The United Nations
University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2001
Number 15

GEOTHERMAL RESOURCES IN MONGOLIA AND POTENTIAL USES

Batbayar Tseesuren
Renewable Energy Corporation,
P.O. Box 479, Ulaanbaatar 210136,
MONGOLIA

ABSTRACT

This paper presents an overview of surveys on geothermal energy that have been made in Mongolia to date and explores possibilities for its use. Mongolia has geothermal resources but geothermal utilization is not widely developed. Hot springs are though used for bathing, health resorts (balneology) and to a small amount for greenhouse heating. The main region of geothermal activity is Khangai, where there are 3 aimag (province) centres and 44 soum (village) centres, with approximately 241,000 people. Most of them are without electricity, using diesel generation in the evenings for 5-6 hours because of high oil costs. Coal and wood are used for heating. Using geothermal energy for heating, electrical generation and industrial purposes are the main incentives for developing a geothermal infrastructure in the rural areas of Mongolia. Bearing in mind that the Mongolian main gross domestic products come from animal husbandry, good possibilities are also to use geothermal energy for wool and cashmere washing and drying.

1. INTRODUCTION

Mongolia is situated in the northern part of Central Asia, far from the oceans, on a high plateau surrounded by mountain ridges. The mountainous country's mean elevation is 1580m above sea level. Mongolia consists of 22 aimags or province (approx. 50,000-110,000 people in each aimag), and each aimag consists of 12-22 soums (each soum or village has approx. 4,000-5,000 people).

The energy sources used in Mongolia can be categorized in two groups. The first group includes traditional sources such as fuel wood, agricultural waste, and animal dung. The second group is commercial, such as petroleum, coal and hydropower. Traditional sources are mainly used in the rural areas. Renewable energy such as solar panels and wind turbines are used for telecommunication, primary schools, hospitals and by some nomadic herders for lighting. Mongolia has 5 hydropower plants which supply electricity for aimag and soum centres.

Most of the hot springs in Mongolia (Figure 1) are used only for bathing and traditional health resort (balneological) purposes, but there are many other possibilities for utilization. The Khangai area has such possibilities, with an important magisterial road between western and central Mongolia. It has 241,000 people and is an area of great tourist attractions (Mongolian Statistics Centre, 2001). In Mongolia, urbanization is increasing from year to year and this requires inexpensive, reliable electricity and heating. Developing the use of geothermal water available in the area for house heating, small electric generation, swimming pools and industrial use would benefit the local people and be an attraction for tourists. The main emphasis of this report is to review existing data and to assess how geothermal heat might meet present needs.

2. THE BENEFITS OF GEOTHERMAL ENERGY

In the 20th century, geothermal energy was harnessed on a large scale for space heating, industry, and electricity generation. For electrical generation, geothermal energy has been produced commercially since 1913 at Larderello in Italy, and for four decades on a scale of hundreds of MW both for electricity generation and direct use. In the year 2000, geothermal resources had been identified in over 80 countries and there are quantified records of geothermal utilisation in 58 countries in the world. Worldwide use of geothermal energy amounts to about 49 TWh/a of electricity and 53 TWh/a for direct use (Table 1).

TABLE 1: Electricity generation and direct use of geothermal energy in 2000 (Fridleifsson, 2001)

	Electricity generation			**Direct use**		
	Installed capacity (MWe)	**Total production**		**Installed capacity (MWt)**	**Total production**	
		(GWh/a)	**(%)**		**(GWh/a)**	**(%)**
Africa	54	397	1	125	504	1
America	3390	23342	47	4355	7270	14
Asia	3095	17510	35	4608	24235	46
Europe	998	5745	12	5714	18905	35
Oceania	437	2269	5	342	2065	4
Total	7974	49263	100	15144	52979	100

Electricity is produced with geothermal steam in 21 countries spread over all continents. The top ten countries in 1999 were (MWe in brackets): USA (2228), Philippines (1909), Italy (785), Mexico (755), Indonesia (590), Japan (547), New Zealand (437), Iceland (170), El Salvador (161), and Costa Rica (143).

Direct application of geothermal energy can involve a wide variety of end uses, such as space heating and cooling, industry, greenhouses, fish farming, and bathing/swimming/health spas. It uses mostly existing technology and straightforward engineering. The technology, reliability, economics, and environmental acceptability of direct use geothermal energy has been demonstrated throughout the world (Fridleifsson, 2001).

Direct application can be based on both high- and low-temperature geothermal resources and is therefore much more widespread in the world than electricity production. Direct application is, however, more site specific for the market, as steam and hot water are rarely transported over long distances from the geothermal site. Table 2 shows the installed capacity and produced energy in the top fifteen direct use countries. The table is based on data from Lund and Freeston (2001).

People in at least 64 countries around the world are enjoying the use of geothermal resources in various forms. The scale of use is, however, very different. The country with the most extensive use of geothermal energy is Iceland, which obtains 50% of its total primary energy from geothermal resources and about 68% of the primary energy is produced by renewable energy sources. Geothermal energy provides 86% of all space heating in Iceland and about 16% of the electricity generation (the remainder is hydropower). Geothermal energy is also used for greenhouses, industry, fish farming, snow melting and bathing (Ragnarsson, 2000). It is surprising to many that in a country with an average temperature of -1°C in January and 12°C in July, swimming in outdoor pools is very popular the year round. In the capital, Reykjavík, (population 110,000) there were 1.7 million visitors to the six public swimming pools in 1999. In the largest outdoor pool there were, on average, 36,000 visitors in January and 57,000 visitors in July in the years 1995-1999. Geothermal energy has not only improved the economy and the environment in Iceland but also significantly improved the quality of life. Polluting fossil fuels (which have to be imported) are only used in Iceland in the transport sector (cars, ships and airplanes).

TABLE 2: World´s top countries using geothermal in direct uses

	Installed (MWt)	**Production (GWh/a)**
China	2282	10531
Japan	1167	7482
USA	3766	5640
Iceland	1469	5603
Turkey	820	4377
New Zealand	308	1967
Georgia	250	1752
Russia	308	1707
France	326	1360
Sweden	377	1147
Hungary	473	1135
Mexico	164	1089
Italy	326	1048
Romania	152	797
Switzerland	547	663

In addition to China, recent examples of a high growth rate in the direct use of geothermal energy are found in countries such as Turkey and Tunisia. In Turkey, the installed capacity for spaceheating (residences and greenhouses) grew from 160 MWt in 1994 to 490 MWt in 1999. This mostly replaced coal heating. The greenhouses in Tunisia do, in fact, replace cooling towers five months per year to cool irrigation water from deep wells from 75 to 30°C in oases in the Sahara desert. The geothermal heat is, therefore, a byproduct of the irrigation water. The main products in the greenhouses are tomatoes and melons for export to Europe.

3. GEOTHERMAL SURVEYS OF MONGOLIA

3.1 Geothermal studies

A comprehensive investigation of the geothermal resources and their possible uses (for heating, power etc.) has, up to now, not been carried out in Mongolia. During the last two decades, some general studies have though been done on the geothermal regime in East Siberia and Mongolia, including the southern Siberian platform, Baikal rift zone, trans Baikal fold area, and Mongolia, four regions differing in their geology and tectonics. The continental crust is highly heterogeneous within the provinces, ranging in age from the early Riphean to the late Cenozoic, according to a Mongolian-Russian survey. The thermal regime in Mongolia was studied, based on 32 heat flow stations. However, this did not cover the South Mongolia Hersynian belt and the Mongol Altai province, where information is scarce. Recently, the Ministry of Agriculture and Industry of Mongolia (1999) instigated a research programme called "Geotherm",including compilation of existing tectonic, geophysical, and hydrogeological material (regional geology, crustal structures, study of hot springs), based on which scientists have reached some conclusions.

3.2 Distribution and use of hot springs in Mongolia

People have used hot springs for bathing and washing clothes since the dawn of civilisation in many parts of the world. In the same way, Mongolia has a considerable experience in health resorts using geothermal water. Geothermal water has been used to treat high blood pressure, rheumatism, skin disease, diseases of the nervous system, ulcers and generally for recuperation after surgery. Depending on the chemical composition of the mineral water and springs, gas availability, peat and sulphurous mud, and climatic conditions, each sanitarium is designated for the treatment of a specific disease. Mongolia has a 42 hot springs, mainly distributed in the central and western provinces. Details of these springs are presented in Table 3. Some places have greenhouses and small scale heating. A map of Mongolian hot spring distribution is shown in Figure 1. The thermal energy (kW) for these springs, that can be used has been calculated, based on the natural flow and temperature and on cooling the water to 35˚C in radiators (last column in Table 3). For this calculation, the following formula is used:

$$Q = m \times c_p\,(T_1 - T_2) \tag{1}$$

where Q = Usable heat (kW);
m = Mass flow (kg/s);
c_p = Specific heat of water (4.19 kJ/kg˚C);
T_1 = Temperature of water from source (˚C);
T_2 = Temperature of water after use (˚C) (T_2=35˚C).

Table 3 shows that some of the hot spring fields are a considerable resource, such as Shargaljuut of Bayankhongor aimag with approx. 6,000 kW, Ikh Onon of Khentii aimag with 2,400 kW, Tsenkher of Arkhangai aimag 2,100 kW and Khujirt and Mogoit of Uvurkhangai aimag with 1,300 and 1,100 kW, respectively. There are many possibilities for using the geothermal energy.

