pt SEI	Exergy e, J/g	10 C SEI	Exergy e, J/g	20 C SEI
Triple point	0.00611	0.01	0	0	0	0.00	1	0.001	3	0.003
	1	99.6	1.303	417	61	0.05	49	0.04	38	0.04
	5	151.8	1.86	640	132	0.11	114	0.10	98	0.09
	10	179.9	2.138	763	179	0.15	158	0.14	139	0.13
	20	212.4	2.447	909	241	0.20	217	0.19	195	0.18
Saturated water	50	263.9	2.921	1155	357	0.30	329	0.29	302	0.28
	90	303.3	3.286	1364	466	0.39	434	0.38	404	0.37
	100	311	3.36	1408	490	0.41	457	0.40	426	0.39
	140	336.6	3.623	1571	581	0.49	546	0.48	512	0.47
	200	365.7	4.014	1827	731	0.61	691	0.61	653	0.60
Critical point	221.2	374.15	4.406	2084	880	0.74	837	0.74	795	0.74
	200	365.7	4.928	2411	1065	0.89	1016	0.89	969	0.90
	140	336.6	5.373	2638	1170	0.98	1117	0.98	1066	0.99
	110	318	5.553	2705	1188	1.00	1133	1.00	1080	1.00
	100	311	5.615	2725	1191	1.00	1136	1.00	1082	1.00
	90	303.3	5.679	2743	1192	1.00	1136	1.00	1081	1.00
	80	295	5.744	2758	1189	1.00	1132	1.00	1077	1.00
Saturated steam	50	263.9	5.973	2794	1162	0.98	1104	0.97	1046	0.97
	20	212.4	6.34	2799	1067	0.90	1005	0.88	943	0.87
	10	179.9	6.586	2778	979	0.82	914	0.80	850	0.79
	5	151.8	6.822	2749	886	0.74	818	0.72	752	0.70
	1	99.6	7.359	2675	665	0.56	592	0.52	521	0.48
	0.025	21.1	8.642	2539	178	0.15	93	0.08	8	0.01
Triple point	0.00611	0.01	9.155	2500.8	0	0.00	(-91)	(-0.08)	(-180)	(-0.17)

Table 2: Specific fluid exergy and specific exergy index (SEI).

approximately 100 °C saturated water at atmospheric condition. The corresponding SEI is approximately 0.05. Medium performance resources therefore have SEI between 0.05 and 0.5.

MAP FOR CLASSIFICATION OF GEOTHERMAL RESOURCES

The equation for the specific exergy index (SEI)

$$SEI = (h-273.16s)/1192$$

is a straight line on a h-s plot which is the Mollier Diagram. Therefore, straight lines of SEI=0.5 and SEI=0.05 can be plotted on the Mollier Diagram and the resultant diagram can be used as a map for the classification of geothermal resources as shown in Figure 2. The area above the line of SEI=0.5 is the high exergy resource zone (equivalent to Armstead's (1983) hyperthermal dry field), the area below SEI=0.05 is the low exergy resource zone (Armstead's semithermal field), and the area in between the two lines is the medium exergy zone (hyperthermal wet field). Hence by plotting the enthalpy and entropy values of a resource on the map, it can be immediately classified correctly the category of a geothermal resource it belongs to.

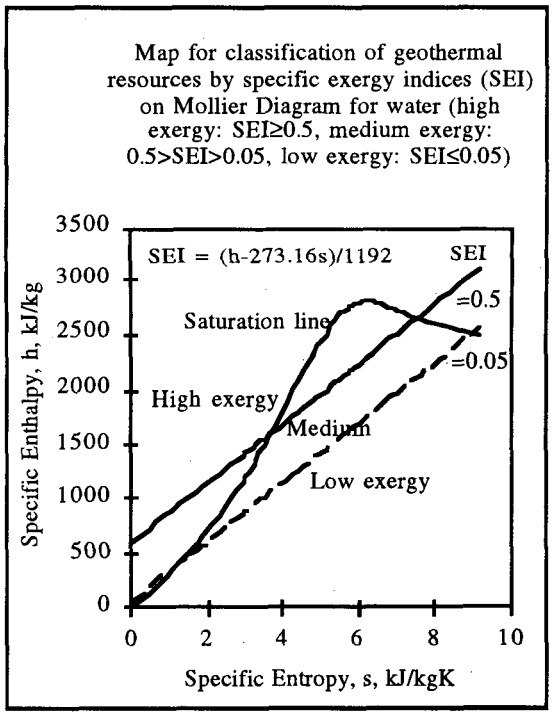

Figure 2: Map for classification of geothermal resources.

Mollier diagram is very useful when analysing adiabatic processes occur in nozzles, diffusers, turbines and compressors (Rogers and Mayhew, 1993). For example, the work done by a fluid flowing through a turbine is equal to the enthalpy change between two points on a vertical line.

The constant pressure lines are straight in the two-phase region but curve slightly upwards in the superheated region as the temperature increases. Constant temperature lines coincide with the constant pressure line in the two-phase region. They then tend towards the horizontal lines as entropy increases.

