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PRELIMINARY GEOTHERMAL ENVIRONMENTAL IMPACT ASSESSMENT FOR THE TORFAJÖKULL AREA, CENTRAL S-ICELAND

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ABSTRACT

The Torfajökull high-temperature area is located within the Torfajökull central volcanic complex in South Iceland. This complex contains anomalously abundant acid volcanics. A large ring structure, probably related to a caldera subsidence, encircles the complex. The geothermal manifestations cover an area of about 140 km^2. They are almost entirely located within the ring structure. Natural output has been estimated to be equivalent to 190-930 kg/s of steam. Basaltic intrusions underlying the silica rocks may be the heat source for the geothermal reservoir. The geothermal manifestations are mostly steaming ground but steam-heated water of the bicarbonate and the acid sulphate type is common in the area. A preliminary review is carried out on possible environmental effects due to drilling in the area in order to decide how to carry out an environmental impact assessment (EIA) and disclose key impacts. In this study, an attempt has been made to identify the likely impact of geothermal exploration, drilling and operations, and potential mitigating measures. As environmentally more advantageous, the result of this study suggests that detailed studies be carried out on the water supply for drilling, on how to get rid of effluent water, and on the monitoring of gas emissions to the atmosphere during drilling operations, as well as a detailed assessment of the biology of the area.

1. INTRODUCTION

This report is the product of a six months' fellowship awarded to the author to study geothermal resources and utilization in Iceland, with emphasis on environmental impact training through the United Nations University, Geothermal Training Programme, at Orkustofnun - the National Energy Authority in Iceland. The training programme started on the 4th of May 2000.

It was first in the 20th century that geothermal energy was harnessed on a large scale for space heating, industry and electricity production. Iceland is richly endowed with geothermal resources. In 1999, the total primary energy consumption (Figure 1) was 121 PJ, supplied by geothermal energy (50%), hydro-power (18%), oil (30%), and coal (2%) (Ragnarsson, 2000).

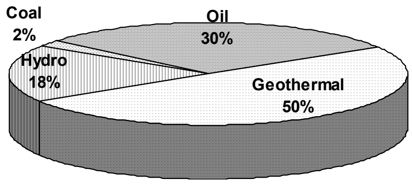

FIGURE 1: Total primary energy consumption in Iceland 1999

The environmental aspects of geothermal development are receiving increasing attention with the shift in attitude towards the world's natural resources. There is also a growing awareness of the need for efficient and wise use of all natural resources, and of the effect of geothermal development on the surrounding ecosystems and landscape. Geothermal power generation is often considered a "clean" alternative to fossil fuel or nuclear power plants. Although geothermal power plants are very clean, it is necessary to monitor the effects of possible geothermal contamination on the environment. Geothermal power generation using a standard steam cycle plant will result in the release of non-condensable gases, and fine solid particles into the atmosphere.

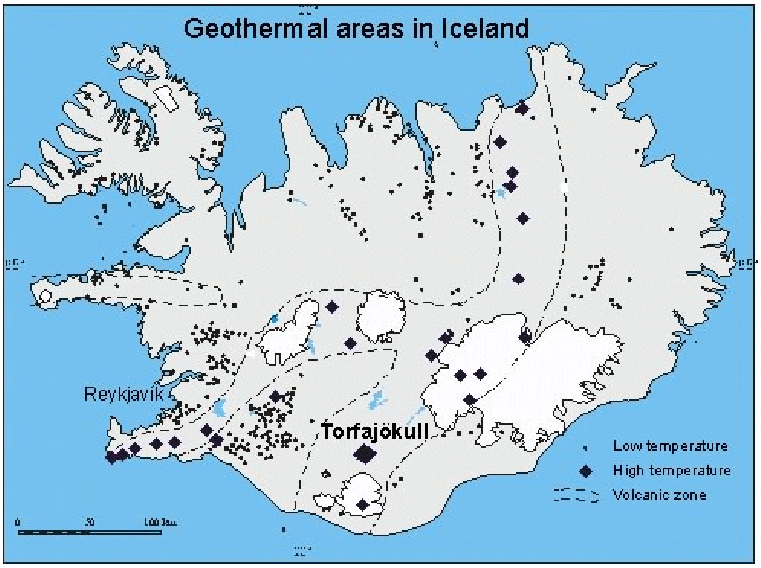

FIGURE 2: Geothermal areas in Iceland

The Torfajökull high-temperature geothermal area is the largest geothermal field in Iceland, located within a central volcanic complex in the southern part of the country (Figure 2). This complex encompasses a large caldera subsidence with an abundance of rhyolitic rocks (Saemundsson, 1972; 1988). Surface thermal manifestations, which include extensive alteration, warm and boiling springs, mudpots, and a large number of fumaroles, cover an area of some 140 km^2. The fumaroles and mudpots appear to be confined to the caldera proper, mostly at altitudes between 850 and 1000 m a.s.l., and virtually all the boiling springs are found there as well. The Torfajökull massif is cut by a multitude of gullies and ravines. This badlands topography is particularly striking in the southern and southeastern parts, and it makes fieldwork rather laborious. The weather is frequently inclement. Winter snowfall is heavy and the snow lingers far into the summer. As a result, the field season is quite short. The southern and southeastern parts of the field appear to have been studied little until now. A popular backpacking trail winds through the central part of the area, which is otherwise relatively inaccessible and almost devoid of vehicular tracks. It is one of the unexploited high-temperature fields in Iceland. This report uses some preliminary results of geological and geochemical studies, including the first data on fumaroles from the southern and southeastern parts of the field (Ólafsson and Bjarnason, 2000), and presents a preliminary environmental assessment of the high-temperature geothermal fields in the Torfajökull area.

2. TORFAJÖKULL - A NATURE RESERVE AREA IN ICELAND

2.1 Nature reserve

An area of 470 km^2 [47.000 hectares] in the vicinity of Torfajökull has been designated a "nature reserve" in Iceland. The rest of the area (south and southeast part) falls into the category of natural monument (The Nature Conservation Register, 1996). Torfajökull is a part of the natural reserve area (Figure 3).

2.1.1 Definitions

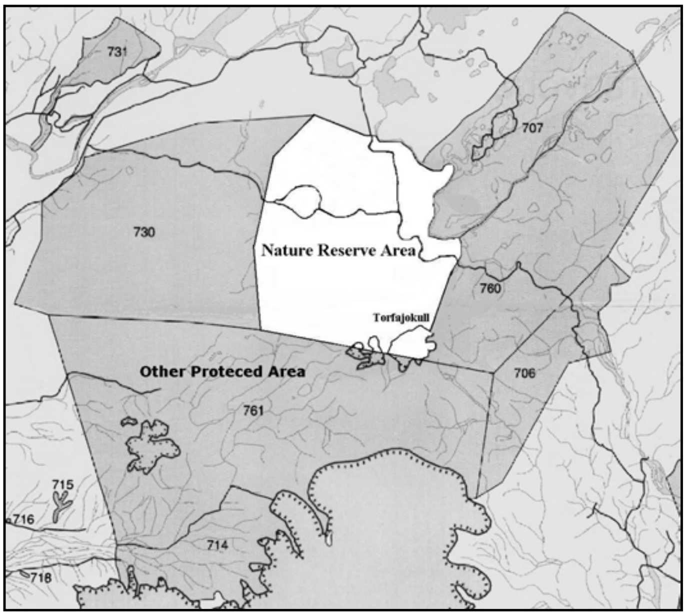

FIGURE 3: Natural protected areas in Torfajökull area

Nature reserves: Areas which are important to conserve because of landscape, vegetation or animal life. The aims for protection are diverse as are the regulations governing reserves. Nature reserves are for the most part privately owned land or highland pasture and regulations concerning them are often subject to agreement between the rightholders and the Nature Conservation Council in Iceland.

Natural monuments: Unusual or unique natural formations, such as waterfalls, volcanoes, hot springs, rocks, caves and lava fields, as well as sites containing fossils and rare minerals. Many natural monuments have the distinction of being generally revered sites and the aim to preserve is to prevent disturbance of the surrounding ground and other damage (The Nature Conservation Register, 1996).