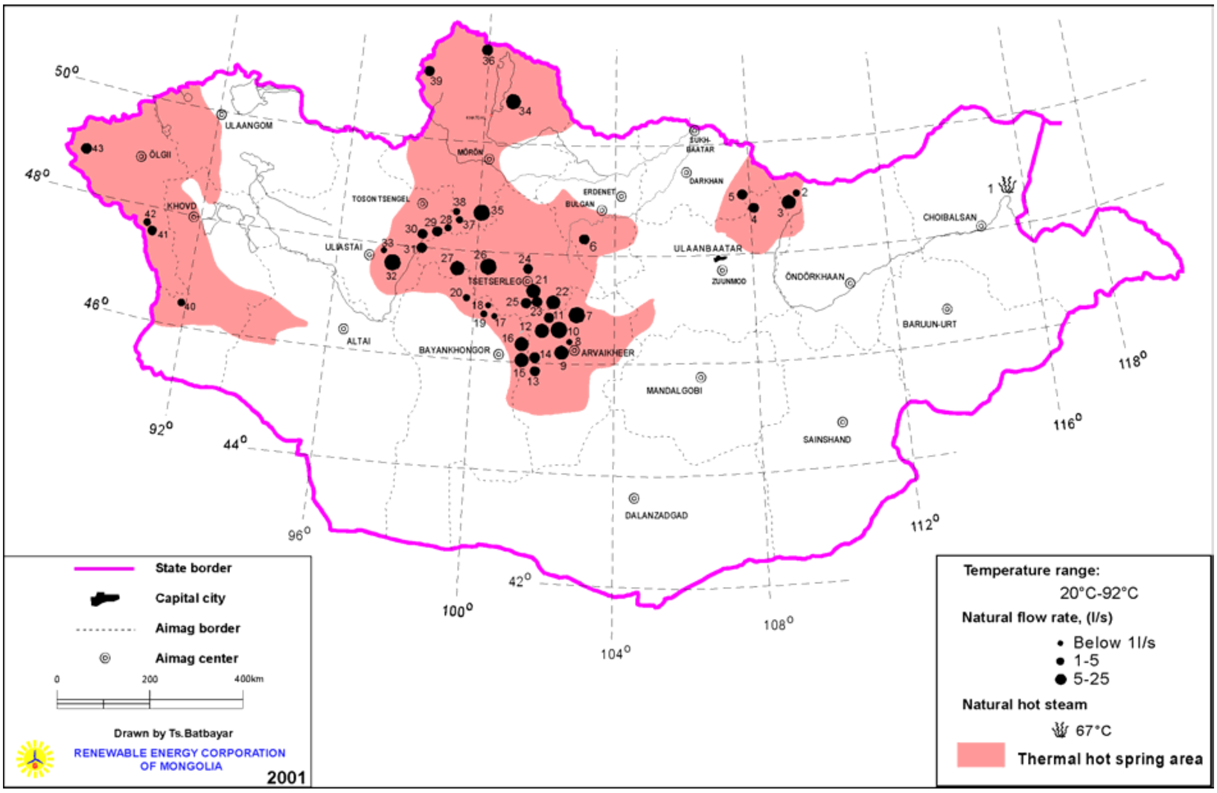


FIGURE 1: Hot springs of Mongolia, numbers refer to springs listed in Table 3

TABLE 3: Hot springs of Mongolia

No.	Name of hot spring	Province	Latitude, grad	Longitude, grad	Elevation (m)	Flow rate (l/s)	Mineral. (mg/l)	Temp. (^{0}C)	Heat >35°C (kW)
6	Utaat minjuur	Dornod	$48^{0}43^{II}$	$115^{0}50^{II}$	720	-	-	67	
2	Baga onon	Khentii	$48^{0}56^{II}$	$108^{0}00^{II}$	1450	0.1	-	73	16
3	Ikh Onon		$48^{0}56^{II}$	$108^{0}49^{II}$	1470	11	-	88	2443
4	Eustii	Tuv	$48^{0}35^{II}$	$107^{0}50^{II}$	1150	3	239.4	34	
5	Euruu	Selenge	$49^{0}00^{II}$	$107^{0}33^{II}$		3	226.8	43	101
6	Saikhan khulj	Bulgan	$36^{0}16^{II}$	$102^{0}58^{II}$	2130	2.3	744.5	55	193
7	Khujirt	Uvurkhangai	$46^{0}54^{II}$	$102^{0}46^{II}$	1748	16	-	55	1341
8	Emt		$46^{0}26^{II}$	$102^{0}47^{II}$	1850	0.5	-	39	8
9	Khuremt		$46^{0}16^{II}$	$102^{0}46^{II}$	1900	5	-	55	419
10	Mogoit		$46^{0}45^{II}$	$102^{0}15^{II}$	1650	7	-	72	1085
11	Khamar		$46^{0}43^{II}$	$102^{0}00^{II}$	1750	4	-	39	67
12	Gyatruun		$46^{0}36^{II}$	$102^{0}00^{II}$	2500	5	200.6	36	21
13	Sharga		$45^{0}50^{II}$	$101^{0}40^{II}$	1900	1	-	30	
14	Taats		$46^{0}10^{II}$	$101^{0}38^{II}$	1335	2.5	-	55	210
15	Baga Shargaljuut	Bayankhongor	$46^{0}13^{II}$	$101^{0}15^{II}$	2150	10	37.3	58	964
16	Shargaljuut		$46^{0}13^{II}$	$101^{0}15^{II}$	2400	25	259	92	5971
17	Uheg		$46^{0}48^{II}$	$100^{0}52^{II}$	2100	5	-	57	461
18	Örgööt		$47^{0}15^{II}$	$100^{0}05^{II}$	-	5	364.3	40	105
19	Teel		$46^{0}51^{II}$	$100^{0}02^{II}$	2200	5	-	32	
20	Tsokhiot		$47^{0}00^{II}$	$99^{0}45^{II}$	-	5	-	23	
21	Tsenher	Arkhangai	$47^{0}20^{II}$	$101^{0}39^{II}$	1860	10	239.9	86	2137
22	Tsagaan Sum		$47^{0}40^{II}$	$102^{0}00^{II}$	1840	8	-	69	1140
23	Gyalgar		$47^{0}12^{II}$	$101^{0}33^{II}$	1900	1	221.6	52	71
24	Shivert		$47^{0}38^{II}$	$101^{0}31^{II}$	1710	4	24.8	55	335
25	Bor tal		$47^{0}12^{II}$	$101^{0}36^{II}$	1880	4.5	258.9	46	207
26	Chuluut		$47^{0}55^{II}$	$100^{0}15^{II}$	2190	1.2	250.5	45	50
27	Noyon		$47^{0}55^{II}$	$99^{0}25^{II}$	2370	6	-	38	75
28	Tsetsuuh	Zavkhan	$48^{0}21^{II}$	$98^{0}30^{II}$	2050	0.2	231.2	36	1
29	Zaart		$48^{0}21^{II}$	$98^{0}46^{II}$	2080	2.8	247	44	106
30	Khaluun us		$48^{0}15^{II}$	$98^{0}24^{II}$	2170	1	236	35	0
31	Khojuul		$48^{0}12^{II}$	$98^{0}08^{II}$	2170	4	181	45	168
32	Otgontenger		$47^{0}45^{II}$	$97^{0}30^{II}$	2510	1.7	223	56	150
33	Ulaan khaalga		$47^{0}55^{II}$	$97^{0}20^{II}$	228	0.2	340.6	37	2
34	Bulnai	Khuvsgul	$50^{0}48^{II}$	$100^{0}48^{II}$	1660	5	501.2	47	251
35	Salbart		$48^{0}35^{II}$	$99^{0}37^{II}$	-	6	-	44	226
36	Urtrag		$51^{0}45^{II}$	$99^{0}42^{II}$	-	3.1	-	21	
37	Tsuvraa		$48^{0}30^{II}$	$99^{0}39^{II}$	-	0.1	-	35	
38	Khunjil		$48^{0}34^{II}$	$99^{0}22^{II}$	1950	0.1	214.8	62	11
39	Jalga		$51^{0}20^{II}$	$98^{0}01^{II}$	-	5	-	40	105
40	Bulgan	Khovd	$46^{0}36^{II}$	$91^{0}23^{II}$	1670	0.6	306.2	29	
41	Gants mog	Bayan-Ulgii	$47^{0}35^{II}$	$91^{0}31^{II}$	2590	1	139.3	31	
42	Chihert		$47^{0}48^{II}$	$90^{0}28^{II}$	2480	0.5	-	25	
43	Tsagaan gol		$48^{0}40^{II}$	$88^{0}12^{II}$	-	3	-	32	
					Total flow, l/s	184.4	Total energy, kW		18438

3.3 Tectonics and general characteristics of heat flow

The latest active tectonic period in Mongolia started at the end of Mesozoic and the beginning of Oligocene, due to the simultaneous development of the south Siberian plate form (mountain part) and the Baikal lake region. At that time, intense tectonic development gave the Mongolian mountains their present appearance.

A geophysical survey on the crustal structure established (affirmed) that accumulative thermal sources (magma lumps) are located near the surface under the Khangai Khentii mountain region. Heat flow in Mongolia was studied from 32 heat flow stations (gradient wells). The data obtained is though not very reliable as it comes from shallow boreholes (not deeper than 150-200 m) drilled through sediments. On average, there is a general westward decrease in heat flow from 62 ± 9 to 40 ± 7 mW/m^2. The observed scatter in heat flow values in southern East Siberia and in Mongolia testifies to variable thermal conductivity due to crustal structures. Besides the local (crustal) anomaly, there is a large regional (mantle) anomaly indicated by gravity, seismic and electrical data (Zorin et al., 1990). The data shows that the Mongolia Siberia mountainous region is underlain by an anomalous mantle, the top of which is marked by low seismic velocities of 7.7-7.8 km/s beneath the Baikal rift. According to this data, the lithosphere under the Siberian platforms is as thick as 200 km, thinning to 55-75 km below the Baikal rift zone, and thickening again beneath the Trans-Baikal fold area to 120-170 km (Dorofeeva, 1992).

The 32 heat flow stations are the basis for the Mongolian heat flow map presenteded in Figure 2. The map published here is based on previously published works (Ministry of Agriculture and Industry of Mongolia, 1999 and Dorofeeva, 1992). The average heat flow in the different tectonic regions is approximately estimated as follows:

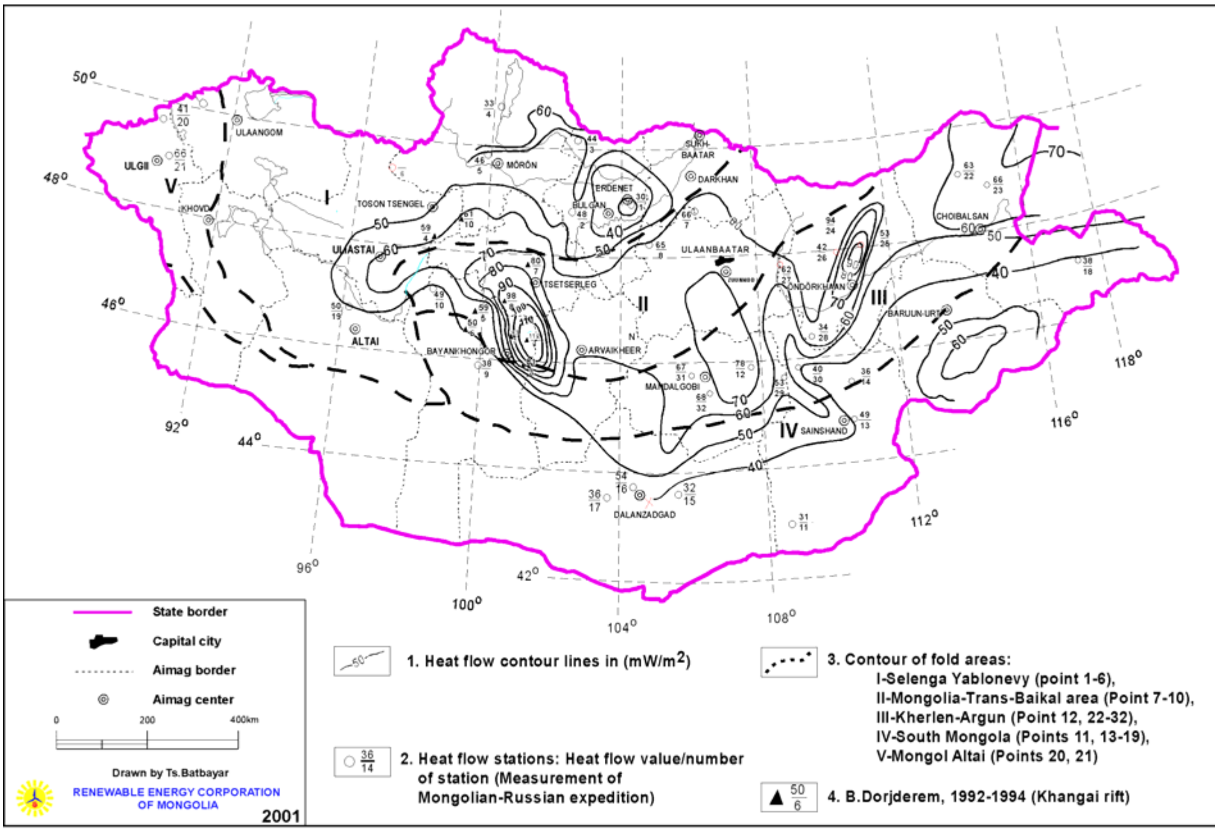


FIGURE 3: Heat flow map of Mongolia (based on information from Ministry of Agriculture and Industry of Mongolia (1999); Dorofeeva, (1992) and maps published by the Geodesy and Cartographical Institute (1980 and 2000)

Mongol Altai mountain region	54 ± 24 mW/m^2
Khangai mountain region	52 ± 6 mW/m^2
Khubsulgul lake region	80 ± 10 mW/m^2
Dornod Mongolian steps	44 ± 6 mW/m^2

However, the heat flow is not uniform, due to specific surface characteristics and structures in the geothermal zone.

3.4 Chemical data

Water from two hot springs from Bayankhongor and two hot springs from Arkhangai has been sampled by the Chemical Institute of Mongolia (Appendix I) and is used in this study. The sites can be found in Figure 1. Points no. 15 and 16 indicate Shargaljuut of Bayan-khongor aimag, point 21 is Tsenkher of Arkhangai aimag, and point 25 is Bor tal of Arkhangai aimag. The chemical composition is shown in Table 4. All the waters presented have high alkalinity and relatively high amounts of fluoride. The four hot springs seem to have bicarbonate waters with some sulphate, but are low in chloride. This is demonstrated by the Giggenbach diagram (1991) shown in Figure 3.

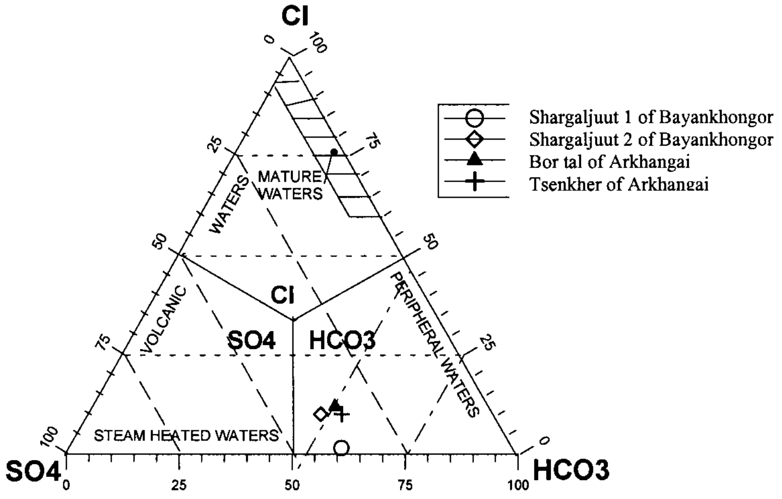


FIGURE 4: Classification of Mongolian geothermal waters according to Giggenbach's Cl-SO$_4$- HCO$_3$ ternary diagram

The geothermal water from Bor tal of Arkhangal aimag appears to be well equilibrated at the wellhead temperature, according to the Na-K-Mg ternary plots of Giggenbach (1988) (Figure, 4). The water from the other wells is equilibrated at wellhead temperatures according to the Na-K-Mg ternary plots of Arnórsson (1991). This would indicate that drilling in these areas would not produce water at considerably higher temperatures than presently found in the hot springs.

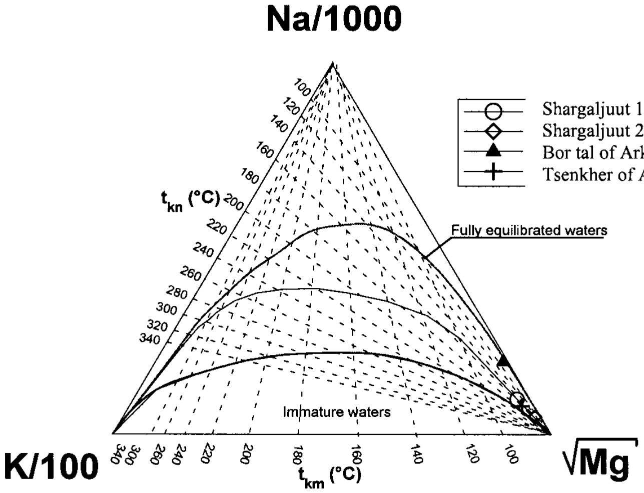


FIGURE 5: The Na-K-Mg ternary diagram showing equilibration of the Mongolian samples

TABLE 4: The chemical composition of geothermal water in 4 hot springs, in mg/l

	Bayankhongor aimag		**Arkhangai aimag**	
	Shargaljuut 1	**Shargaljuut 2**	**Bor tal**	**Tsenkher**
Temp. (˚C)			49.5	84.3
pH			9.7	9.4
CO_2	58	70.4	61.6	54.6
H_2S	13.1	10.2		10.6
NH_3	0.944	0.944	0.66	0.09
B	0.2	0.2	0.5	1
SiO_2	105	79.5	175.3	128.2
Na	76.9	95.1	108.75	84.3
K	2.38	2.5		2.9
Ca	3.21	6.1	3.2	2.2
Mg	0.49	3.5		0.94
Fe	1.5	0.76		0.2
F	11.3	7.4	4.8	25
Cl	5.67	24.8	24.1	17.7
SO_4	50.6	72.5	54.3	45.3

Results of calculations based on chalcedony and Na/K geothermometers are used to evaluate the temperature in geothermal reservoirs (Table 5). In the Bayankhongor area the reservoir temperature indicated by the calculated chalcedony geothermometer is close to the production temperature. The differences could be due to a decrease in temperature when the water rises to the surface. The calculated sodium-potassium geothermometer gives almost the same values as the chalcedony geothermometer which further indicates near-equilibrium at production temperature. As for Bor tal of Arkhangal, the chalcedony temperature is much higher than the hot spring temperature, indicating that the reservoir temperature may be as high as 120˚C. Both the calculated chalcedony and the Na/K geothermometers are close to the production temperature in Tsenkher of Arkhangai aimag. Probably the reservoir temperature in Arkhangai area exceeds 100˚C.