Constant dryness fraction lines are normally added to the Mollier diagram. Dryness, x, at any pressure or temperature can be easily determined from the Mollier diagram by dividing the straight lines in the ratio x to (1-x). Large-scale Mollier diagrams for practical use normally only show the part of the diagram above 2000 kJ/kg.

It follows that given any two independent thermodynamic properties (p, T, h, s, x, v) of a fluid, the SEI can be easily determined from a full Mollier diagram, thereby classify a geothermal resource accordingly.

APPLICATION OF CLASSIFICATION MAP TO KNOWN RESOURCES

Using data estimated from Figures 8.4 and 8.5 of Armstead (1983), wells for geothermal fields at Wairakei, Ohaaki (Broadlands), Cerro Prieto, Otake, Larderello and the Geysers are plotted on the classification map as shown in Figure 3. Tianjin 90 °C water (Cai, 1995) and Fuzhou 65 °C water (Hochstein, 1990) are also plotted in Figure 3. As expected, the Geysers and Larderello are high exergy resources, and Tianjin and Fuzhou are low exergy resources. Wairakei deep wells have higher pressure and lower enthalpy than shallow wells. One would expect the deep wells to have higher exergy for its higher pressure but the map clearly shows that the shallow wells are higher in specific exergy and hence a better resource exergitically. This appears to indicate that it is better to tap into shallow low pressure steam resources than into deep high pressure water, from thermodynamic point of view in addition to economic reason. Indeed, at constant enthalpy, SEI is insensitive to pressure within the range of a geothermal resource. Besides, separated geothermal water is a major and expensive disposal problem. This is further exemplified in Figure 3 that a geopressured resource of 1000 bar abs and 200 °C (h=903 kJ/kg) (Sanyal et al, 1995) is no better than the low pressure shallow Wairakei resource (p=5 bar abs, T=152 °C, h=1339 kJ/kg).

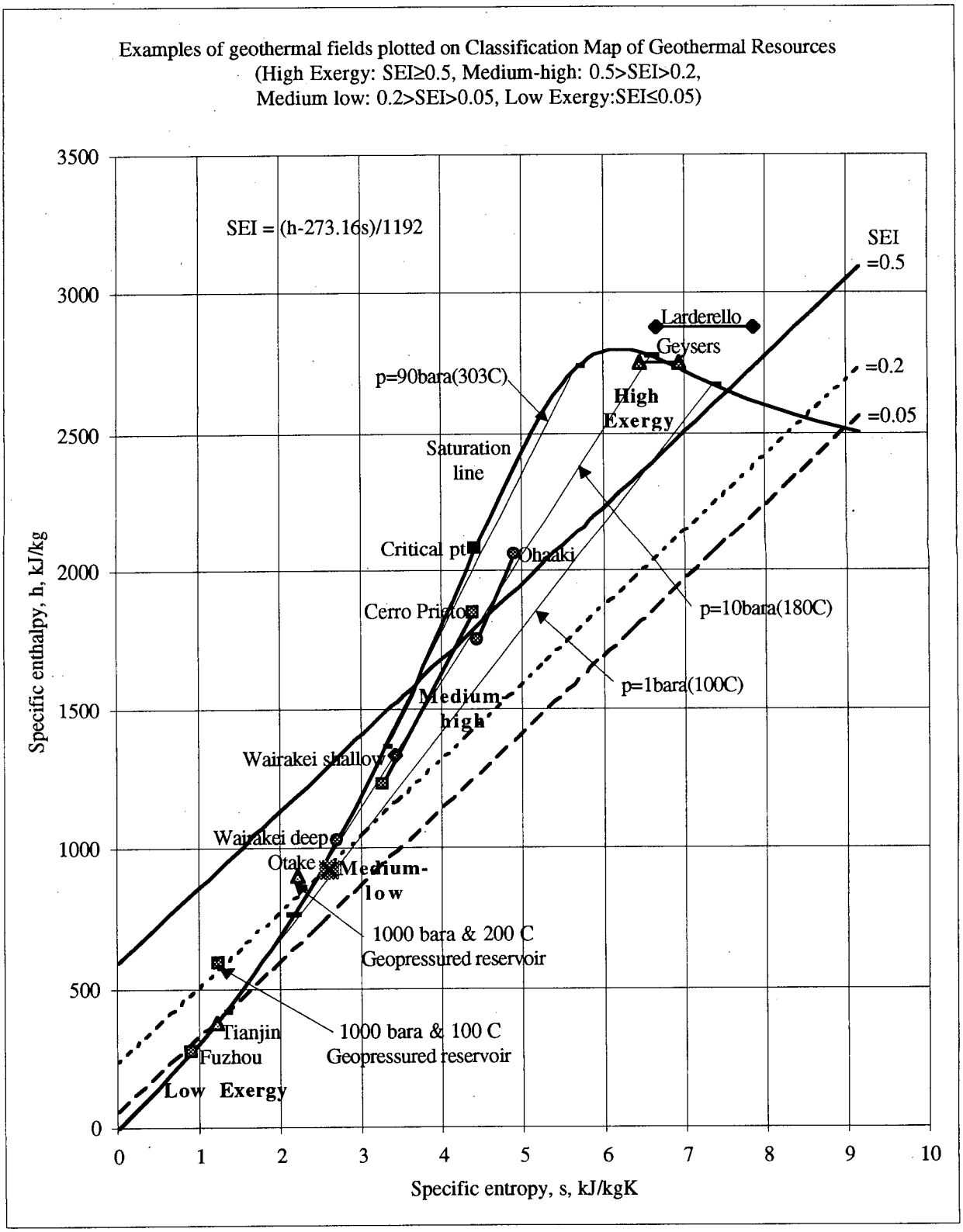

Figure 3: Examples of geothermal fields plotted on Classification Map of Geothermal Resources.