2.1.2 History

The area has, as far as is known, been mostly uninhabited. The name of the lake Frostastadavatn however suggests that a farm named Frostastadir existed in early times and indeed there are some folk tales that tell of the farm Frostastadir. No physical remains have been found. There are also some folk tales regarding the name Torfajökull and several other place names that might be derived from the name Torfi recounting that a man of that name lived with his wife, or a large household, in the area to escape from the plague, or that two young lovers (the man being Torfi) were escaping from the young lady's father. Others think it more likely that the name derives from the word "torf" (meaning turf or sod). There are two old routes in the area "Fjallabaksleid nyrdri" and "Fjallabaksleid sydri", (Northern and southern roads beyond the mountains). The southern route is believed to have been used from the time of settlement (before the year 1000) but first records of the total northern route being used are from the early 19th century. However, each end of the route must have been known to the local people and been used to get to the fishing lakes, Veidivötn, and to gather sheep in the autumn. The springs at Landmannalaugar were well known and their water reputed to have curative properties (Magnússon, 1985).

2.1.3 Ownership

The area is traditionally denoted as "afréttur" ("highland pasture"), i.e. land that is grazed by sheep from all farms in the area but not belonging to individual farmers. In a new law that is in preparation, this land will be designated as "þjódlenda" ("state property with free access"). Thereafter problems of ownership should not arise should the area be utilized.

2.1.4 Natural conditions and protection

In Torfajökull, the surface natural thermal manifestations include extensive alteration, warm and boiling springs, mud pots, and a large number of fumaroles. The natural features are extensive post-glacial lava fields with a lot of volcanic glass-obsidian and steep-sided mountains. The steam vents, mud pools and warm springs are the major tourist attractions in this area. Some monitoring of natural manifestations has been carried out till now and is included in plans for environmental tasks at Orkustofnun. This monitoring should be continued and funds should be set aside for it. The Torfajökull geothermal area is in a volcanically active area and relatively good permeability might be expected. Short-term variation in surface geothermal manifestations is expected to be mainly due to changes in water level (which in turn are related to variations in precipitation). More long-term changes might be due to sealing by deposits, etc., but these are often opened up again by earthquake activity. It is important to monitor such natural changes and estimate their extent to obtain background levels with which changes occurring after the start of utilization can be compared. The question of who pays for such monitoring is important, as possible prospective users such as the National Power Company are not willing to pay for work in areas they may not develop, and the government is reluctant to award money to such projects. The solution that seems to be most agreeable to all parties is for the government to pay now but if the field is developed the developer has to pay the government back the money spent on such monitoring.

2.2 Tourism

The area is very popular with tourists, both Icelanders and foreign visitors. There are several tourist huts, the most popular one being in Landmannalaugar where 15-16,000 visitors stay overnight every year. Day visitors are numerous and it can be estimated that 40-50,000 people visit the area as tourists every year. Naturally most of them visit during the summer but in recent years snow scooters and large four-wheel drive vehicles have made the area more accessible. Several hiking trails run through the area, the most popular being "Laugavegurinn" ("The hot spring trail") which is taken by 2-3000 hikers every year (Baldursson, 1996; 1997). In a general report on tourism in Iceland, Checchi and Company and the Architects Collaborative Inc. (1975) recommended that geothermal areas be given high priority in development of tourism. Torfajökull was, however, not selected as a priority area for development, most probably due to its remoteness. Opening up the area by way of new roads would change conditions drastically and might bring in greatly increased numbers of tourists. Due to its uniqueness and popularity, there is likely to be strong opposition to any kind of utilization of geothermal resources in the Torfajökull area.

2.3 Aesthetics

A geothermal plant must be located close the resource, so there is often little flexibility in its siting. Like many other geothermal areas, Torfajökull high-temperature geothermal field is of unique beauty, with historical interest and popular tourist attractions. From the aesthetic standpoint, it should be kept as natural as possible. So the protection of the numerous small hot springs, mud pools, fumaroles, boiling pools and all other natural manifestations must be considered. In the past, human intervention has changed the character of geothermal fields leaving features that are now considered part of nature. A detailed study should be conducted in Torfajökull to find out if its unique features are likely to decline when drilling takes place. The impact on the natural features in Torfajökull field must be kept to the absolute minimum.

3. WEATHER CONDITIONS

The weather is frequently inhostile in the Torfajökull area. The temperature conditions are mostly controlled by altitude and distance from the sea. The mean annual temperature is probably 0-1°C. July is the warmest month and the mean annual July temperature at Landmannalaugar is 7-8°C, although on certain days it can reach 15-20°C. The mean temperature of the coldest months is extremely variable from one year to another. Frosts may occur during all the summer months although it is least likely in July. In the southeast corner of the Torfajökull area, the annual precipitation is probably between 2,000 and 3.000 mm, but diminishes quite fast to the north and is probably below 1000 mm in the northernmost part of the area.

It is common for a weather boundary to lie across the northern part of the Torfajökull area i.e. across the mountains south of Bláhnúkur, Brennisteinsalda and Háalda. During southeasterly winds and southwesterlies it is often dry and warm (Föhn winds) at Landmannalaugar and over the northernmost part of the nature reserve, even though at the same time there is fog and rain at Hrafntinnusker and further to the south. Northerly winds, on the other hand, are usually cold and clear all over the area (Magnússon, 1985). Winter snowfall is heavy and the snow lingers far into the summer. Vegetation is also sparse in this area. The four nearest meteorological stations to the Torfajökull area are Búrfell, Lónakvísl, Veidivatnahraun and Kirkjubaejarklaustur.

3.1 Precipitation

Precipitation was gauged in 1996-1998 at the Veidivatnahraun meteorological station, located approximately 50 km north-northeast of the Torfajökull area. From 1996 to 1998, the yearly precipitation in this area was 639 mm, 572 mm, 540 mm each year, respectively, with maximum monthly precipitation of about 110 mm in November 1998, and minimum about 9 mm in March 1997. But the weather information is from quite distant place. As mentioned above the annual precipitation is probably between 2,000 and 3,000 mm in the southeast corner of Torfajökull and probably below 1,000 mm in the northernmost part. This northernmost pattern is likely to be similar to that at Veidivatnahraun whereas a totally different pattern most close to the one at Kirkjubaejarklaustur, would be expected in the southeastern part. So, it is necessary to set up meteorological stations and monitor the weather for some time in the actual Torfajökull area before exploitation. Figure 4 shows monthly precipitation from 1996 to 1998 in the Veidivatnahraun area.

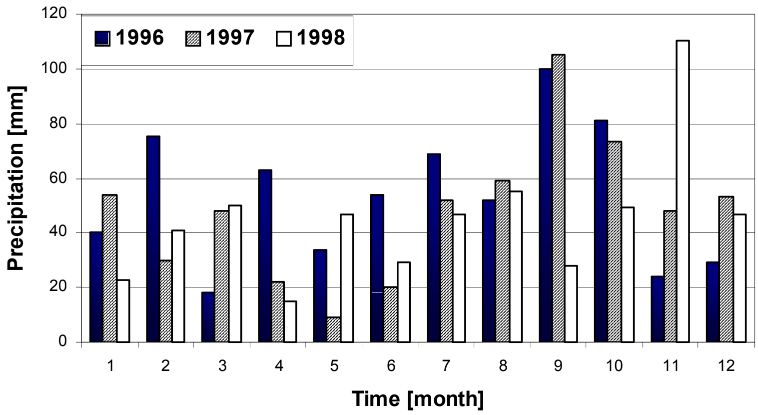

FIGURE 4: Monthly precipitation at Veidivatnahraun 1996-1998

3.2 Temperature and humidity

Temperature data for Veidivatnahraun meteorological station from 1.1.1999 to 31.7.2000 are shown as monthly average temperatures in Figure 5, showing maximum temperature in July 2000 of about 14.2°C, and minimum in March, 1999, about -14°C.

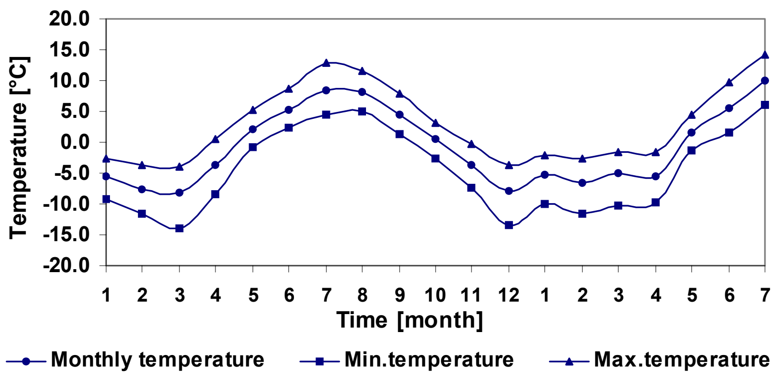

FIGURE 5: Monthly air temperatures at Veidivatnahraun for the period 1.1.1999 - 31.7.2000

Humidity in Iceland is generally high due to high precipitation. Humidity data for this area was collected from 1.1.1999-31.7.2000 at the Veidivatnahraun meteorological station. Maximum humidity was recorded in March 2000, about 90% but minimum in January 1999, about 37%. Monthly humidity at the Veidivatnahraun station for the monitoring period is shown in Figure 6.