TABLE 5: Calculated geothermometer temperatures, in ˚C, for four geothermal hot springs in Mongolia

Hot spring	**Measured temp.**	**Chalcedony temp.**	**Na/K temp.**
Shargaljuut 1	88	101	99
Shargaljuut 2	76	86	88
Bor tal	49.5	117	
Thenkher	84.3	109	106

Cooling of geothermal water during utilization may result in scale deposition. The type of scaling depends on the chemical composition of the geothermal water, the temperature of the water and the type of material in the distribution system.

The WATCH program (Bjarnason, 1994) was used to predict the potential danger of scaling, based on the chemical composition of the geothermal water (the WATCH calculations are attached in Appendix II). The ionic balance for the samples calculated gave values ranging from –7.68% to -0.78% at Shargaljuut 1 and 2, which is acceptable for equilibrium calculations. The data can, thus, be used for interpretation. The ionic balance for the sample from Bor tal also has a low value (-2.24%) and the sample can be used for calcite prediction, but the ionic balance for Tsenkher is very poor. Based on the data in Table 3, the WATCH program was used to calculate the saturation indices, log Q/K, to see when minerals start to

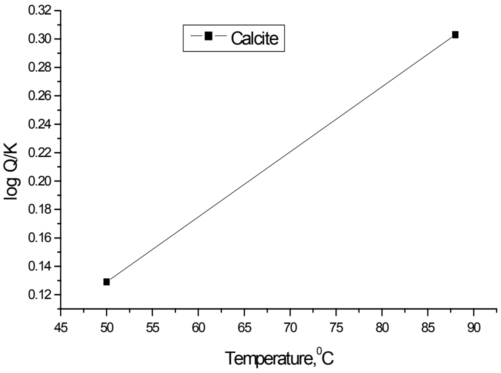


FIGURE 6: The saturation index for calcite for Shargaljuut 1 of Bayankhongor aimag

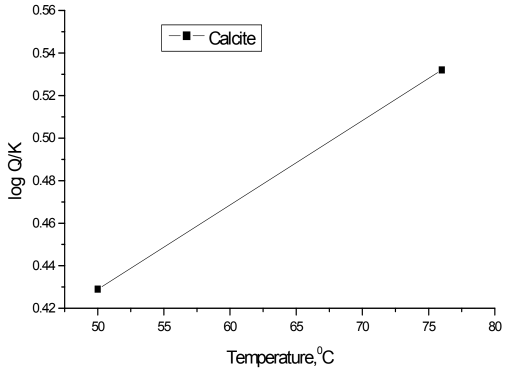


FIGURE 7: The saturation index for calcite for Shargaljuut 2 of Bayankhongor aimag

precipitate, assuming conductive cooling to 50°C. When Q = K, the solution is exactly saturated or in equilibrium with the respective mineral. If Q > K it means that there is supersaturation with respect to that mineral. Figures 5, 6, and 7 show the dependence of the saturation index on the temperature for calcite. Lower temperatures during geothermal water utilization, seem to indicate less scaling problems with calcite. The scaling potential in Shargaljuut 1 and Bor tal is lower than in Shargaljuut 2. If a value of log Q/K for calcite exceeds 0.5, experience warns of the danger of calcite scaling.

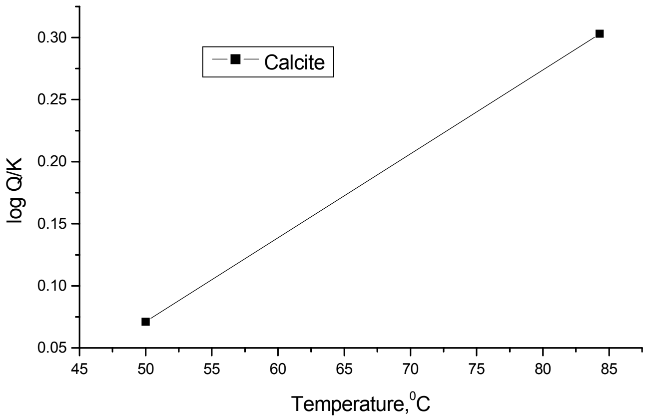


FIGURE 8: The saturation index for calcite for Bor Antal of Arkhangai aimag

3.5 Geological structures associated with geothermal activity

Geothermal manifestations are widely found in the world, but with different characteristics depending on the siting and the geological developmental history. Geothermal resources in Mongolia are mainly distributed in Khangai, Khentii, and around the Khubsugul Mongol Altain plate forms, Dornod-Dariganga and Orkhon-Selenga regions, due to developments during the second geodynamic Cenozoic age. The Mongolian geothermal structurural map was made based on regional geological studies (Ministry of Agriculture and Industry of Mongolia, 1999) and is shown in Figure 8. Outlines of the different geothermal regions and their transitional zones are given in Table 6. The Khangai open geothermal system has attracted the interest of researchers and its location is favourable with regards to social and economic conditions.

3.6 Khangai geothermal system

The central fold mountains contain the Khangai geothermal system which is a block structure system limited by the Tarvagatai, Baidrag, Tamir and, Orkhon rift. The Khangai ridge geothermal system is divided by tectonic formations as follows (Figure 9):

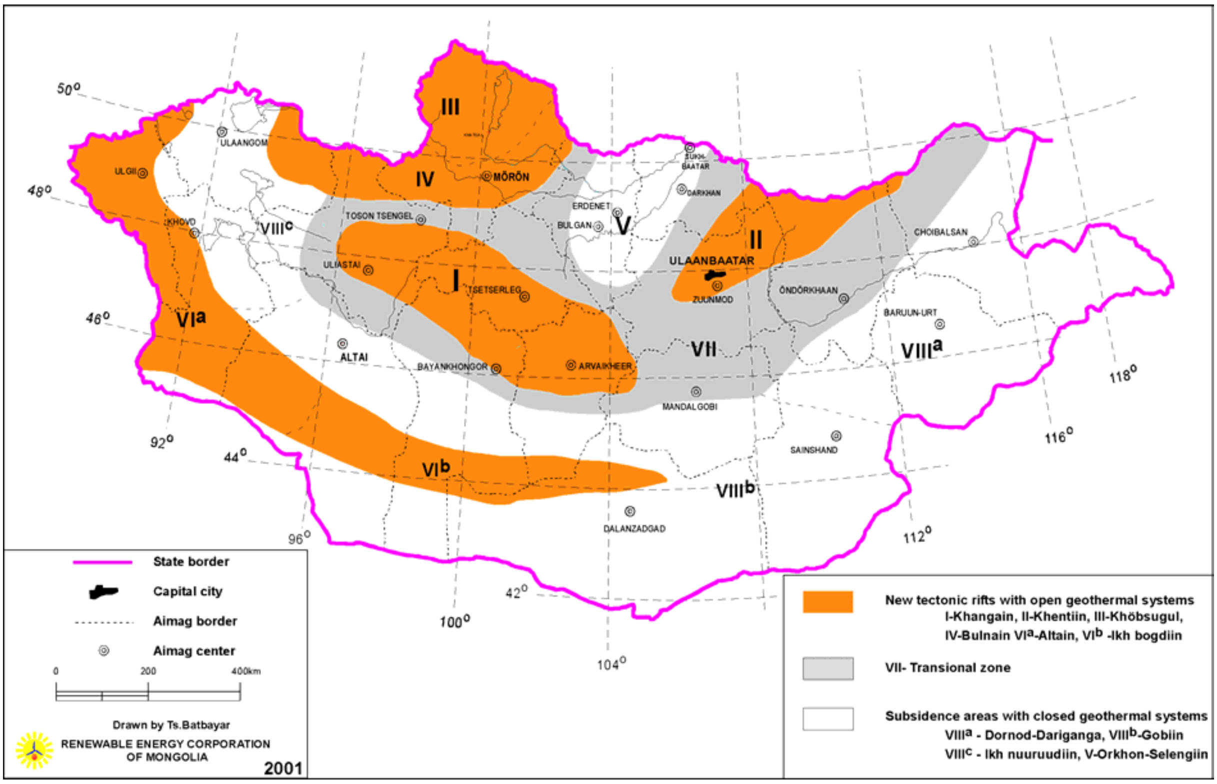


FIGURE 9: The main geothermal structures of Mongolia (map based on information from the Ministry of Agriculture and Industry of Mongolia, (1999), and maps published by the Geodesy and Cartographical Institute (2000))

TABLE 6: General characteristics of Mongolian geothermal systems

Geothermal zone	**System's name**	**Subsystem**	**Type of cover**	**Heat flow (mW/m^2)**	**Geothermal gradient (˚C/km)**	**Contents of water**	**Minera-lization (g/l)**
Fold plateform zone	Hangai	Tarvagatai-Uliastai Baidrag-Tamir Orkhon-Taats	Open Semi-open	75-100	45 -80	SO_4 HCO_3 / Na SO_4 HCO_3 / Na	< 0.5
	Hentii	Hoit Hentii Onon-Ulz	Semi-open Closed	40-50	35 -50	SO_4 HCO_3 / Na SO_4 HCO_3 / Na	< 1.0
	Hovsgoliin	Nuuriin Morongiin	Semi-closed Closed	35-50	25 -40	SO_4 HCO_3 / Na	< 1.0
	Bulnain	Bulnain	Open	30-40	20 -25	SO_4 HCO_3 / Na	< 0.5
	Altain	Altain Ih Bogdiin	Semi-closed Closed	40	20 -30	SO_4 HCO_3 / Na	37.260
Transitional zone		Mongol-Dauriin Bayanhongoriin Bulganii Santiin Zaamariin	Closed	40	20 -35	Cl SO_4 / Na	37324
Largest subsidence zone	Dornot-Dariganga,	Dornotiin				Cl SO_4 / Na Ca	5-25 (150)
	Gobiin Ih nuuruudiin,	Darigangiin				Cl SO_4 / Na	20-80 (300)
	Orhon-Selenge	Sainshandiin Gobiin	Closed	40	20 -35	Cl SO_4 / Na Mg	20-80 (300)
		Nuuruudiin Orhon-Selenge					37548

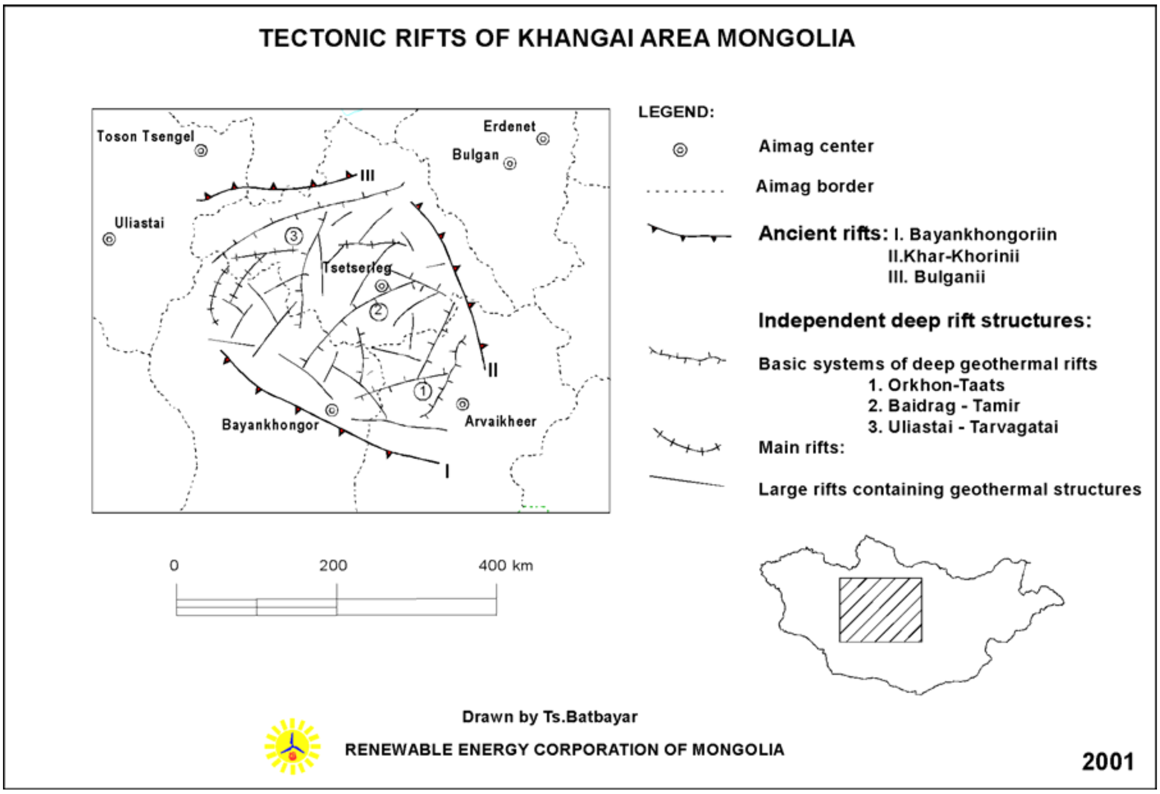


FIGURE 10: Deep tectonic rift structures in the Khangai area (based on Ministry of Agriculture and Industry of Mongolia, 1999; Geodesy and Cartographical Institute, 2000)

1. Tarvagatai-Ulaistai
2. Baidrag-Tamir;
3. Orkhon-Taats

The above sub-systems have independent configurations in the density of faults (rifts), in the character of their relationships with vertical and horizontal mobility, their ages, central position of tension axis, open and closed hydrothermal structures, physical and chemical factors and thermal activity. The tectonic rifts are associated with major lines and in some places are distributed as a grid. The conditions are suitable for geothermal activity.

The physical and chemical status of hot spring resources distributed in the Khangai mountains (ridge) corresponds both to the basic geotectonic structures and differentiated specific characteristics. Particularly it can be said that hot springs distributed in the Tarvagatai-Uliastai sub-system, generally contain sulphate-bicarbonade and sodium-sulphate-chloride, are with comparatively low flow rate (0.1-6 l/s), and a medium temperature (35-62˚C). There is thick cover of sediments, and the underground water level is comparatively high due to the altered physical state. The Orkhon-Taats and Baidrag-Tamir sub-systems are southernmost in the Khaingai geothermal system. Hot springs in this area contain sodium bicarbonade and have higher temperature (53-92˚C), higher flowrate (4-50 l/s) and low mineralization (0.1-0.2 g/l) and the highest contents of floride and silica.