It is now quite clear from Figure 3 that most of the so called 'water-dominated' fields fall within the 'Medium' exergy two-phase zone of the Classification Map. However, the area in which Medium Exergy resources can fall in is bounded by the 1 bar abs pressure line, the SEI=0.5 line, and the saturation line with the exception of geopressured systems which can fall to the left of the saturation line. For high enthalpy (h >1600 kJ/kg) two-phase resources such as Ohaaki and Cerro Prieto, they can fall in the High Exergy zone as shown in Figure 3. For this reason, it is appropriate to define a line of SEI=0.2 to differentiate two-phase resources that fall near the Low Exergy zone, thereby dividing the Medium zone into a 'Medium-high' and a 'Medium-low' zone. A line of SEI=0.2 is chosen because it cuts the saturation liquid line at 20 bar abs which is within the maximum WHP at Wairakei. A line of SEI=0.25 would cut the saturation line at more than 30 bar abs which would exceed the typical WHP as shown in Figure 1. This means that the highest known geopressured system of approximately 1000 bar abs and 200 °C falls just inside the Medium-high zone, and Otake just inside the Medium-low zone. This also means that resources with enthalpy less than 1000 kJ/kg is likely to fall in the Medium-low zone. Similarly, Low exergy resources have enthalpy less than approximately 400 kJ/kg.

As for hot-dry rock (HDR) system, that would depend on the resultant fluid condition at the wellhead. Hochstein (1990) gives a temperature of up to 200 °C at 3 km depth. This is equivalent to about 70 °C/km temperature gradient. Shulman and Whitelaw (1995) proposed a 7 km deep well in a 90 °C/km gradient to produce a resultant fluid condition of 60 bar abs and 275 °C at the wellhead (h=1417 kJ/kg, s=3.392 kJ/kgK). This gives a respectable but optimistic SEI=0.4. However, this indicates that HDR is a 'better' resource than geopressured system from exergy point of view. It indicates that mining for heat (temperature) is better than mining for pressure. It also supports the notion of 'Heat Mining' being an appropriate term used by Armstead and Tester (1987) as 'A New Source of Energy'.

CONCLUSIONS

Temperature or enthalpy alone cannot define a geothermal resource unambiguously because two thermodynamic properties are required to define the state of the fluids of a geothermal resource.

Geothermal resources can be classified into high energy resources by their ability to generate electricity directly, and into low energy resources which are good for direct uses only.

Geothermal resources should be classified by their ability to do work. Therefore, exergy, being a measure of the maximum available work and a function of enthalpy, entropy and the sink condition, should be used to classify geothermal resources.

The specific exergy of the geothermal fluids at the wellhead should be use as the definition point of a geothermal resource. The thermodynamic properties of geothermal fluids are assumed to approximate that of pure water and steam.

The specific exergy of the geothermal fluids can be normalised by the maximum saturated steam exergy to give a Specific Exergy Index (SEI) which is robust and insensitive to fluid pressure and sink condition. Therefore, the triple point of water is chosen as the sink condition because it simplify the computation of SEI as enthalpy and entropy are zero at the triple point. The equation becomes SEI=(h-273.16s)/1192.

Geothermal resources with SEI≥0.5 are classified as high exergy resources; resources with 0.5>SEI>0.2 are medium-high; 0.2>SEI>0.05 are medium low; and resources with SEI≤0.05 are classified as low exergy resources. These SEI values correspond approximately to dry saturated steam at 1 bar absolute (SEI=0.5), saturated water at 20 bar absolute (SEI=0.2), and saturated water at 1 bar absolute (SEI=0.05).

Straight lines of SEI=0.5, 0.2, and 0.05 can be drawn on enthalpy and entropy (Mollier) diagram to form the Classification Map of Geothermal Resources.
The Mollier diagram normally also has lines of constant pressure, temperature, density and dryness. This aids the plotting of the thermodynamic states of geothermal fluids on the Classification Map.

Dry geothermal steam resources clearly has SEI≥0.5 and therefore are high exergy resources. Similarly, hot water resources at atmospheric pressure clearly has SEI≤0.05 and therefore are low exergy resources (enthalpy below 400 kJ/kg). Two-phase resources with enthalpy above 1600 kJ/kg are likely to be high exergy resources; those below 1000 k/kg are likely to be medium-low; and those between 1000 and 1600 kJ/kg are medium-high.

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