3.3 Wind patterns

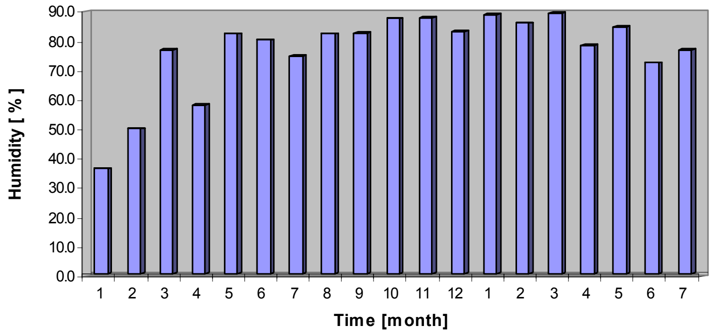

FIGURE 6: Monthly humidity at Veidivatnahraun from 1.1.1999 to 31.7.2000

Wind conditions were measured 1994-1999 at Búrfell, located approximately 35 km east-southeast of Torfajökull, at Lónakvísl, located approximately 33 km to Torfajökull, at Veidivatnahraun, about 50 km to the north-northeast of Torfajökull, and at Kirkjubaejarklaustur, located approximately 56 km to the east of Torfajökull. Hourly wind direction and wind speed were noted to make a wind rose plot, and it is seen that the most common wind directions are northeasterly and southeasterly. Figure 7 shows the yearly wind pattern at the stations nearest to Torfajökull area from 1994-1999.

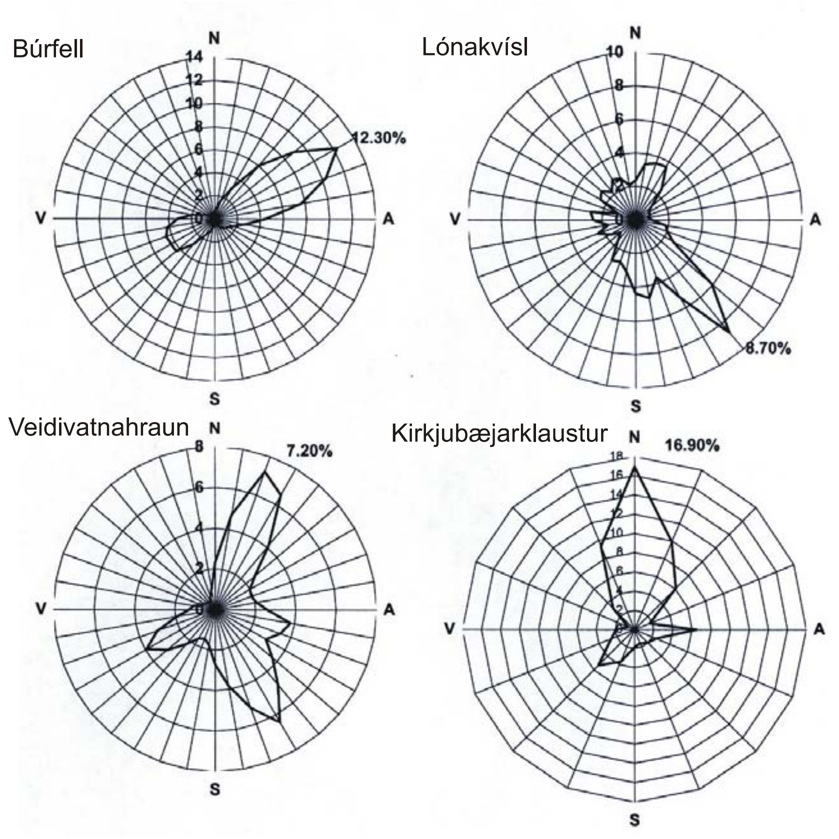

FIGURE 7: Frequency of wind directions at the meteorological stations closest to the Torfajökull area (1994-1999)

4. GAS CONCENTRATION IN STEAM

Torfajökull geothermal field is an unexploited natural area without any industrial or other air polluting activities. Only some gases from geothermal manifestations escape to the atmosphere. Samples of steam for chemical analysis have been collected from fumaroles throughout the Torfajökull area. The chemical composition of steam from selected fumaroles is shown in Table 1. The concentrations of H_2S, CO_2 and

H_2 are higher than others, and it seems desirable to monitor the first two in the area. Samples of steam for chemical analysis were collected from fumaroles throughout the Torfajökull area (Ólafsson and Bjarnason, 2000). Even though only a tiny fraction of the fumaroles could be sampled, an attempt was made to cover the entire field fairly evenly in order to obtain a representative picture.

TABLE 1: Chemical composition of steam from the Torfajökull area (Ólafsson and Bjarnason, 2000) (SMOW = Standard mean ocean water)

Sample no.	**613**	**158**	**214**	**166**	**607**	**605**	**671**	**674**	**672**	**140**
CO_2 (mmole/kg)	132	242	67	128	370	8330	2000	21,100	370,000	819
H_2S (mmole/kg)	10.7	4.40	3.79	10.2	21.1	38.5	14.5	0.81	15.9	20.1
H_2 (mmole/kg)	16.6	3.55	4.17	25.3	41.8	47.9	49.7	36.3	383	28.9
CH_4 (mmole/kg)	0.24	0.21	0.085	1.42	0.19	0.036	0.035	0.59	9.37	0.70
N_2 (mmole/kg)	0.54	0.90	0.33	2.66	0.58	3.67	2.11	26.4	663	2.14
Ar (mmole/kg)	0.014	0.02	0.008	0.055	0.011	0.057	0.032	0.39	8.19	0.042
B (mg/kg)	<0.03	<0.03	<0.03	0.08	<0.03	<0.03	0.04	0.04		0.065
Cl (mg/kg)	0.27	0.17	0.04	0.25	0.33	0.09	0.13	0.11		0.76
Hg (ng/kg)	40	70	100	30	20		140	90		120
ΔD (‰ SMOW)	-90.7	-88.7	-78.2	-76.6	-87.9	-89.3	-85.2	-103.6		-96.8
$\delta^{18}O$ (‰ SMOW)	-13.3	-13.6	-11.5	-11.7	-13.3	-13.5	-12.5	-19.13		-15.4

The fumarole sampling points are shown as circles on the map in Figure 8, and Table 1 displays the chemical composition of ten representative samples. The respective numbers indicate the sampling location on the map. The total concentration of gas in steam spans a wide range, from approximately 20 to almost 25,000 mmole/kg, with a single extreme value of nearly 400,000 mmole/kg. Carbon dioxide is the main gas constituent in most samples and generally represents 80-99% of the total gas. Hydrogen sulphide and hydrogen are the other principal components, accounting for 0.1 to 10% of the total. The nitrogen concentration is below 1% in all samples except two. These exceptional samples may have been contaminated by atmospheric air. Methane amounts to less than 0.2% of most samples.

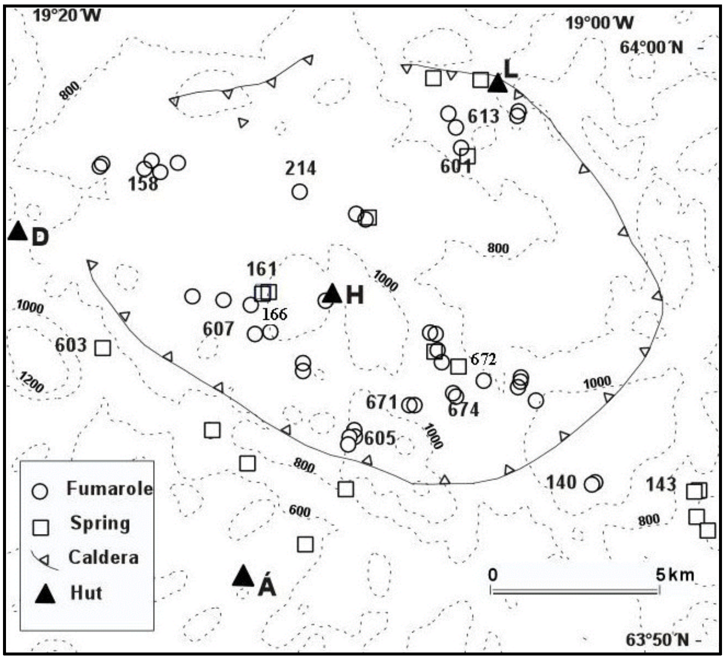

FIGURE 8: Sampling locations for steam and water

The highest gas concentrations, by far, are found in the southern and southeastern parts of the field. The carbon dioxide concentration, in particular, is very high there. The concentrations of hydrogen sulphide and hydrogen are also generally highest in the southern and southeastern parts, but the pattern is much less pronounced than for carbon dioxide. As a result, the concentration ratios of carbon dioxide to the other gases are very much higher in the south and southeast than in other parts of the field.