When hot water rises to the surface through a fault, its pressure declines and steam separates from the water. Gas in the hot steam consists of nitrogen (N_2 80-90%) and hydrogen sulphide (H_2S). High nitrogen content affirms that the hot springs originate from rain water which has infiltrated deep into the ground. The Shargaljuut and Tsenkher hot spring have high temperature, more discharge and a lot of floride. It has been shown that the Baidrag-Tamir, and Orkhon-Taats hydrogeothermal sub-systems draw their thermal energy from a magmatic centre found at comparatively shallow depth. Vertical and horizontal tectonic movement in the Khangai ridge zone date from the same age as the Baikal rift zone movement. Also, the Khangai rift zone is the centre of the mainland rift zone (Baikhal-Khuvsgul-Khangai-Altai). The Khangai geothermal system is interesting and its tecto-magmatic operations are still active and growing.

4. EXISTING HEATING SYSTEMS AND REQUIREMENTS

4.1 Present heating systems in the capital city and province centres

Mongolia has centralized heating systems for official buildings in large cities. For example, the capital city, Ulaanbaatar, and some industrial province centres have a thermal power plant supplying heat during the winter season. Thermal energy is carried by water, outlet temperature of 150-70˚C, return temperature 90-70˚C. The temperature control system is in the central heating plant and changes are made in the supply temperature depending on weather conditions. The heating season starts 15th October and ends 15th April. The district heating system is turned off during the rest of the year. The heating equipment (radiator) for buildings is made of cast iron. Many villages and towns are heated by coal furnaces. The soum centres have their own heating systems.

4.2 Present heating system in soum centres

The installed capacity of the heating systems in the soum centres is 0.8-3.0 MWt, and estimated peak heat load is 0.4-2.0 MWt. The heating plants supply the public buildings in the town centres. Hot water is distributed from a coal furnace and pumped to consumers in underground-insulated pipelines. All consumers have heating control systems (Figure 10).

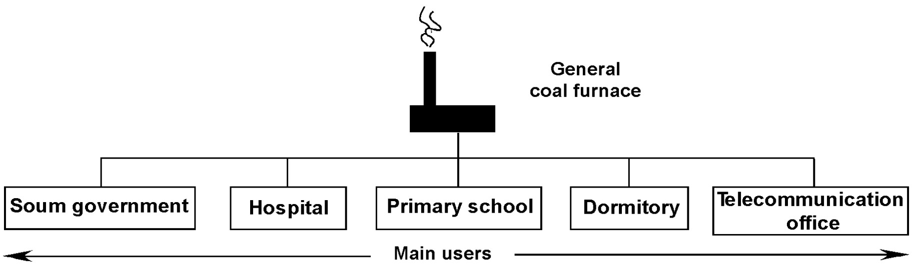


FIGURE 11: Present heating system scheme in a typical soum centre

4.3 Heating systems for different house types

Heating schemes of different house types in Mongolia are shown in Figures 11, 12 and 13. The building material is still mostly brick walls with a thickness of 64 cm. It is a standard wall thickness suitable for extreme weather. Also, wide use is made of reinforced precast concrete buildings. The overall heat transfer coefficient "U" for concrete buildings is equal to 1 W/m^2 ˚C. The overall heat transfer coefficient "U" of buildings built before 1970 follows the European standard. Recently, there have been

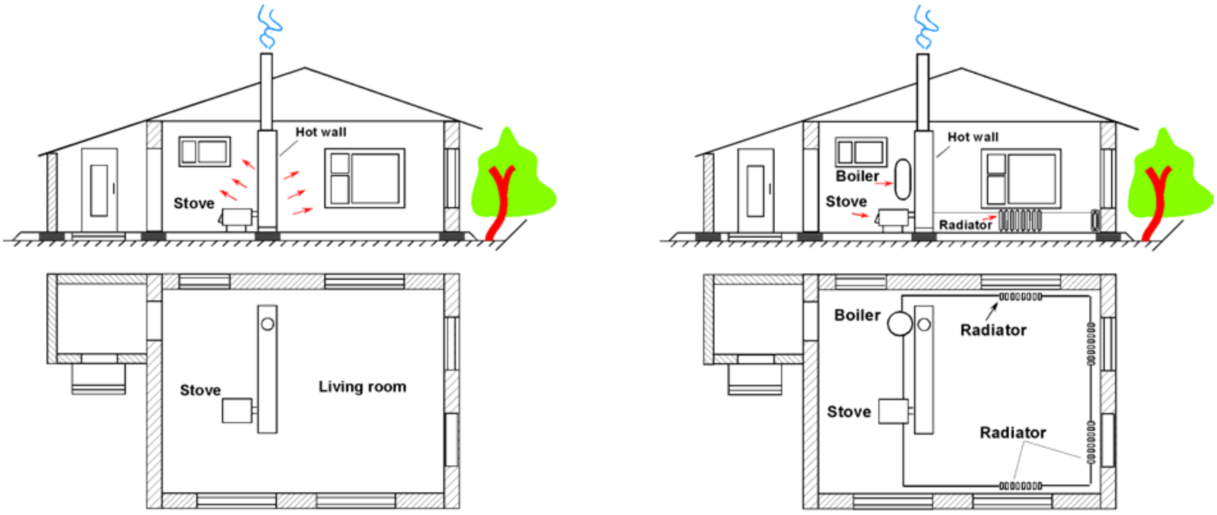


FIGURE 12: Individual house heating scheme

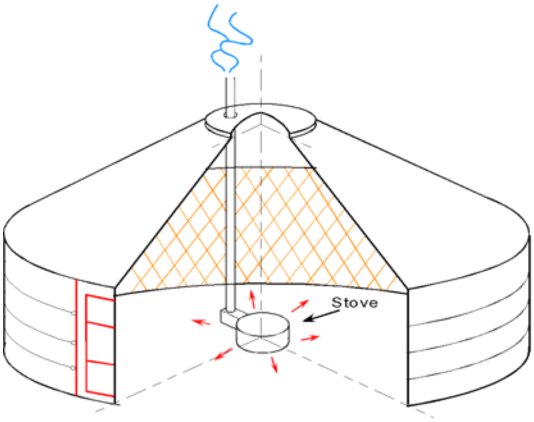


FIGURE 13: “Ger” heating

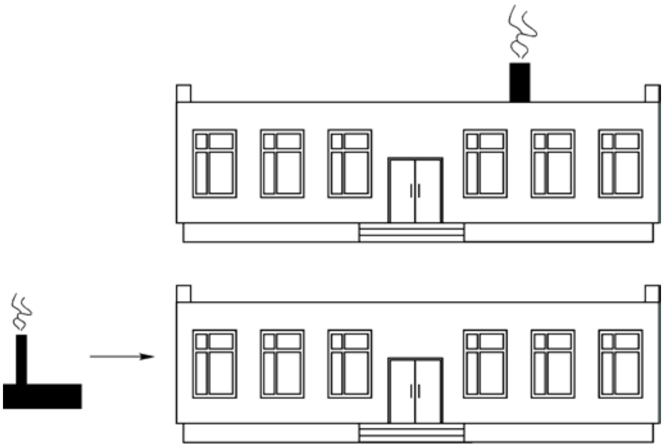


FIGURE 14: Public building heating system

developments in civil construction in Mongolia. Wall thickness of buildings has been reduced to 38 cm, and special insulating wall materials used. Independent private houses are not common in Mongolia. In these, walls are commonly built of wood and the sides are covered by sand and cement mortar. Such wall could really be made of a number of materials in a number of layers and is called a composite wall. Generally, the walls are constructed of 15-20 cm of wood with a layer of mixed sand and cement on both sides of the wood.

4.4 Climate in Mongolia

Landlocked, in the centre of the world’s largest landmass, with a size of 1,566,000 km^2, Mongolia’s climate has great extremes. Temperatures in the Gobi can reach 40°C in summer and -40°C in winter. Temperatures even fall to -50°C in Hubsugul aimag (province) in the north. In summer, the central and southwest regions have average temperatures of 27°C, while in the rest of the country, temperatures stay between 22 and 25°C in the daytime.

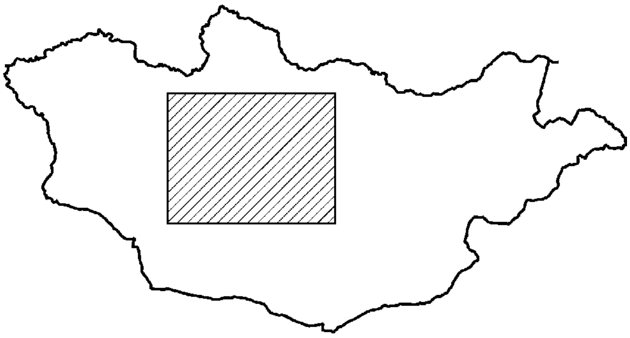


FIGURE 15: The Khangai region of Mongolia

One target region for geothermal development is the Khangai mountain region, where most geothermal areas are found, shown in Figure 14 and the ambient temperature variation is illustrated in Figure 15. These are calculated by using meteorological temperature data from Arkhangai, Uvurkhangai and Bayankhongor, for 45 soums in the Khangai mountain region (Meteorological Institute of Mongolia, 1990a, 1990b, 1990c).

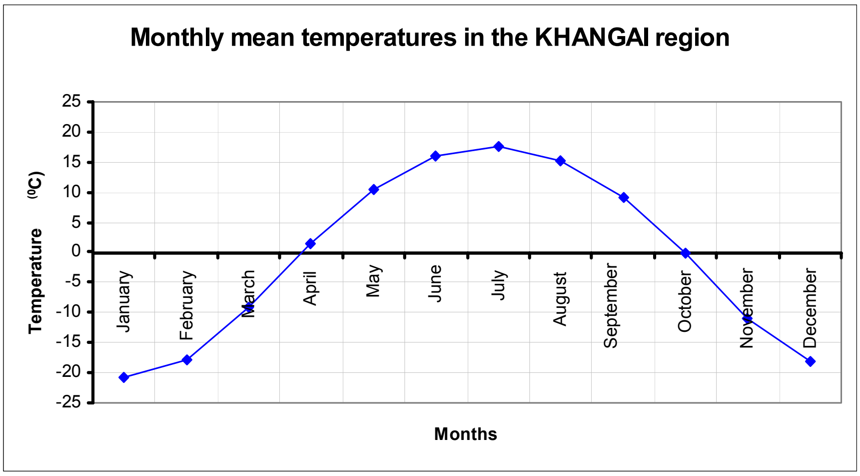


FIGURE 16: The ambient temperature variation for the Khangai region of Mongolia

Average wind speed in the Khangai area is 3-5m/sec. In summer temperatures stay around 20˚C, and as low as 11-16˚C in the daytime in the Altai and Khentii Mountains and Huvsgul Lake. In the rest of the area, temperatures will be around 15-20˚C. Forecasts warn of possible floods, especially in rivers around Huvsgul Lake in the Altai Mountain area where the water level may suddenly rise by 1-2 m.

Global warming has its effects in Mongolia. Experts say that the average annual temperature has risen by 1-2˚C, making winters milder and summers hotter. With less rain, the ground dries out, losing its water absorbing capacity which subsequently leads to an increased danger of floods. As an example losses of life were recorded in a sudden flood after 40 minutes of heavy rain in the capital city in June 2001. Dozens of "gers" were taken away by the mud mass.

4.5 Current geothermal usage in Mongolia

Today in Mongolia, some hot springs in the Khangai area are used to a small extent for house heating, greenhouse heating and space heating. In the Shargaljuut village of Bayankhongor aimag (Figure 1, hot spring 16) house heating is by using geothermal hot springs (T=92˚C, Q=25l/s) since 1960. It is one of the best examples of geothermal energy use for heating in Mongolia. A schematic of another example of current use of a geothermal hot spring is illustrated in Figure 16. This hot spring, in Tsenkher of Arkhangai aimag (Figure 1, hot spring 21), is cascaded for greenhouse, house heating and bathing.

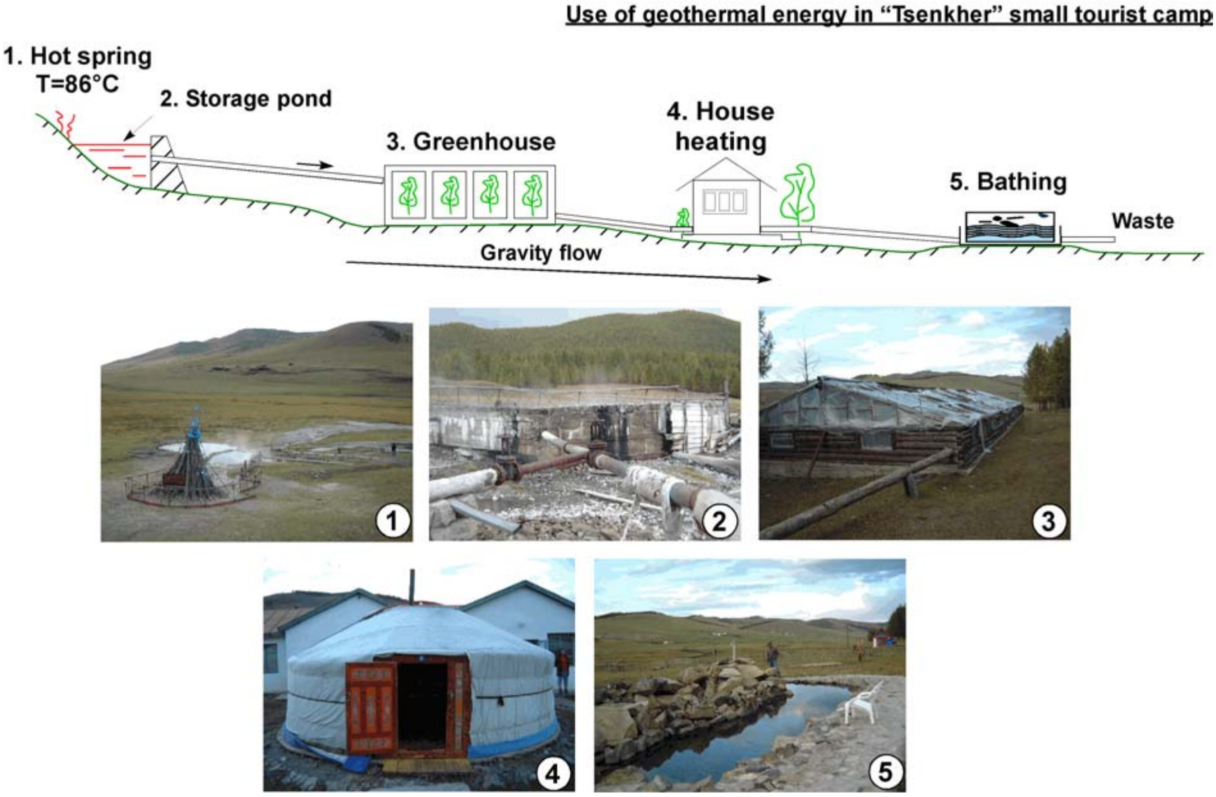


FIGURE 17: Examples of geothermal hot spring use in Mongolia from the Tsenkher geothermal field

4.6 Possibilities of using geothermal energy in Mongolia and requirements

The Mongolian Khangai area is rich in geothermal resources. New technology opens possibilities for more extensive use of geothermal energy in Mongolia. In Mongolian rural areas, small users (Soum centre, "bag" centre, rest houses and tourist camp) are located far from each other. All of them are without electricity and heat. Oil and coal costs and their transportation costs are very high. And these are not possible to connect to general electric grid lines. The development of clean, reliable, inexpensive energy such as geothermal energy is, thus, of major importance.

Most people from the soum centres go up to the mountains in summer time to build up their herds. In winter time, they gather in the soum centres. Spring, summer and autumn seasons are very active periods in Mongolian rural areas. At that time, nomads gather all kind of animal wool, cashmere, dairy products and agricultural products. Many soum centres are placed along large roads, some with big markets. Electric power generation was considered marginal in the rural areas. Figure 17 shows a possible design for a cascaded geothermal energy system at a winter centre. A pre-feasibility study shows the possibility of using binary power plants where geothermal resources are available. However, Mongolia first requires drilling wells and also downhole pumps (DHP) will be required to get enough water to be able to install binary power plants. This is very important and will be an incentive for developing direct use of geothermal energy.

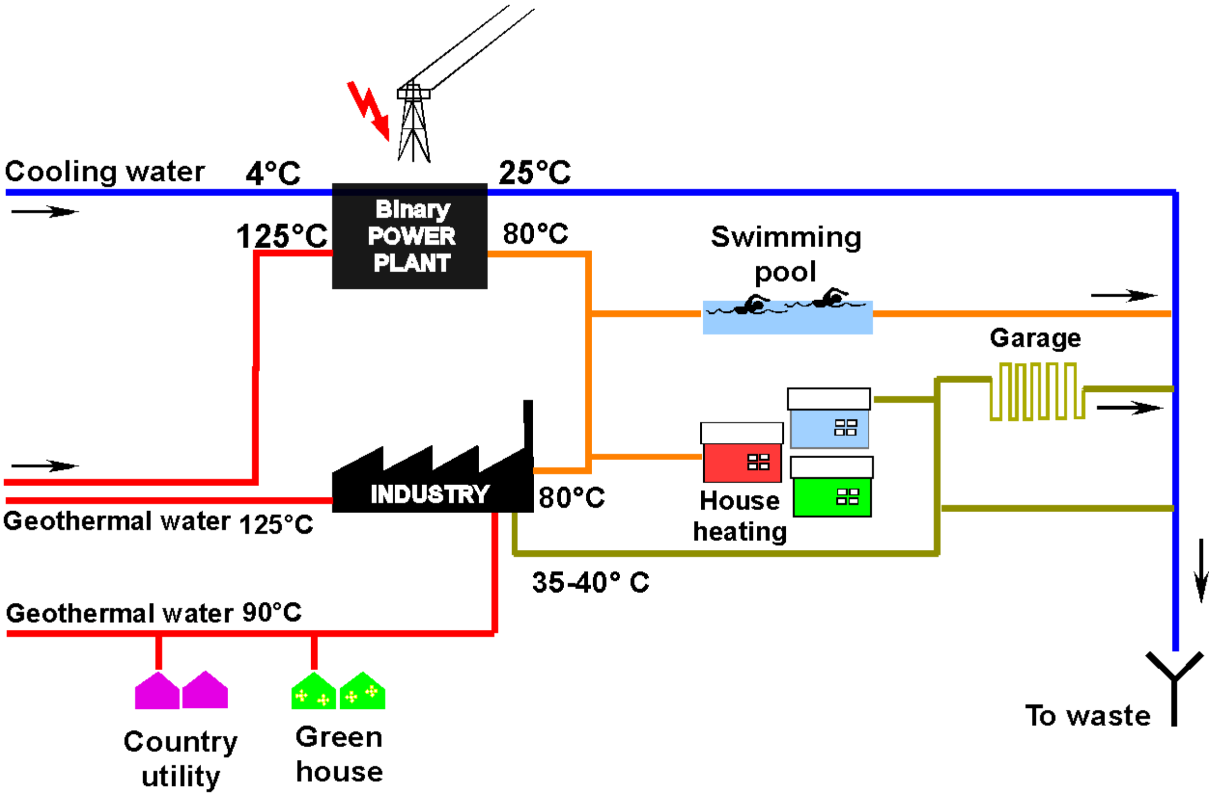


FIGURE 18: Possible "winter centre" design (cascaded use of geothermal energy)

5. POTENTIAL USE OF GEOTHERMAL ENERGY

5.1 Effect of temperature on use sector

The Lindal diagram (Gudmundsson et al., 1985), named after Baldur Lindal, the Icelandic engineer who first proposed it, indicates the temperature range suitable for various direct use activities (Figure 18). Typically, the agricultural and aquacultural uses require the lowest temperatures, with values between 25 and 90°C. The amount and types of chemicals, such as arsenic and boron, on plants and animals in some areas are a problem with direct use, thus, heat exchangers are often necessary. Space heating requires temperatures in the range of 50-100°C, with 40°C useful in some marginal cases, but heat pumps can extend the range down to 4°C (Lund, 1996).

Cooling and industrial processing normally requires temperatures above 100°C. In Iceland, the leading use of geothermal energy is for district heating. More than 85% of the population enjoys geothermal heat in their homes from 27 municipal district heating services and 200 private systems in rural areas. About 50% of the country's primary energy use is supplied by direct heat and electrical energy derived from geothermal resources (Ragnarsson, 2000).

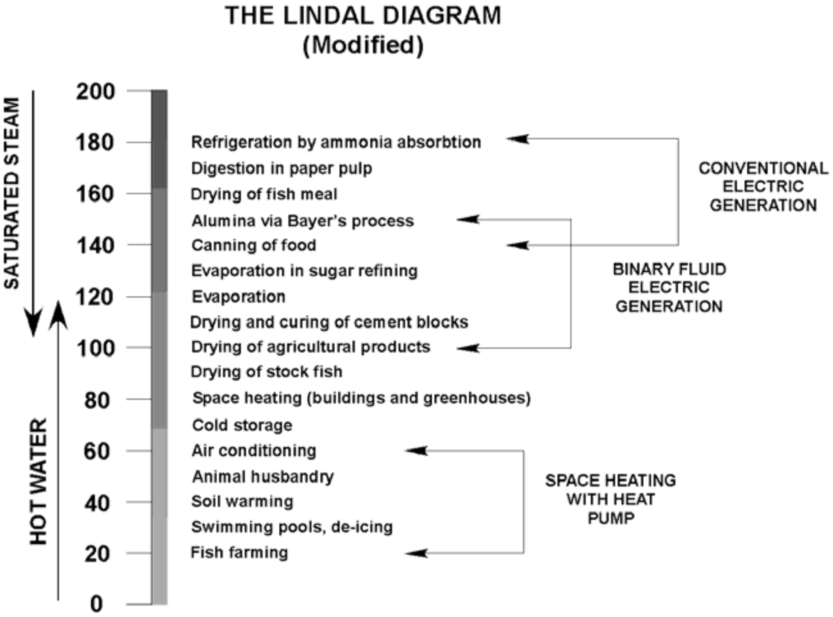


FIGURE 19: The Lindal diagram

5.2 Space conditioning

Space conditioning includes both heating and cooling. Space heating with geothermal energy is a practical application. Absorption space cooling with geothermal energy with absorption heat pumps has not been popular because of the high temperature requirements. Geothermal heat pumps (ground water and ground coupled) have become popular in the US, Canada, Germany and Switzerland and are used for both heating and cooling.

5.3 District heating

District heating originates from a central location, and supplies hot water or steam through a network of pipes to individual dwellings or a block of buildings. The heat is used for space heating, domestic water heating, and industrial process heat. District heating is widely used in the colder regions of the world using fossil fuels. In a few countries, district heating from geothermal sources can be found. A geothermal well field is then the primary source of heat; however depending on the temperature, the district heating may be a hybrid system, which would include fossil fuel and/or heat pumps, for peaking. In Mongolia, all soums and aimag centres are generally supplied heat from coal furnaces during the winter (from October to April). Their installed heating capacity is 0.8-3.0 MW for each soum since 1960. For Mongolia a possible hybrid system design for using geothermal energy and a coal furnace is shown in Figure 19. This design is similar to the Sudureyri heating system in Iceland, which uses an electric boiler, an oil boiler and geothermal springs/wells for its heating. The village's heat consumption and number of users (customers) comprise the same conditions as Mongolian soum centres.

5.4 Greenhouses

In Mongolia, only few geothermal hot springs are used for greenhouses. These include the Khuremt hot spring (Figure 1 hot spring no. 9), Teel (hot spring 19), Baga Shargaljuut (hot spring 15) and Tsenkher (hot spring 21), a total of four hot springs used for greenhouses. Exploitation of the Tsenkher field has been described before. The greenhouse exploitation and effectiveness are normal but most of them were founded 30 years ago and their technical equipment is now out-of-date. Increased production is possible by updating the houses. What is needed is a new greenhouse design suitable for the Mongolian climate, based on local possibilities and foreign experience. Exploitation of geothermal heat in greenhouse heating can considerably reduce operation costs, in some cases 35% of the production costs (vegetables, flowers, house plants and tree seedlings).

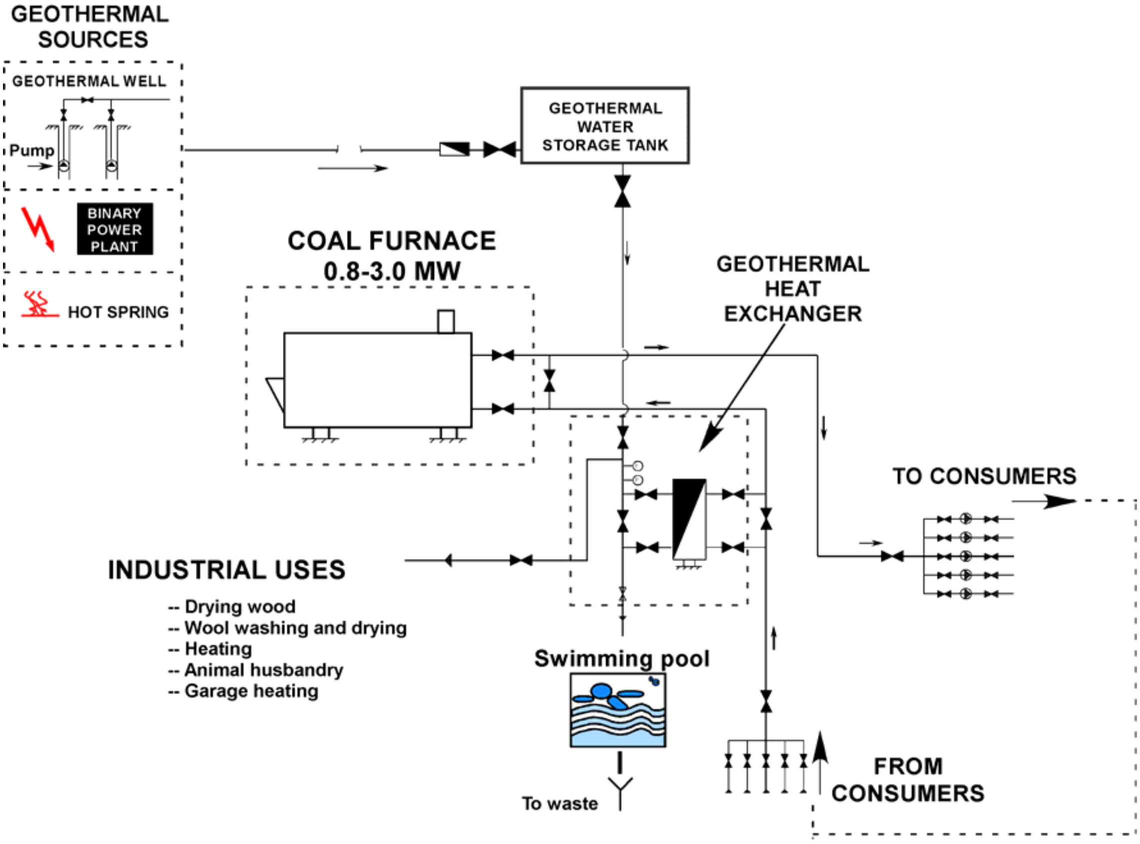


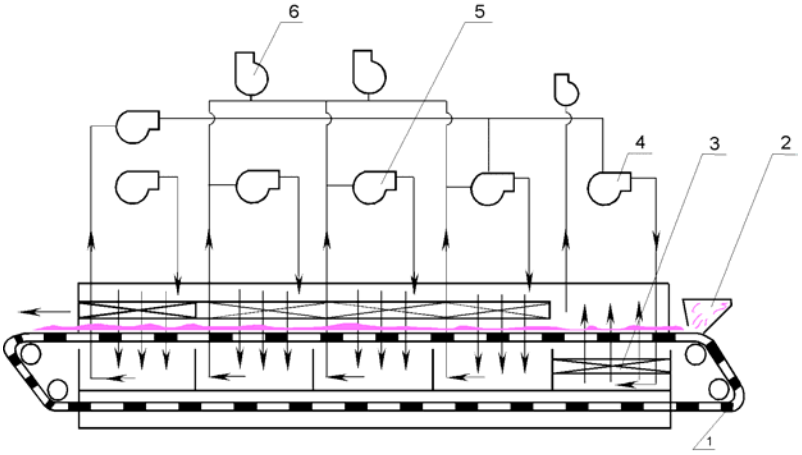
FIGURE 20: Possible hybrid heating system design for a Mongolian soum centre

5.5 Wool washing

Mongolia has the biggest resource of cashmere in the world. The biggest production is in the Bayankhongor aimag, where the main geothermal activity is also found. The estimated thermal potential of this area is 7.5 MWt (heat >35˚C, see Table 3). It is suitable to develop geothermal energy there to support the agriculture. The grease and dirt in raw wool has to be washed with hot water at 50˚C . By adopting a heat exchanger and mix some cold water to the geothermal water so that hot water of 50˚C can be obtained directly or indirectly, a lot of heat energy is saved.