The concentration of mercury in steam ranges from 20 to 600 ng/kg. The highest concentrations are found in the southern and southeastern parts of the geothermal area. The chloride concentration does not display any clear geographical pattern. It ranges from 0.05 to 0.76 mg/kg, but five out of every six samples were found to contain less than 0.40 mg/kg. The concentration of boron in steam ranges from less than 0.03 mg/kg, which is the detection limit for the analytical method used, to roughly 0.5 mg/kg.

Subsurface temperatures were estimated on the basis of gas geothermometers. Seven such geothermometers were applied to the samples reported in Table 1. The results are presented in Table 2. These are the CO_2, H_2S, H_2, CO_2/H_2, and H_2S/H_2 geothermometers of Arnórsson and Gunnlaugsson (1985), the CO_2/N_2 geothermometer of Arnórsson (1987), and the CH_4/CO_2 geothermometer of Giggenbach (1991).

TABLE 2: Gas geothermometer temperatures (°C) in the Torfajökull area

Sample no.	613	158	214	166	607	605	671	674	672	140
CO_2	272	290	249	271	302	404	349	452	714	323
CO_2/N_2	308	310	303	268	330	354	338	335	327	318
CH_4/CO_2	331	358	344	275	378	646	545	518	524	358
H_2S	293	276	273	292	306	318	299	241	301	305
H_2	303	289	290	307	311	312	313	310	331	308
CO_2/H_2	316	289	307	322	315	278	296	263	256	300
H_2S/H_2	312	300	306	320	316	308	325	371	359	310

As CO_2 is a greenhouse gas, and H_2S poisonous and the concentrations are relatively high, their concentrations in steam should be monitored. H_2S in atmospheric gas should be monitored as well as the possible product of its oxidation, SO_2, which is a polluting gas, and finally, Hg that can be very harmful if its atmospheric concentration rises.

5. GROUNDWATER AND EFFLUENT WATER

The experience of geothermal problems in the world associated with the increasing number of geothermal power plants has shown that there is a danger of environmental impact, although not as severe as that of more conventional power plants using coal, oil and nuclear power. The disposal of spent brines and condensate/cooling water is considered one of the major environmental drawbacks since they contain a variety of substances in suspension and solution. Many of these substances, such as arsenic, mercury, lead, zinc, boron and sulphur, are biologically harmful even in low concentrations and can interfere with aquatic, animal and vegetation growth rates and their reproduction processes and lead to pollution of underground water supplies.

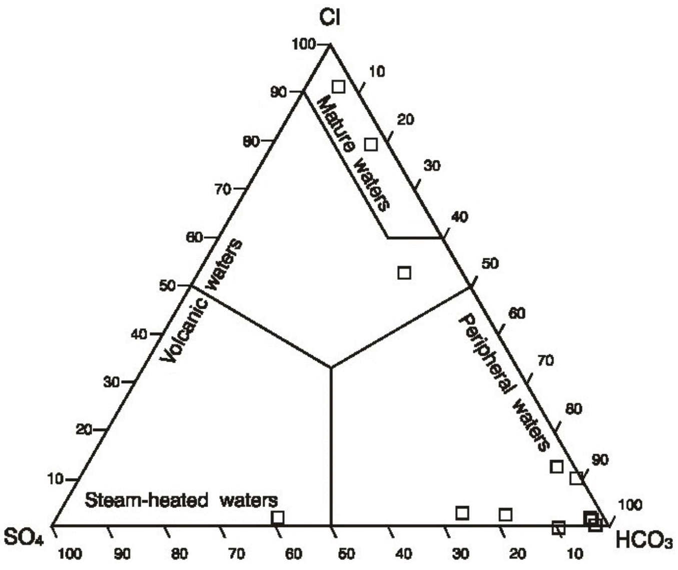

FIGURE 9: The SO_4-Cl-HCO_3 classification diagram for water in the Torfajökull area

Samples of water have been collected from hot and warm springs, some of which are located within the caldera and some just outside it (Ólafsson and Bjarnason, 2000). These are indicated by squares on the map in Figure 8. The chemical composition of four representative samples is presented in Table 3. The thermal spring water is mostly of the bicarbonate type in the southern part of the Torfajökull field and primarily of the sodium chloride type in the northern part, where the chloride concentration reaches 575 mg/l (Figure 9).

TABLE 3: Chemical composition of selected hot spring in the Torfajökull area

Sample no.	**601**	**161**	**603**	**143**
Temperature (°C)	100	96.5	91.8	69.5
pH/°C	8.96/22	8.83/21	7.24/22	6.87/14
CO_2 (mg/l)	25.2	67.5	573	1023
H_2S (mg/l)	4.86	3.79	0.06	<0.03
SiO_2 (mg/l)	200	120	111	229
B (mg/l)	7.93	0.066	0.83	1.78
Li (mg/l)	0.07	0.09	0.12	0.34
Na (mg/l)	356	57.4	387	365
K (mg/l)	14.6	4.43	9.74	39.5
Mg (mg/l)	0.03	0.15	0.56	8.67
Ca (mg/l)	15.0	1.87	5.19	27.4
F (mg/l)	9.61	9.53	20.7	8.57
Cl (mg/l)	575	3.13	115	29.2
Br (mg/l)	2.19	0.006	0.35	0.08
SO_4 (mg/l)	18.9	20.6	31.1	38.3
Al (mg/l)	0.26	0.18	0.037	0.017
Mn (mg/l)	0.017	0.025	0.0035	0.026
Fe (mg/l)	0.16	0.014	0.058	0.40
Hg (ng/l)	<5	65	16	15
TDS (mg/l)	1200	258	1020	1287
δD (‰ SMOW)	-74.6	-79.8	-75.5	-75.1
$\delta^{18}O$ (‰ SMOW)	-8.43	-11.26	-10.82	-10.2

Boiling pools with acid sulphate waters are found throughout the Torfajökull area. Most of these represent drowned fumaroles. Examples of alkaline springs with very low chloride content, e.g. sample 161, are also found within the caldera. The mercury concentration in the spring water ranges from less than 5 ng/l, which is the limit of the analytical method used, to 70 ng/l. There is a single extreme value of 800 ng/l. The spring at Landmannalaugar, labelled L on the map in Figure 8, yields a chalcedony geothermometer temperature (Fournier, 1977) of 182°C, and a surface temperature of 77°C. The chalcedony temperatures of the remaining springs are lower and rather evenly distributed over a range of 85-170°C. Their surface temperatures range from 24 to 100°C. The quartz geothermometer temperature (Fournier and Potter, 1982) for Landmannalaugar is 200°C. This geothermometer, which yields temperatures of 20-25°C above those of the chalcedony geothermometer, is probably more appropriate for the springs with the highest indicated temperatures. Most of the hot spring waters seem to be close to fluorite saturation. Although unusual for Iceland, where most rocks are basaltic, this is to be expected in the Torfajökull area, where rhyolite dominates the geology.