5.6 Drying wool

Although the Lindal diagram shows many potential industrial and process applications of geothermal energy, the world's uses are relatively few. Mongolian main gross domestic product comes from animal husbandry. There are very important possibilities in using geothermal energy for wool and cashmere washing and drying. The drying equipment can consist of a geothermal net conveyor belt drier (Figure 20).



1 - Net conveyor, 2 - Wool feeder, 3 - Heat exchanger, 4 - Air blower, 5 - Circulation blower, 6 - Moisture exhaust blower

FIGURE 21: Wool drying process (redrawn after Xing and Wu, 2000)

The known parameters in the heat calculations for such conveyor belt driers as shown in Figure 20 are the following:

Product capacity of dry wool, Wp = 280 kg/h;
Moisture content by wet basis of moist wool , ω_1 = 40%;
Moisture content by wet basis of dry wool, ω_2 = 15%;
Specific heat of dry wool, Cs = 1.26 kJ/kg ˚C;
Environmental temperature, t_0 = 15˚C;
Absolute air humidity, d_0 = 0.0078 kgH_2O/kg dry air;
Corresponding air enthalpy, i_0 = 34.72 kJ/kg;
Drying temperature, t_1 = 70˚C in the fifth unit, 90˚C in the others.

Tong (1996) proposed the heat calculation equations, integrating geothermal parameters. The main calculations are as follows:

Dehydration quantity is expressed as W (kg/h), so that:

$$W = Wp(\varpi_1 - \varpi_2) / (1 - \varpi_1) \tag{2}$$

The quantity of heat for evaporating water is expressed as Q_1 (kJ/h), so that:

$$Q_1 = W(2491 + 1.884t_2 - 4.186\theta_1) \tag{3}$$

where t_2 = Exhaust air temperature (˚C); and
θ_1 = Initial temperature of moist wool (˚C).

The quantity of heat for heating wool is expressed as Q_2 (kJ/h), so that

$$Q_2 = Wp(Cs(1 - \varpi_2) + 4.186\varpi_2) \times (\theta_2 - \theta_1) \tag{4}$$

where θ_2 = Final temperature of dry wool (˚C).

Heat losses of the drier are expressed as Q_3 (kJ/h), so that:

$$Q_3 = (0.10 \approx 0.15) \times (Q_1 + Q_2) \tag{5}$$

Consumption of the drying medium is expressed as L (kg/h), so that:

$$L = (Q_1 + Q_2 + Q_3) / (i_1 - i'_2) \tag{6}$$

where i_1 = Enthalpy of heated air at temperature 1 and absolute humidity d_0 ;
i'_2 = Enthalpy of heated air at temperature t_2 and absolute humidity d_0.

The total quantity of heat for drying wool is expressed as Q (kJ/h), so that:

$$Q = L(i_1 - i_0) \tag{7}$$

Absolute humidity of the exhaust air is expressed as d_2 (kg H_2O / kg dry air), so that:

$$d_2 = d_0 + W / L \tag{8}$$

The quantity of heat supplied by the heat exchanger is expressed as Q_t (kJ/h), so that:

$$Q_t = Q / \eta \tag{9}$$

where η = Heat efficiency of the heat exchanger, usually 0.96~0.98.

The quantity of geothermal water flow is then expressed as G (kg/h), so that:

$$G = Q_t / [1.486(t_{w1} - t_{w2})] \tag{10}$$

where t_{w1} and t_{w2} are the temperatures of the geothermal water flowing in and out of the heat exchanger, respectively.

If we use geothermal water for washing and drying wool and cashmere, conventional energy can be saved. The energy savings can be about 7×10^9 kJ/yr and a saving of standard coal of 380 tons/yr.

5.7 Power generation - the present power system in Mongolia

Current general Mongolian rural electrification is illustrated in Figure 21. Japanese consultants carried out a brief investigation of the Shargaljuut area and reported in 1994 that this area has a potential for small scale geothermal power generation. Further investigations will be required to verify the extent of the resource but if sufficient fluids are encountered with a temperature of 120°C or higher, the installation of a small binary-cycle geothermal power plant could be feasible. Hot water discharged by the power plant would be available for district heating and other down stream uses, thus resulting in high overall plant efficiency. Two or three shallow wells would be required to produce fluids at a rate of 60 tons/h (with power plant inlet temperature 120°C) to generate 300 kW of electricity from a binary plant which typically has a 85-90% availability factor. Electric generating costs are expected to be about 10-15 c/kWh, competitive with existing diesel based generation. It is estimated that the present population of the Shargaljuut area totals 2500 people and sufficient demand exists in the area for the addition of a 300kW binary cycle geothermal power plant (Worley International, 1995). Water requirements for a binary cycle power generation diagram are illustrated in Figure 22. According to this diagram if the power plant inlet temperature is 120°C, the needed water is 22 l/s to generate 300 kW (see also Dorj (2001)on the Kalina power generation).

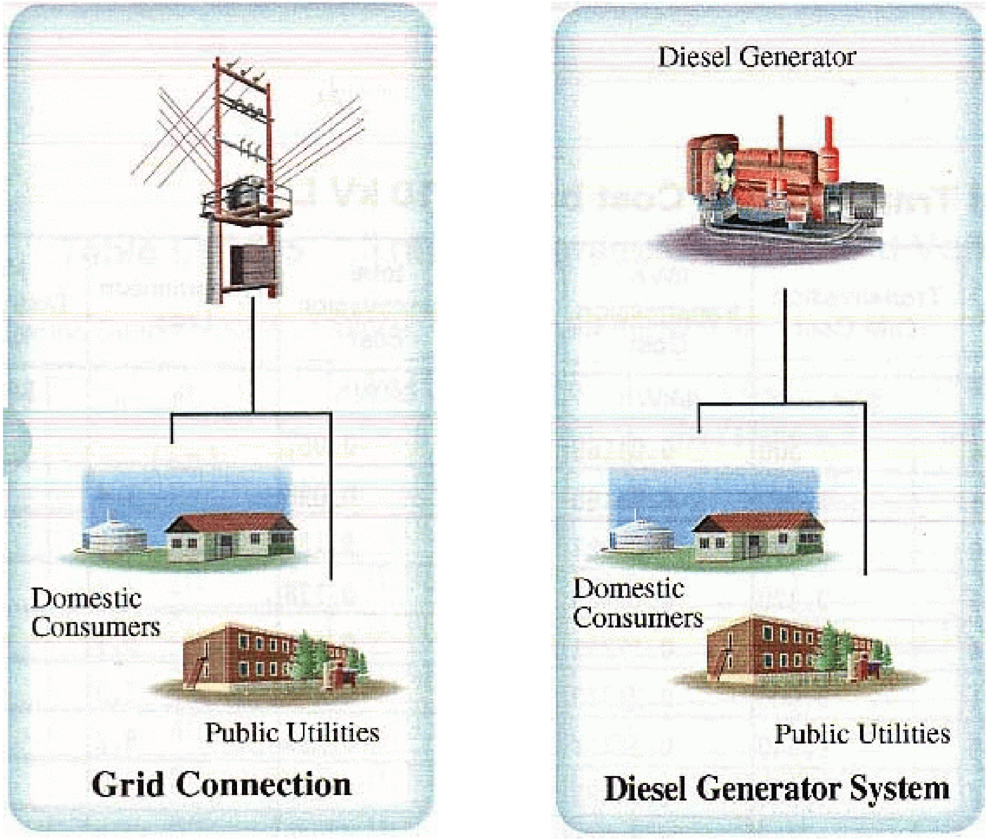


FIGURE 21: Current electric power system in Mongolia (JICA, 1999)

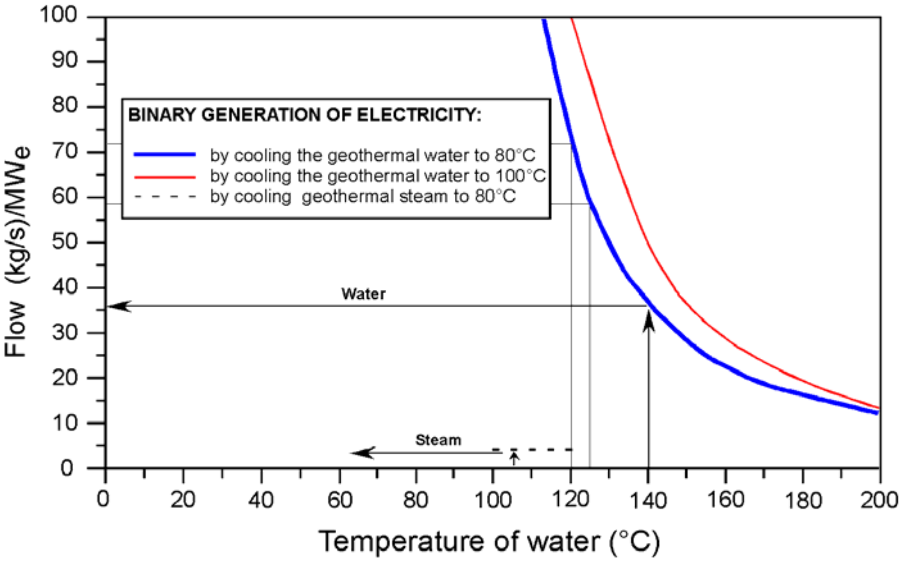


FIGURE 23: Water flow requirements for binary generation of electricity (Thórhallsson, 2001)

6. DIRECT USE DEVELOPMENT PROGRAMME AND FUTURE PROSPECTIVE

Geothermal energy is a new energy sector in Mongolia. Therefore, plans to develop geothermal energy and how to implement projects have to be made. The use of low- (less than 90˚C) and moderate-temperature (90-150˚C) geothermal resources for direct use applications has increased significantly in the world since the late 1970s. A geothermal direct use project utilizes a natural resource, a flow of geothermal fluid at elevated temperatures, which is capable of providing heat to buildings, greenhouses, aquacultures, and/or industrial processes. First of all, plans should consider an immediate general study on the resources in Mongolian available for geothermal development. Geothermal utilization requires a unique blending of skills to locate and assess the resource, and to concurrently match the varied needs of the user in order to develop successful projects. Each resource development project is unique. A flow chart (Figure 23) serves as a guideline of logical steps to take in the development of a project. The development of a project should be approached in phases so as to minimize risk and costs. A relationship diagram between expenditure and risk prior to geothermal development is illustrated in Figure 24. In this diagram it is shown that high risks exist in the first reconnaissance of geothermal resources.

For the direct use developmental diagram, we first need to fulfill the following requirements in Mongolia:

1. Incorporate geological data from geological surveys, geophysical databases and hydrogeological study material. Select a site which has good future prospects and where it is possible to develop study methods with foreign experts.

2. Conduct geophysical studies in selected areas and get a pre-evaluation of their geothermal potential.

3. Make long term plans for supplying heat to Bayankhangor, Uvurkhangai, and Arkhangai aimags, as these aimags currently use finite fossil fuel resources which are high in cost for transportation and mining.

4. At the same time, continue geothermal studies for the bigger cities Ulaanbaatar, Erdenet, Darkhan for possible use of geothermal energy from wells with downhole pumps.

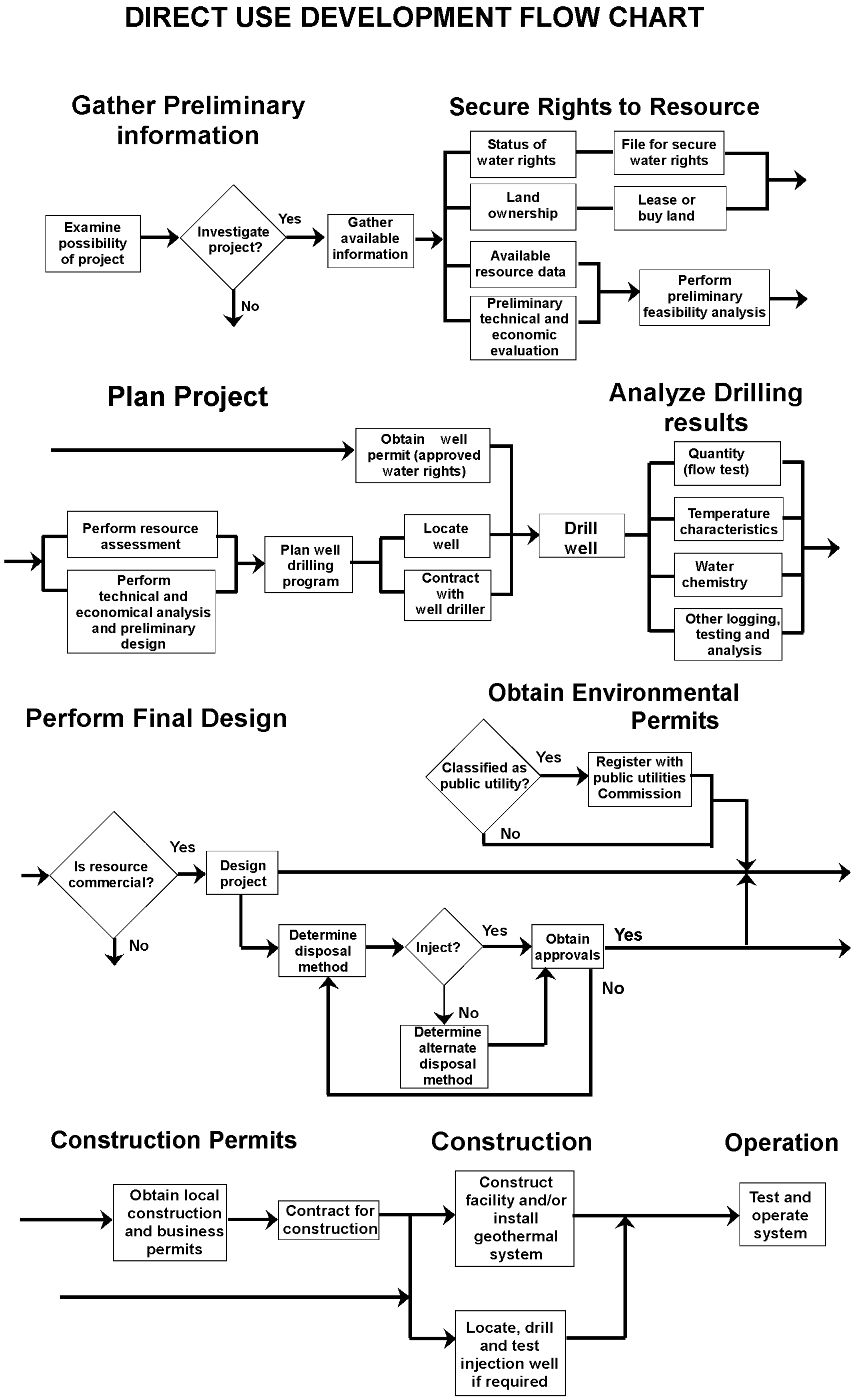


FIGURE 24: Direct use development chart (based on Lienau and Lunis, 1989)

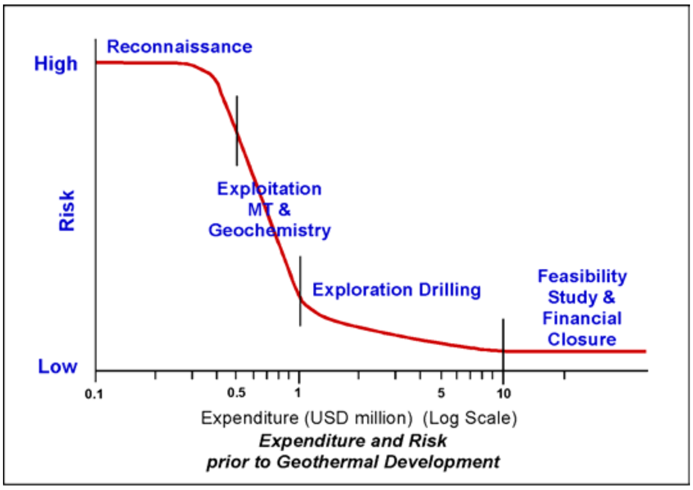


FIGURE 25: Expenditure and risk prior to geothermal development (Legmann, 2001)

7. CONCLUSIONS

The possible utilization of geothermal energy in Mongolia has been studied from the technical point of view and has been found to have a future. There is a need to train specialists for the exploitation of geothermal energy and to incorporate geological data from geological surveys, geophysical databases and hydrogeological study material, into a geothermal database for site selection surveys.

The hot springs can be used for various purposes, like heating and greenhouse exploitation but existing schemes need to be modernized . A very suitable first step might be to develop geothermal direct use in animal husbandry, such as wool/cashmere washing or drying and in milk farming etc. The natural cumulative flow of springs has only 18MWt of usable heat (>35˚C), but with drilling of production wells this could probably be increased considerably. Some places are though relatively large, for example the Bayankhongor area with 7.5 MWt, the Arkhangai area with 4.0 MWt, and the Uvurkhangai area with 3.2 MWt. These offer good possibilities to develop tourism, greenhouses, agriculture and animal husbandry.

Most of the hot springs are located far from soum centres. To bring geothermal water to soum centres would be relatively expensive for piping, and long distance piping is not very suitable for the extreme climate of Mongolia. Technical and economical evaluations are required due to these long distances and limited market in rural areas where most of the geothermal activity is. Therefore, it is advisable to study the possibilities of drilling near the soum centres. This is very important and, if successful, is an incentive for developing direct use of geothermal energy.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the Government of Iceland and the United Nations University, Geothermal Training Programme for the opportunity to broaden my knowledge in the field of geothermal energy. I sincerely thank Mr. Lúdvík S. Georgsson for selecting me to attend the 2001 six month training course and for all his help during the course. Also, I would like to thank Dr. Ingvar Birgir Friedleifsson, and Ms. Gudrún Bjarnadóttir for all their kindness and wonderful care. I would like to specially thank Mr. Sverrir Thórhallsson who assisted me in planning and designing my project, supervised me, shared with me his experiences and showed me around Iceland to see actual uses of geothermal energy. Also, my deepest thanks to my colleagues of Mongolian Renewable Energy Corporation for allowing this training and their help in providing data for my report.

REFERENCES

Arnórsson, S., 1991: Geochemistry and geothermal resources in Iceland. In: D´Amore, F. (co-ordinator), *Applications of geochemistry in geothermal reservoir development.* UNITAR/UNDP publication, Rome, 145-196.

Bjarnason, J.O., 1994: *The speciation program WATCH, version 2.1.* Orkustofnun, Reykjavík, 7 pp.

Dorj, P., 2001: Design of small geothermal heating systems and power generators for rural consumers in Mongolia. Report 3 in *Geothermal Training in Iceland 2001.* UNU G.T.P., Iceland, 27-57.

Dorofeeva., R.P., 1992: Geothermal regime of east Siberia and Mongolia. *Papers presented at the International conference on Industrial uses of geothermal energy, Reykjavík, Iceland*, 9 pp.

Fridleifsson, I.B., 2001: Geothermal energy for the benefit of the people. *Renewable and Sustainable Energy Reviews, 5,* 299-312.

Geodesy and Cartographical Institute, 1980: *Atlas of Mongolia*. Geodesy and Cartographical Institute, Ulaanbaatar, Mongolia.

Geodesy and Cartographical Institute, 2000: *Map of Mongolia, scale 1:2.500.000.* Geodesy and Cartographical Institute, Ulaanbaatar, Mongolia.

Giggenbach, W.F., 1988: Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. *Geochim. Cosmochim. Acta, 52*, 2749-2765.

Giggenbach, W.F., 1991: Chemical techniques in geothermal exploration. In: D'Amore, F. (coordinator), *Application of geochemistry in geothermal reservoir development*. UNITAR/UNDP publication, Rome, 119-142.

Gudmundsson, J.S., Freeston, D.H., and Lienau, P.J., 1985: The Lindal diagram. *Geoth. Res. Council, Transactions, 9,* 15-19.

JICA, 1999: *Master plan for supplying renewable energy in Mongolian rural areas*. Nippon Koey Co., Japan, interim report.

Legmann, H., 2001: *Lectures on geothermal engineering at Ormat.* UNU G.T.P., Iceland, unpublished lecture notes.

Lienau, P.J., and Lunis, B.C. (eds.), 1989: *Geothermal direct use engineering and design guidebook.* Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, Or., 401 pp.

Lund, J.W., 1996: *Lectures on direct utilization of geothermal energy.* UNU G.T.P., Iceland, report 1, 123 pp.

Lund, J.W., and Freeston, D.H., 2001: Worldwide direct uses of geothermal energy. *Geothermics, 30,* 1-27.

Meteorological Institute of Mongolia, 1990a: *Meteorological compilation of Bayankhongor aimag.* Meteorological Institute of Mongolia, Ulaanbaatar, Mongolia.

Meteorological Institute of Mongolia, 1990b: *Meteorological compilation of Arkhangai aimag.* Metrological Institute of Mongolia, Ulaanbaatar, Mongolia.

Meteorological Institute of Mongolia, 1990c: *Meteorological compilation of Uvurkhangai aimag.* Metrological Institute of Mongolia, Ulaanbaatar, Mongolia.

Ministry of Agriculture and Industry of Mongolia., 1999*: Geotherm, sub-programme of the Mineral resource programme, Mongolia.* Ministry of Agriculture and Industry of Mongolia, Ulaanbaatar.

Mongolian Statistics Centre, 2001: *Statistics of Mongolia, 2000 census.* Mongolian Statistics Centre, Ulaanbaatar, Internet webpage, http://statis.gov.mn/index_m.asp .

Ragnarsson, Á., 2000: Geothermal development in Iceland 1995-1999. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohuku, Japan,* 363-375.

Thórhallsson, S., 2001*: Geothermal Engineering*. UNU G.T.P., Iceland, unpublished lectures.

Tong J., 1996: Fluidized drying technique and equipment. *China Construction Press, Beijing*, 21-25.

University of Texas, 2001: *Map of Mongolia*. University of Texas, Austin, Internet website, http://www.lib.utexas.edu/maps/

Worley International, 1995: *Power system master plan interim report.* Asian development bank and Government of Mongolia, project report TA No. 2095-MON, 423 pp.

Xing B., and Wu Y., 2000: Drying wool and other direct uses of geothermal energy in Hebei, China. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 3589-3592.

Zorin, Y.A., Novoselova, M.R., Turtanov, E.Kh., and Kozhevnikov, V.M., 1990: Structure of the lithosphere of the Mongolian-Siberian mountainous province*. J. Geodyn., 11,* 327-342.

APPENDIX I: Chemical data (from Chemical Institute of Mongolia)

No.	Name of field	pH/Eh	T (˚C)	Unit	Kation								Summary kation
					Fe^{2+}	Fe^{3+}	NH_4^+	K^+	Na^+	Ca^{2+}	Mg^{2+}	Mn^{2+}	
1	**Shargaljuut 1 of Bayankhongor**	9.25/-110	88	mg/l	1	0.5	1	2.38	76.9	3.21	0.49	1	86.4
				mg/eq	0.03	0.02	0.05	0.06	3.34	0.16	0.04	0.03	3.73
				equ %	0.8	0.5	1.34	1.6	8.88	4.29	1.06	0.8	
2	**Shargaljuut 2 of Bayankhongor**	9.20/-100	76	mg/l	0.4	0.36	1	2.5	95.1	6.1	3.5	0.25	109
				mg/eq	0.01	0.02	0.05	0.06	4.13	0.3	0.28	0.01	4.86
				equ %	0.2	0.4	1.02	1.23	85	6.17	5.76	0.2	
3	**Tsenkher of Arhangai**	9.40/-112	84.3	mg/l	0.1	0.1	0.1	2.92	84.3	2.2	0.94	0.75	90.92
				mg/eq			0.01	0.07	3.66	0.11	0.04	0.02	3.89
				equ %			0.25	1.8	94.1	2.83	1.03		
4	**Bor tal of Arkhangai**	9.7/125	49.5	mg/l			0.7	108.8		3.2	-		113.62
				mg/eq			0.04	4.35		0.16	-		436
				equ %			0.86	93.95		3.45	-		

No.	Name of field	Unit	Anion											Summary anion
			HCO_3^-	CO_3^{2-}	Cl^-	F^-	Br^-	I^-	SO_4^{2-}	HS^-	$HSiO_3^-$	NO_2^-	NO_3^{2-}	
1	**Shargaljuut 1 of Bayankhongor**	mg/l	76.3	4.2	5.67	11.3	0.2	0	50.6	13	16.8	0.01	2	180
		mg/eq	1.25	0.14	0.16	0.62			1.05	0.39	0.21			3.82
		equ %	32.7	3.66	4.19	16.2			27.5	10.2	5.49			
2	**Shargaljuut 2 of Bayankhongor**	mg/l	61.1	36	24.8	7.4	0.2	0	72.5	10.1	17.9	0.01	2	232
		mg/eq	1	1.2	0.69	0.41			1.51	0.3	0.23			5.34
		equ %	18.7	22.5	12.9	7.67			28.3	5.62	4.3			
3	**Tsenkher of Arhangai**	mg/l	68.34	7.2	17.7	25	0.2	0	45.3	10.47	17.73	0.01	2	194
		mg/eq	1.12	0.24	0.5	1.32			0.94	0.32	0.19			4.12
		equ %	27.2	5.83	12.1	32			22.8					
4	**Bor tal of Arkhangai**	mg/l	24.4	60	24.1	4.8			54.3		11.7	ne/obn		179.3
		mg/eq	0.4	2	0.7	0.25			1.13		0.15			4.63
		equ %	8.64	43.19	15.12	5.39			24.4		3.24			

No.	Name of field	Mineralization									Summary mineral.
		HBO_2^-	H_4SiO_4	Sr	Li	Pb	Cs	Okis	CO_2	H_2S	
1	**Shargaljuut 1 of Bayankhongor**	0.8	147	0.08	0.3	0.06	0.07	15.6	0	13.1	415
2	**Shargaljuut 2 of Bayankhongor**	0.8	105	0.08	0.3	0.06	0.07	15.6	0	10.2	448
3	**Tsenkher of Arhangai**	4.13	183	0.08	0.22	0.05	0.07	7.84	0	10.6	438
4	**Bor tal of Arkhangai**	2.08	212.8								505.72