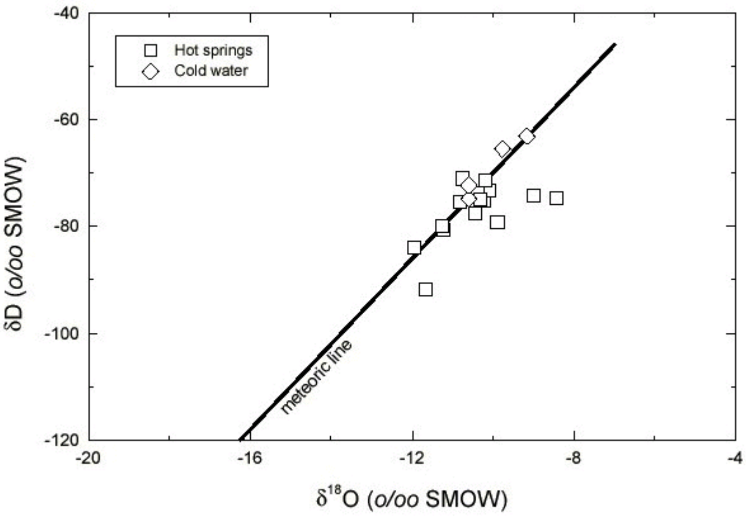

FIGURE 10: Hydrogen and oxygen isotope ratios in hot and cold water samples from Torfajökull area

Figure 10 displays a crossplot of the hydrogen and oxygen isotope ratios for the water samples. Most of the thermal water, indicated by squares, falls on the meteoric line, though some samples appear to be oxygen-shifted. Cold water samples, shown as diamonds, presumably represent the local precipitation. Ólafsson and Bjarnason (2000) suggest that the geothermal water derives from local precipitation.

Acid sulphate water is, like bicarbonate water, low in chloride, and this feature together with low pH and high sulphate determines the distinguishing characteristics. This water may be very low in sodium and potassium and have low Na/K ratios. Sulphate is always the dominant anion and for waters low in sodium and potassium, hydrogen ion is the dominant cation. Bicarbonate water is considered to tend to form when steam containing little or no hydrogen sulphide mixes with shallow non-thermal water. Such steam could originate by boiling of water which has equilibrated at a depth of a few hundred metres (therefore, of relatively low temperature) or that the steam has reacted extensively with the rock in the upflow, either due to slow or long passage, losing its hydrogen sulphide in the process. The acid sulphate water, on the other hand, forms by condensation of hydrogen sulphide bearing steam in oxygenated surface water and subsequent oxidation of sulphide to sulphate, as has been demonstrated worldwide. In Hrafntinnusker boiling hot springs occur containing very low chloride, indicating that they are composed of steam-heated surface water. Yet they are distinctly alkaline, low in dissolved carbonate and possess many other characteristics of sodium-chloride waters. This water is considered to be surface water heated by secondary steam, which is, therefore, low in gas. The chloride concentrations in the sodium-chloride water in the Landmannalaugar area are variable due to mixing with cold water in the upflow and steam loss by boiling (Arnórsson, 1985). The highest reported chloride concentration is 535 pm (Table 3). This is to be contrasted with chloride levels of 10-100 ppm in geothermal water in Iceland associated with basaltic rocks (and not affected by sea-water mixing). Sigvaldason and Óskarsson (1976) showed that acid rocks in Iceland are higher in chloride than basaltic ones. The relatively high chloride concentrations in the water below Landmannalaugar are, thus, attributed to dissolution from the acid volcanics overlying the presumed basalt sheet intrusion heat source.

As for other geothermal reservoir waters in Iceland associated with acid volcanics, fluoride concentrations are relatively high in the sodium-chloride type water (5-25 ppm) and seem to be controlled by fluorite solubility in the reservoir (Arnórsson et al., 1983). Compositional features of the sodium-chloride water emerging in boiling hot springs are, apart from chloride and fluoride, similar to those of water discharged from boreholes in basaltic terrain in different parts of Iceland. Arnórsson et al. (1983) have shown that the composition of the borehole water is governed by chemical equilibrium between solutes and alteration minerals.

Mixed water containing a sodium-chloride component differs from boiled water in many respects, being relatively high in total carbonate, most likely because the mixing process has prevented boiling and, therefore, degassing of the hot water. Further the mixed water is relatively high in calcium and magnesium probably subsequent to mixing (Arnórsson, 1985). The mixed water is devoid of H_2S, most likely due to oxidation. In contrast to the mixed water, water in boiling hot springs has relatively high Na/K-ratios. Na-K geothermometry temperatures for the boiling hot springs water are significantly below those of quartz. The cause is considered to be relatively effective removal of potassium from the boiling water in the upflow either by precipitation of K-feldspate or adsorption on clay minerals.

Sodium chloride type water with as much as 500 ppm Cl^-, representing boiled and variably mixed reservoir water occurs in the northeastern part of the field, around Landmannalaugar in the north. The fumarole steam generally contains 0.2-0.4% total gases by volume. CO_2 is always the dominant gas constituent (>70%) but H_2S and H_2 amount to 2-8% and 0-10%, respectively. Ground radon and mercury concentrations are anomalous over upflow zones of geothermal steam. Helium isotope ratios as high as 23.14 times atmospheric have been reported indicating a relatively primitive undegassed mantle source (Poreda et al., 1992). Hot spring chemistry at Landmannalaugar indicates subsurface temperatures of 265°C. Gas chemistry indicates even higher temperatures (>300°C) for this and other parts of the geothermal area.

6. CHANGES IN NATURAL ACTIVITY

Natural surface manifestation such as hot springs, mud pools, geysers, fumaroles and steaming ground are associated with most geothermal systems (Brown, 1995). Because of their unique nature these are often tourist attractions, or are used by local residents. Geothermal development that draws from the same reservoir can potentially affect these features. These visible signs of geothermal activity are part of a country's heritage and in any geothermal development they must be taken into account during environmental impact assessment. Before any development takes place, the natural features associated with a geothermal field are catalogued with as much information and for as long as possible to provide a data baseline for later comparison. During the exploration phase, the heat flow of natural features is estimated, and samples for chemical analysis are collected. These data can be used to monitor the features. Geothermal features do change, e.g. self-sealing is followed by movement such as earthquakes which can break the seals and thus affect surface manifestations.

In connection with a large environmental study in Iceland a project aimed at the study of unexploited geothermal areas was initiated. The main aim of the project was to define and initiate monitoring schemes for natural features in unexploited geothermal areas and to develop research methods for that purpose (Ármannsson et al., 2000). The status of environmental knowledge for the unexploited high-temperature geothermal areas in Iceland was defined in the beginning. Concurrently, background data on some unexploited areas were collected and monitoring schemes were initiated in a few selected areas. A schedule of the work needed to carry out an environmental impact assessment for a 20 MW power plant in each of the unexploited Icelandic geothermal areas was prepared together with an estimate of the cost. Methods were developed to measure the mass flow of steam in fumarole outlets (Gíslason, 1997) and for the monitoring of geothermal areas by aerial thermograph remote sensing methods (Árnason, 1997). The concen-tration of sulphur gases and mercury in atmospheric air was measured in four unexploited geothermal areas (Ívarsson et al., 1993). Torfajökull is the largest unexploited geothermal area in Iceland, abundant in natural surface mani-festations (Figure 11).

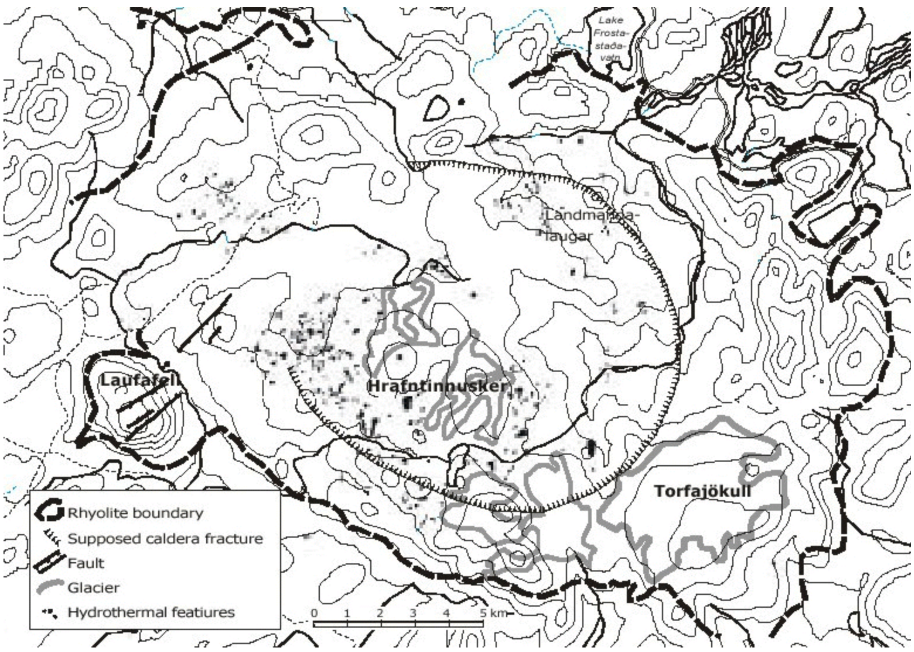

FIGURE 11: Torfajökull geothermal manifestations (Arnórsson et al. 1987)

6.1 Hydrothermal eruptions

Although relatively rare, hydrothermal eruptions constitute a potential hazard in active geothermal fields and need to be included in an environmental impact assessment. The causes and mechanisms of hydrothermal eruptions have been reviewed by Bromley and Mongillo (1994). Eruptions occur when the steam pressure in the near surface aquifers exceeds the overlying lithostatic pressure and the overburden is then ejected forming a crater. The resulting vent can vary from 5 to 500 m in diameter and up to 500 m in depth although most eruptions will be relatively shallow. In assessing the likelihood of a hydrothermal eruption, increasing steam flow to the surface accompanying reservoir pressure drawdown or an expanding steam zone are some of the factors to be considered. A further consideration is reinjection under pressure of fluids at temperatures >100°C into shallow environments. There is the possibility that such water will rise rapidly to the surface and heat the local pore water, resulting in an eruption.