APPENDIX II: Results of WATCH calculations on the chemical data

```
ICELANDIC WATER CHEMISTRY GROUP                                      Program WATCH, version 2.1 / 1994

BOR TAL OF ARKHANGAI AIMAG

     Water sample (mg/kg)          Steam sample
     pH/deg.C          9.70/ 23.0  Gas (volume %)           Reference temperature deg.C : 117.1  (Chalced.)
     CO2              61.60        CO2                 .00
     H2S                .00        H2S                 .00  Sampling pressure  bar abs. :   1.0
     NH3                .66        NH3                 .00  Discharge enthalpy    kJ/kg : 491. (Calc.)
     B                  .50        H2                  .00  Discharge             kg/s :    .0
     SiO2            175.30        O2                  .00  Steam fraction at collection:    .0000
     Na              108.75        CH4                 .00
     K                  .00        N2                  .00  Measured temperature   deg.C : 49.5
     Mg                .000
     Ca                3.20        Liters gas per kg
     F                4.800        condensate/deg.C   .00/  .0   Condensate (mg/kg)
     Cl               24.10                                      pH/deg.C           .00/  .0
     SO4              54.30        Total steam (mg/kg)           CO2                .00
     Al                .000        CO2                 .00       H2S                .00
     Fe                .000        H2S                 .00       NH3                .00
     TDS                .00        NH3                 .00       Na                 .00

     Ionic strength =   .00579
     Ionic balance :   Cations (mol.eq.) =  .00480759 Anions (mol.eq.) =  .00491674  Difference (%) = -2.24

     Chemical geothermometers (degrees C)
     Quartz      143.3   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
     Chalcedony  117.1   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
     K is zero. Cannot compute Na-K geothermometer temperature.

     Log solubility products of minerals in deep water at 49.5˚C
                   Theor.    Calc.                   Theor.    Calc.                      Theor.    Calc.
     Adularia      -16.602   99.999     Albite, low   -15.919   99.999     Analcime      -12.781   99.999
     Anhydrite      -5.855   -7.884     Calcite        -9.744   -8.984     Chalcedony     -2.711   -2.733
     Mg-Chlorite   -79.978   99.999     Fluorite      -10.526  -11.736     Goethite       -4.023   99.999
     Laumontite    -26.448   99.999     Microcline    -17.863   99.999     Magnetite     -28.391   99.999
     Ca-Montmor.   -81.836   99.999     K-Montmor.    -39.610   99.999     Mg-Montmor.   -83.061   99.999
     Na-Montmor.   -39.675   99.999     Muscovite     -20.239   99.999     Prehnite      -36.298   99.999
     Pyrrhotite    -91.251   99.999     Pyrite       -134.668   99.999     Quartz         -2.946   -2.733
     Wairakite     -24.330   99.999     Wollastonite   10.322    9.947     Zoisite       -35.568   99.999
     Epidote       -42.231   99.999     Marcasite    -112.244   99.999     Talc           14.560   99.999
     Chrysotile     22.311   99.999     Sil. amorph.   -2.132   -2.733

TSENKHER OF ARKHANGAI PROVINCE

     Water sample (mg/kg)          Steam sample
     pH/deg.C          9.40/ 23.0  Gas (volume %)           Reference temperature deg.C :  108.7 (Chalced.)
     CO2              54.60        CO2                 .00
     H2S              10.60        H2S                 .00  Sampling pressure  bar abs. :    1.0
     NH3                .09        NH3                 .00  Discharge enthalpy    kJ/kg :   456.  (Calcul.)
     B                 1.00        H2                  .00  Discharge              kg/s :     .0
     SiO2            128.20        O2                  .00  Steam fraction at collection:  .0000
     Na               84.30        CH4                 .00
     K                 2.90        N2                  .00  Measured temperature  deg.C :   84.3
     Mg                .940
     Ca                2.20        Liters gas per kg
     F               25.000        condensate/deg.C   .00/  .0   Condensate (mg/kg)
     Cl               17.70                                      pH/deg.C           .00/  .0
     SO4              45.30        Total steam (mg/kg)           CO2                .00
     Al                .000        CO2                 .00       H2S                .00
     Fe                .200        H2S                 .00       NH3                .00
     TDS                .00        NH3                 .00       Na                 .00

     Ionic strength =   .00515
     Ionic balance :   Cations (mol.eq.) =  .00389031  Anions (mol.eq.) =  .00501023 Difference (%) =-25.17

        Chemical geothermometers (degrees C)
     Quartz      135.7   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
     Chalcedony  108.7   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
     Na/K        105.9   (Arnorsson et al., Geochim. Cosmochim. Acta, vol. 47, pp. 567-577, 1983)

     Log solubility products of minerals in deep water at 84.3˚C
                   Theor.    Calc.                   Theor.    Calc.                      Theor.    Calc.
     Adularia      -16.895   99.999     Albite, low   -16.186   99.999     Analcime      -12.977   99.999
     Anhydrite      -5.731   -8.037     Calcite        -9.591   -9.288     Chalcedony     -2.773   -2.792
     Mg-Chlorite   -80.105   99.999     Fluorite      -10.529  -10.378     Goethite       -4.348   -2.160
     Laumontite    -26.791   99.999     Microcline    -18.211   99.999     Magnetite     -29.039  -18.799
     Ca-Montmor.   -83.563   99.999     K-Montmor.    -40.559   99.999     Mg-Montmor.   -84.752   99.999
     Na-Montmor.   -40.598   99.999     Muscovite     -20.663   99.999     Prehnite      -36.513   99.999
     Pyrrhotite    -95.463  -69.327     Pyrite       -140.706  -93.277     Quartz         -3.021   -2.792
     Wairakite     -24.503   99.999     Wollastonite   10.563    9.398     Zoisite       -35.706   99.999
     Epidote       -42.902   99.999     Marcasite    -117.795  -93.277     Talc           15.063   24.868
     Chrysotile     22.952   30.451     Sil. amorph.   -2.173   -2.792
```

```
Aquifer liquid cooled to  50.0 øC
Ionic balance :   Cations (mol.eq.) =  .00388303  Anions (mol.eq.) =  .00500405 Difference (%) =-25.23
  Chemical geothermometers (degrees C)
Quartz      134.5   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
Chalcedony  107.4   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
Na/K        106.1   (Arnorsson et al., Geochim. Cosmochim. Acta, vol. 47, pp. 567-577, 1983)

Log solubility products of minerals in deep water
              Theor.    Calc.                    Theor.    Calc.                    Theor.    Calc.
Adularia      -19.664   99.999     Albite, low   -18.715   99.999     Analcime      -14.883   99.999
Anhydrite      -4.966   -7.935     Calcite        -8.720   -8.649     Chalcedony     -3.297   -2.801
Mg-Chlorite   -82.885   99.999     Fluorite      -10.737  -10.295     Goethite       -6.429   -4.003
Laumontite    -30.213   99.999     Microcline    -21.446   99.999     Magnetite     -33.553  -22.646
Ca-Montmor.  -101.365   99.999     K-Montmor.    -50.170   99.999     Mg-Montmor.  -102.214   99.999
Na-Montmor.   -49.974   99.999     Muscovite     -25.002   99.999     Prehnite      -39.270   99.999
Pyrrhotite   -125.035  -88.599     Pyrite       -185.595 -112.714     Quartz         -3.632   -2.801
Wairakite     -26.535   99.999     Wollastonite   12.603   10.695     Zoisite       -37.927   99.999
Epidote       -47.739   99.999     Marcasite    -158.572 -112.714     Talc           19.326   28.845
Chrysotile     28.483   34.447     Sil. amorph.   -2.521   -2.801
```

SHARGALJUUT 1 OF BAYANKHONGOR PROVINCE

```
Water sample (mg/kg)          Steam sample
pH/deg.C          9.25/ 23.0  Gas (volume %)            Reference temperat.  deg.C :  101.4 (Chalced.)
CO2             58.00         CO2                .00
H2S             13.10         H2S                .00    Sampling pressure bar abs. :    1.0
NH3               .94         NH3                .00    Discharge enthalpy   kJ/kg :  425.  (Calcul.)
B                 .20         H2                 .00    Discharge             kg/s :     .0
SiO2           105.00         O2                 .00    Steam fraction at collection:    .0000
Na              76.90         CH4                .00
K                2.38         N2                 .00    Measured temperature deg.C :   88.0
Mg               .490
Ca               3.21         Liters gas per kg
F              11.300         condensate/deg.C   .00/  .0   Condensate (mg/kg)
Cl               5.67                                       pH/deg.C           .00/  .0
SO4             50.60         Total steam (mg/kg)           CO2                .00
Al               .000         CO2                .00        H2S                .00
Fe              1.500         H2S                .00        NH3                .00
TDS               .00         NH3                .00        Na                 .00

Ionic strength =   .00453
Ionic balance :   Cations (mol.eq.) =  .00364325 Anions (mol.eq.) =  .00393408  Difference (%) = -7.68

Oxidation potential (volts) :     Eh H2S=  -.459   Eh CH4= 99.999   Eh H2= 99.999   Eh NH3= 99.999
Chemical geothermometers (degrees C)
Quartz      129.1   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
Chalcedony  101.4   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
Na/K         98.5   (Arnorsson et al., Geochim. Cosmochim. Acta, vol. 47, pp. 567-577, 1983)

Log solubility products of minerals in deep water
              Theor.    Calc.                    Theor.    Calc.                    Theor.    Calc.
Adularia      -17.169   99.999     Albite, low   -16.436   99.999     Analcime      -13.162   99.999
Anhydrite      -5.626   -7.780     Calcite        -9.462   -9.159     Chalcedony     -2.830   -2.844
Mg-Chlorite   -80.267   99.999     Fluorite      -10.536  -10.868     Goethite       -4.624   -1.545
Laumontite    -27.118   99.999     Microcline    -18.535   99.999     Magnetite     -29.598  -16.711
Ca-Montmor.   -85.230   99.999     K-Montmor.    -41.469   99.999     Mg-Montmor.   -86.386   99.999
Na-Montmor.   -41.485   99.999     Muscovite     -21.071   99.999     Prehnite      -36.734   99.999
Pyrrhotite    -99.123  -63.025     Pyrite       -146.014  -84.712     Quartz         -3.088   -2.844
Wairakite     -24.676   99.999     Wollastonite   10.782    9.316     Zoisite       -35.861   99.999
Epidote       -43.493   99.999     Marcasite    -122.662  -84.712     Talc           15.520   23.201
Chrysotile     23.536   28.890     Sil. amorph.   -2.211   -2.844

Aquifer liquid cooled to  50.0 øC
Ionic balance :   Cations (mol.eq.) =  .00362133 Anions (mol.eq.) =  .00391837 Difference (%) = -7.88

Chemical geothermometers (degrees C)
Quartz      128.3   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
Chalcedony  100.5   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
Na/K         98.8   (Arnorsson et al., Geochim. Cosmochim. Acta, vol. 47, pp. 567-577, 1983)

Log solubility products of minerals in deep water
              Theor.    Calc.                    Theor.    Calc.                    Theor.    Calc.
Adularia      -19.664   99.999     Albite, low   -18.715   99.999     Analcime      -14.883   99.999
Anhydrite      -4.966   -7.699     Calcite        -8.720   -8.591     Chalcedony     -3.297   -2.851
Mg-Chlorite   -82.885   99.999     Fluorite      -10.737  -10.801     Goethite       -6.429   -3.328
Laumontite    -30.213   99.999     Microcline    -21.446   99.999     Magnetite     -33.553  -20.636
Ca-Montmor.  -101.365   99.999     K-Montmor.    -50.170   99.999     Mg-Montmor.  -102.214   99.999
Na-Montmor.   -49.974   99.999     Muscovite     -25.002   99.999     Prehnite      -39.270   99.999
Pyrrhotite   -125.035  -81.296     Pyrite       -185.595 -103.139     Quartz         -3.632   -2.851
Wairakite     -26.535   99.999     Wollastonite   12.603   10.505     Zoisite       -37.927   99.999
Epidote       -47.739   99.999     Marcasite    -158.572 -103.139     Talc           19.326   26.859
Chrysotile     28.483   32.561     Sil. amorph.   -2.521   -2.851
```

SHARGALJUUT 2 OF BAYANKHONGOR PROVINCE

```
     Water sample (mg/kg)         Steam sample
     pH/deg.C          9.20/ 23.0  Gas (volume %)            Reference temperature deg.C : 85.5  (Chalced.)
     CO2              70.40       CO2                 .00
     H2S              10.20       H2S                 .00    Sampling pressure  bar abs. :  1.0
     NH3                .94       NH3                 .00    Discharge enthalpy   kJ/kg  :358.  (Calcul.)
     B                  .20       H2                  .00    Discharge              kg/s :   .0
     SiO2             79.50       O2                  .00    Steam fraction at collection:   .0000
     Na               95.10       CH4                 .00
     K                 2.50       N2                  .00    Measured temperature  deg.C : 76.0
     Mg               3.500
     Ca                6.10       Liters gas per kg
     F                7.400       condensate/deg.C   .00/  .0   Condensate (mg/kg)
     Cl               24.80                                     pH/deg.C           .00/  .0
     SO4              72.50       Total steam (mg/kg)           CO2                .00
     Al                .000       CO2                 .00       H2S                .00
     Fe                .760       H2S                 .00       NH3                .00
     TDS                .00       NH3                 .00       Na                 .00
     Ionic strength =   .00591
     Ionic balance :   Cations (mol.eq.) =  .00476190 Anions (mol.eq.) =  .00479914 Difference (%) =  -.78

     Chemical geothermometers (degrees C)
     Quartz      114.7   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
     Chalcedony   85.5   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
     Na/K         88.1   (Arnorsson et al., Geochim. Cosmochim. Acta, vol. 47, pp. 567-577, 1983)

     Log solubility products of minerals in deep water
                   Theor.    Calc.                     Theor.    Calc.                     Theor.    Calc.
     Adularia      -17.829   99.999     Albite, low   -17.039   99.999     Analcime      -13.613   99.999
     Anhydrite      -5.406   -7.378     Calcite        -9.200   -8.668     Chalcedony     -2.960   -2.967
     Mg-Chlorite   -80.790   99.999     Fluorite      -10.567  -10.969     Goethite       -5.204   -2.372
     Laumontite    -27.920   99.999     Microcline    -19.312   99.999     Magnetite     -30.807  -18.711
     Ca-Montmor.   -89.396   99.999     K-Montmor.    -43.729   99.999     Mg-Montmor.   -90.471   99.999
     Na-Montmor.   -43.690   99.999     Muscovite     -22.086   99.999     Prehnite      -37.327   99.999
     Pyrrhotite   -107.069  -71.873     Pyrite       -157.760  -93.945     Quartz         -3.243   -2.967
     Wairakite     -25.126   99.999     Wollastonite   11.289    9.715     Zoisite       -36.311   99.999
     Epidote       -44.784   99.999     Marcasite    -133.386  -93.945     Talc           16.581   26.013
     Chrysotile     24.897   31.946     Sil. amorph.   -2.297   -2.967

     Aquifer liquid cooled to  50.0 øC
     Ionic balance :   Cations (mol.eq.) =  .00472543 Anions (mol.eq.) =  .00476637 Difference (%) =  -.86

     Chemical geothermometers (degrees C)
     Quartz      114.6   (Fournier & Potter, GRC Bulletin, pp. 3-12, Nov. 1982)
     Chalcedony   85.4   (Fournier, Geothermics, vol. 5, pp. 41-50, 1977)
     Na/K         88.3   (Arnorsson et al., Geochim. Cosmochim. Acta, vol. 47, pp. 567-577, 1983)

     Log solubility products of minerals in deep water
                   Theor.    Calc.                     Theor.    Calc.                     Theor.    Calc.
     Adularia      -19.664   99.999     Albite, low   -18.715   99.999     Analcime      -14.883   99.999
     Anhydrite      -4.966   -7.315     Calcite        -8.720   -8.291     Chalcedony     -3.297   -2.967
     Mg-Chlorite   -82.885   99.999     Fluorite      -10.737  -10.923     Goethite       -6.429   -3.645
     Laumontite    -30.213   99.999     Microcline    -21.446   99.999     Magnetite     -33.553  -21.623
     Ca-Montmor.  -101.365   99.999     K-Montmor.    -50.170   99.999     Mg-Montmor.  -102.214   99.999
     Na-Montmor.   -49.974   99.999     Muscovite     -25.002   99.999     Prehnite      -39.270   99.999
     Pyrrhotite   -125.035  -84.765     Pyrite       -185.595 -106.715     Quartz         -3.632   -2.967
     Wairakite     -26.535   99.999     Wollastonite   12.603   10.581     Zoisite       -37.927   99.999
     Epidote       -47.739   99.999     Marcasite    -158.572 -106.715     Talc           19.326   28.684
     Chrysotile     28.483   34.618     Sil. amorph.   -2.521   -2.967
```