6.2 Subsidence

Withdrawal of fluid from any type of underground reservoir will normally result in a reduction of pressure in the formation pore space, and this can lead to subsidence. One of the major causes of subsidence is the compaction of clays. Its extent is therefore very much dependent on clay types in the formation. Subsidence has been observed in groundwater reservoirs and geothermal reservoirs. Subsidence has a number of implications for geothermal development and also for the effect on the surrounding field as it can seriously affect the stability of pipelines, drains and well casing in a geothermal field. If the field is close to a populated area, then it can lead to instability in dwellings and other buildings. In more remote areas, where there may be no habitation, the local surface water systems may be affected. Therefore, the effects and likelihood of subsidence must be addressed in the environmental impact statement. Before exploitation, a baseline levelling and gravity survey with installation of levelling stations needs to be undertaken. There should be a number of separate surveys to cover as long a time as possible before exploitation so that local tectonic changes in level, if any, can be subtracted from those due to exploitation.

6.3 Thermal emissions

Geothermal power plants utilize only a part of the thermal energy of the geothermal fluid to provide the primary energy for conversion to power production. The efficiency of geothermal power plants is lower than that of other types of power plants. Because the efficiency is so low the waste heat per MW of electricity generated is larger than from other types of power plants and needs to be dissipated in an environmentally acceptable way. A portion of the waste heat in the water component of water-dominated geothermal systems is increasingly being used for binary cycle power plants. Thus, the temperature and waste heat will be reduced. Also, many geothermal developments now dispose of geothermal wastewater by deep reinjection, from which the environmental impact due to heat is negligible. In many geothermal fields, there are areas of steaming ground, springs and other features where special thermal habitats have been established. The roots of most plants cannot survive temperatures much above 50°C, and in addition, the soils of this type of ground are often very acidic. In these cases, only very tolerant species can survive and a unique flora may evolve. At temperatures between about 50 and 70°C only mosses and lichens can survive. Above that temperature, vegetation is absent. Changes in thermal areas, such as increased steam flow due to exploitation, may change the distribution of these thermally adapted plants with the possibility of rendering some of the species vulnerable to extinction. The possibility needs to be included in the environmental impact assessment.

6.4 Water usage

Water is required for drilling, reinjection, well testing, and cooling in the power stations. The impact the requirements will have on the water situation depends on the locality. In arid areas the problem of suitable water can be acute, and geothermal water produced from first wells has been used as a water supply for subsequent drilling. There is a large meltwater component in Torfajökull, fresh surface water is variable, and precipitation is abundant, so drilling fluids should be available either from the surface or by drilling.

6.5 Solid wastes

Generally, geothermal development produces significant amounts of solid waste and suitable disposal methods need to be found. Because of the heavy metals, particularly arsenic, contained in geothermal water these solid wastes are often classed as hazardous. These heavy metals must be disposed of safely. Other solid wastes include drilling mud and cement, not normally considered hazardous, and construction debris and normal maintenance debris, which can be considered hazardous in the presence of asbestos in insulation material. Disposal of hazardous solid waste on site is a vexing problem; reinjection is one solution to the disposal of heavy metals. When transporting waste, care must be taken to avoid spills. The disposal sites need to be periodically monitored, and such sites could become a long-term liability.

7. STATUS ANALYSIS OF PRELIMINARY ASSESSMENT BEFORE DRILLING

7.1 Preliminary exploration before drilling

Surface exploration of the Torfajökull area has been in progress since 1992 and a basis for future environmental monitoring has been laid. Earlier some geological and geochemical studies had been reported by Arnórsson (1985) and Arnórsson et al. (1987). The results of the chemical studies are described by Ólafsson and Bjarnason (2000). Their conclusion is that the geothermal manifestations are quite transient. The reasons for this variability are likely to be the large amounts of precipitation in the area, the large amount of snow that melts during the summer or possibly condensation of steam during upflow. The area may be developed in the not too distant future. Very few studies of the geothermal system had been carried out in the area previously and thus no changes could be reported. There was, however, considerable knowledge of the geology of the area available.

7.2 Cost assessment before drilling

As states embark on geothermal development with the ultimate objective of improving the socio-economic conditions of their constituents, the costs and impacts of such development on the intended beneficiaries become the yardstick of the acceptability and of the success of the geothermal project. So it is absolutely necessary to make a cost analysis before drilling. A brief description of the status of the various items studied for this assessment follows and the actual estimated cost is shown in Table 4.

TABLE 4: Cost of preliminary environmental assessment before drilling

Item	Cost (Millions ISK)
Description of geothermal manifestations	1
Geochemistry	4.5
Geophysics	13
Microearthquake activity	18
Atmospheric gas	14.1
Levelling and gravity	19
Remote sensing (temperature)	1
Microorganism study	19
Total	**90**

The basic studies for evaluation of the area are nearly finished. A final version of a geothermal map is ready for publication, all geophysical fieldwork is finished and the geochemical studies only need filling in. Studies that basically need to be done for environmental assessment (microearthquake activity, atmospheric gas, levelling and gravity, remote temperature sensing and microorganism study) have not yet been carried out. The cost estimate for the first three items is, therefore, the remaining cost of a large project but for the latter five it is for full-scale studies (Table 4).

The area is very large and it is extremely unlikely that the start of utilization would cover the whole area. It was, however, not within the scope of this project to choose the first site for drilling. The whole area can be divided into 7-10 sub-areas, in each of which production could be initiated and it is not certain that such preliminary studies would be carried out over the whole area if only a small part were to be utilized. The estimate is, thus, a maximum estimate.

Ragna Karlsdóttir (pers. comm.), team leader, gave the information that only minor office work remained before the publication of the geothermal map and that all geophysical fieldwork was completed although considerable interpretation of the measurements done remained to be carried out. These two items are based on her estimates. Magnús Ólafsson (pers. comm.) gave the estimate for the geochemical work needed to complete the preliminary exploration before drilling. Knútur Árnason (pers. comm.) said that earthquake activity could be estimated using SIL stations in the vicinity but this was nowhere near sufficient to establish background values for microearthquakes in the area. He said that in order to get a good estimate of the natural seismicity, 8 stations should preferably be run for five years, but a fair estimate could be obtained by operating portable seismic stations for 3 months which is a more realistic option. Halldór Ármannsson and Magnús Ólafsson (pers. comm.) estimate that spot measurements of H_2S could be completed in 10 days. The results would be used to determine where stations for monitoring H_2S, SO_2 and Hg would be installed. It is assumed that it would be practical to install three stations at one time but twelve stations would be needed to cover the whole area. Hjálmar Eysteinsson (pers. comm.) suggests that GPS measurements be run in 125 points, each measurement taking at least 4 hours. The gravity measurements require considerable mobilization and instalment work. When ready, one person can do the actual measurements over one week. Remote sensing involves temperature measurements by IR scanning, and the scans would cover the whole Torfajökull area, or 20×25 km^2. The highest point of the area is Háskerdingur at 1280 m, with geothermal manifestations ranging from an altitude of 550 m at lake Álftavatn to 1050 m in Hrafntinnusker. The mean altitude is assumed to be 800 m and flying altitude would be 1800 m a.s.l. Photographic strips 2 km wide with a 25% overlap would be obtained, making a total of 14 strips. The interpretation involves printing the strips to a certain scale (e.g. 1:25000 or larger) with each temperature value printed with a certain colour, or temperature values can be grouped and each group represented by a colour. A statistical evaluation of the strips reveals size and temperature of each geothermal patch (Kolbeinn Árnason, pers. comm.). Tryggvi Thórdarson (pers. comm.) assumes that there are on the order of 2000 geothermal manifestations in the area, 500 of which would be visited for the microorganism study. The fieldwork is assumed to demand two field trips and regular dispatch of samples to Reykjavík for analysis, as they do not keep well. All manifestations that appear to be biologically remarkable will be sampled but others will be grouped and representative samples collected. The manifestations and their ecological regime will be described, their position and altitude determined, photographs taken, pH, temperature, conductivity and possibly H_2S determined on the spot, and samples for microscopy, cultures of remarkable species and for analysis of variability collected. The flow of the hot springs will be measured wherever possible but otherwise estimated.

8. ENVIRONMENTAL IMPACT OF DRILLING

8.1 Overview

The environmental impact of geothermal development is receiving increasing attention with a general shift in attitude towards the world's natural resources. Most countries have embodied their environmental concerns in legislation. Although the actual legislation varies in detail for different countries, the overall requirements, and the purpose and need for legislation are recognized worldwide. The principal difference probably lies in the administration of legislation, rather than its content. The different types of geothermal fields and geothermal development have varying impacts and legislation needs to cover all possible developmental scenarios. In general, as development proceeds, the legislation requirements move from environmental impact reports during the predevelopment stage, to gaining consent for development and finally to a monitoring role during production. Environmental impact assessment (EIA) is important for the predevelopment stage of drilling; EIA legislation was introduced in Iceland in 1993, and developed comprehensively in 1997. The law on EIA in Iceland was published formally this year.

Introduction of compulsory EIA has met with strong resistance from many quarters, particularly in the United Kingdom. Planners argued with partial justification that they were already making such assessments. Many developers saw it as yet another costly and time-consuming constraint on development. There are definitions e.g. that of Munn (1979), which refer to the need "to identify and predict the impact on the environment and on man's health and well-being of legislative proposals, policies, programmes, projects and operational procedures and to interpret and communicate information about the impacts". The narrow U.K. Department of Environment/Welsh office (1988) operation definition: "the term environmental assessment describes a technique and a process by which information about the environmental effects of a project is collected, both by the developer and from other sources, and taken into account by the planning authority in forming their judgements on whether the development should go ahead." United Nations Economic Commission for Europe (1991) defines EIA as an assessment of the impact of a planned activity on the environment." In essence EIA is a systematic process that examines the environmental consequences of developmental actions and alternatives in advance.

The EIA methodology approach in the 1970s followed in the tracks of economic science in the direction of models, matrices, networks, input and output (Gilpin, 1995). Methodology, like cost benefit analysis which compares the social costs with the social benefits of a project all expressed as far as practicable in monetary terms, have been used. Others like opportunity cost, the multiplier, contingent valuation, travel cost approach and hedonic price technique are sparingly used because of their complexity in application. Leopold et al. (1971), working with the US Geology Survey, produced a methodology in which matrices are used for the entire field of EIA. Of all the methodologies, checklists have tended to survive as a guide to the potential impacts of a project. For this project, a checklist for impact identification has been prepared (Appendix I: Checklist used for the project). The checklist is used because unlike other methodologies mentioned, it is simple and descriptive. For impact assessment of drilling, matrices are quite useful and more detailed, and are used for this study too.

8.2 Road construction

The amount of land that is disturbed by road construction during geothermal development can be quite large (Brown, 1995); it is estimated that about 12 hectares are needed for road construction alone when 15 wells are drilled. In general, geothermal systems are often located in volcanic environments, where the terrain is steep and access difficult. Furthermore, such an environment may also have severe erosion problems. Road construction in these steep situations normally involves extensive intrusion into the landscape and can often cause slumping or landslides with consequent loss of vegetation. The lack of vegetation can then cause greatly accelerated erosion with the possibility of further slumping or landslides.

Most of the warm springs in the Torfajökull area are located on the rim of the caldera or just outside it, at an altitude of around 600 m. This is a sparsely vegetated relatively inaccessible region, which is almost devoid of vehiclular tracks. The weather is frequently inclement. Winter snowfall is heavy and the snow lingers far into the summer. Therefore road construction in the Torfajökull area is difficult, stabilization of the roads in such an environment is difficult and land affected by development is correspondingly increased.

8.3 Drill Site

For drilling pads in this area, the solution to erosion and landslides will be to drill a number of deviated wells from a single drilling pad. In this way a large volume of reservoir can be tapped at depth, while requiring only a small area, which can be situated on a stable land surface. The application of this technique also means that fewer and shorter roads need be built.

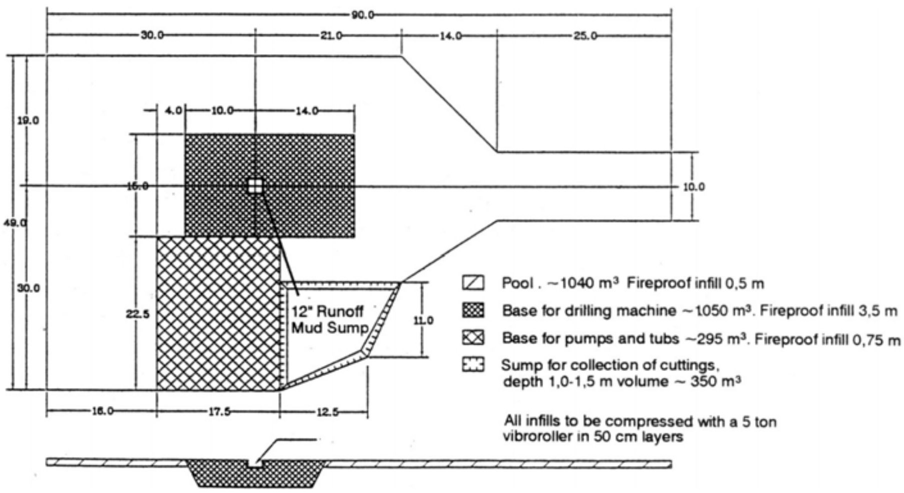

FIGURE 12: Drill pad for a high-temperature well (Thórhallsson, pers. comm.)

For the drill site, one drill pad occupies about 0.4 hectares, which should be cleared of vegetation and compacted (Figure 12), or the exposure of the area around each well site will create a major erosion hazard. Erosion of cut slopes takes place by runoff and slumping, but much of the sediment is deposited at the foot. Erosion of the fill slopes is more serious because of the lack of compaction and because the sediment is likely to be carried further downslope. Runoff, which accumulates on the pad itself usually finds its way out through the fill slope, and where this is not vegetated, the potential for gully erosion is high.

8.4 Cable tool drilling

The cable tool rig is not a true drill in the strict sense of the word since it does not rotate, but employs a heavy hammer bit that pounds and crushes the rock. This drilling method is common for cold water drilling and before rotary equipment was taken into use in Iceland it was extensively used for geothermal drilling. The cable tool drilling rigs have the advantage of being cheap to buy and requiring only two men to operate. Among the disadvantages of this drilling method are the slow penetration rate compared with rotary drilling, especially at depths below 200-300 m, and that in geothermal drilling blow-out prevention equipment cannot be adapted. The cable tool rig is, therefore, unsuitable for drilling in areas where the water temperature exceeds 100°C and in lower temperature wells, where free-flow may be dangerous when using this method.

The main role of the cable tool rig in geothermal drilling in Iceland is to pave the way for the rotary drilling equipment. This means that the rig is brought to start drilling the first 25-70 m and to set the conductor pipe to keep the loose surface layers from falling into the hole. The rotary drilling rig is very ineffective at shallow depths, as sufficient weight cannot be applied to the drill bit, so it is necessary to get the hole started by another drilling method. This also mitigates the erosion impact in the loose soil.

8.5 Transportation

The traffic impact is important in drilling activity. Before drilling starts the area has a certain amount of traffic. When drilling starts the traffic increases as the rig and all its accessories are transported to the drill site.

The rotary drilling rig is transported on set trailers pulled by a truck. Transport takes about a week depending on the number of trucks and the distance. About 130 tons of casing, 140 tons of cement with an additional 25 tons of drilling mud and 30 tons of diesel oil and some lubrication oil are expected to be transported to the drill rig during the drilling of a well. The rig will be removed a week after drilling is finished. This can lead to an increase in dust, noise, vehicular emissions and increased traffic. Occasional traffic delays will occur at various points in the project area. The assessment of significance will focus on who will be affected to what degree and whether the change is significant. Some of the affected groups are people at home, or in work places. Special interest groups are children, the elderly and disabled, and sensitive locations include schools, hospitals and places of worship. In the Torfajökull area, there is a natural reserve with conservation value and sites of tourist attraction. Impacts like vibration accidents, and spilling of hazardous loads are also possible.

8.6 Drilling fluids

Water is required for drilling; a typical shallow well requires 1000 m^3/day, which may be lost to the formation. A deeper well may require up to 3,000 m^3/day (Brown, 1995) for periods up to several months. Completion testing and injection testing can use up to 10,000 m^3/day of water. In Iceland up to 40 l/s or 35,000 m^3 of water are required for 24 hours of drilling. If this water is discharged, care must be taken to have it disposed of into a well designed for this purpose, as the quality of the water can be affected by suspended solids and chemical content change (Brown, 1995). The water from drilling can create serious gullying if discharged directly to the surface, e.g. into valleys. This can be a problem in the steep parts of Torfajökull if proper disposal methods are not applied.

After use, drilling muds are produced as solid alkaline waste that may contain many other chemicals (Table 5), Ármannsson (1997). Drilling muds are either lost to the circulation in the well or end up in the drilling sumps as solid waste for disposal. A drilling mud like bentonite is mostly used when hole clearing is inadequate or when well stability is a problem.

TABLE 5: Chemical composition of bentonite and perlite (% of mass) (Ármannsson, 1997)

Material	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	LOI[1)]	WS[2)]	AS[3)]
Bentonite	64.1	20.0	3.66	0.16	1.52.	2.38	2.18	0.49	6.26	0.1	0.5
Perlite	73.0	12.5	0.7	0.1	1.0	0.5	4.5	4.8	1.3		

[1)] LOI = Loss on ignition, [2)] WS = Water solubility, [3)] AS = Acid solubility

8.7 Drilling

The drilling pad accommodates the drill rig and the associated equipment including drill pipes. As drilling takes place, cuttings from the drill head are flushed out with water, frequently mixed with drilling detergent to assist in the collection of cuttings. The detergent used must be capable of withstanding high temperature. Bentonite drilling mud mixed with some barium is often used. If the well erupts, a heavy substance barium sulphate is usually added. This is essentially an inert material but can smother plants and does not support plant growth and in this respect is similar to a hard compacted surface. Other wastes produced include petroleum products from lubricants and fuels plus cement wastes as spills. Air pollution can result from non-condensable gas emissions and exhaust smoke from generators and compressors. In vapour-dominated reservoirs, air-only drilling takes place and this requires large compressors, which, in effect, increase noise to unbearable levels. A drill rig is seen from afar during drilling and may be regarded as visual pollution but it is removed after drilling.

8.8 Casing and cementing

The largest diameter casing used in a well is required only where the surface soils are so incompetent that the washing and eroding action of the drilling mud would create a large cavity at the surface. Conductor casing controls such erosive action. Surface casing is of a smaller diameter and its function is to protect the freshwater table and provide an anchor for blowout-preventer equipment. The amount of surface casing required, therefore, depends on the depth of the freshwater table with a minimum of 60 m and a maximum of 400 m and is cemented all the way to the surface. If the fresh groundwater table is below the surface casing, the control authority requires that the fresh water be protected by setting either intermediate or production casing and cementing it with enough cement to completely fill the casing well bore annulus from the shoe to the surface (Corsi, 1995).

Cementing well casings is carried out for a number of reasons. Where conductor casing is required, it must be cemented in order to prevent the drilling fluid from circulating outside the casing, and thus, cause surface erosion, which the casing was designed to prevent. Surface casing must be cemented in order to seal off and protect freshwater formations. Cement also effectively protects the casing from corrosive environments, notably corrosive fluids that may be present in the surface formations.

8.9 Demobilization

The demobilization can bring about loss of habitat that can be associated with leaving abandoned plants, equipment and scrap without any attempt to rehabilitate them. During demobilization, a slotted liner is put in, the drill rig is transported away and flow equipment is erected i.e. pipes, additional vents, and atmospheric separators (silencers). An aerated shelter at the wellhead is desirable. Unplanned, careless and disorganized removal can cause further loss of habitat. Once the structures are removed the sites can be left to recover or be rehabilitated to achieve comparable status with the neighbouring area.

8.10 Warm-up, flow initiation and flow

The main impacts of well testing are water effluent that may contain toxic chemicals from the fluids, and noise. After completion tests a well is normally closed in order to warm up and to build up pressure. This is common with wells that can self-discharge. For wells which cannot self-discharge, it is common practise to compress them using compression time. Some wells have to be airlifted to initiate flow. Noise impact may be experienced from the large compressors used. Testing of wells has often had a deleterious effect on local vegetation with some plants being scalded by escaping steam and spray. The effect is more severe during vertical discharge carried out to clear wells; this should take as short a time as possible, preferably not more than one hour. The wastewater from a tested well can cause serious gullying when discharged directly to a steep area, and must possibly do so in the fragile soils found in the Torfajökull area.

During well testing, care should be taken not to discharge the wastewater directly to steep areas but to sumps made to contain this wastewater. Failure to do so can cause serious gullying.

9. ENVIRONMENTAL ASSESSMENT FOR DRILLING

9.1 Checklist

A project such as drilling is always likely to be subject to EIA in accordance with Icelandic law. The possible environmental impacts of drilling in the Torfajökull area are listed in Appendix I. The impacts that could result if drilling were implemented are also discussed where appropriate. Only those elements of the environment which may be impacted or might be considered to produce cumulative effects are included in the discussion. Since exploration is sparse, it is not realistic to estimate various needs.

9.2 Land

Land is required for drill pads, access roads, steam lines, power plant and transmission lines. Estimation of land required for geothermal development is an important task in EIA. During road construction and drill site preparation, unstable land conditions may result and changes in geological substructure can occur. The Torfajökull massif is cut by a multitude of gullies and ravines particularly in the southern and southeastern parts. A popular backpacking trail winds through the central part of the area, which is otherwise relatively inaccessible and almost devoid of vehicular tracks. Vegetation is sparse, so if it is exposed to erosion agents, it should be given over to revegetation with grass on the cut slopes, fill slopes and well pads themselves. For drilling pads in the steep part of the area, the solution to erosion and landslides will be to drill a number of deviated wells from a single drilling pad. In this way a large volume of the reservoir can be tapped at depth, while requiring only a small area, which can be situated on stable land at the surface.

9.3 Air

During drilling, air pollution can result from non-condensable gas emissions, exhaust gas from generators, compressors, and vehicles. There may be objectionable hydrogen sulphide odours, as it produces an unpleasant odour. Eye irritation and respiratory damage may not be of any significances as the Torfajökull area is not inhabited and only used by tourists. As drilling is a temporary activity, no significant long term air quality impacts are expected, but long term monitoring of hydrogen sulphide, sulphur dioxide and possibly heavy metals such as mercury in atmospheric air should be implemented.

9.4 Water

Water is required as a drilling fluid. The wells to be drilled in this area will be deep and may require at least 4000 m^3/day of water supply; during well testing, up to 10,000 m^3/day of water may be used. The amount of water used as drilling fluid is enormous and should be discharged with utmost care into well designed sumps or possibly re-injected as this can affect the quality of the groundwater. In parts of Torfajökull springs, streams or lakes may provide an adequate amount of water for drilling fluids. In other parts drilling may be necessary.

9.5 Noise

Noise is one of the most ubiquitous disturbances to the environment from geothermal development particularly during the construction and operation phases. Noise can be considered as unwanted sound and an attempt should be made to minimise this impact. Torfajökull is in a remote area where the natural level of noise is low and any additional noise is very noticeable. In such areas, tourists will probably regard any noise as an intrusion into their otherwise quiet environment. Animal behaviour is also affected by noise with reports of changes in size, weight, reproductive activity and behaviour. Torfajökull field is not an inhabited area, so there will be no serious noise impacts during early stages, however, the temporary noise impact may be felt at the tourist huts of Landmannalaugar and Hrafntinnusker. The noise impact will decline later, when wells have been drilled and tested. So in Torfajökull, noise impact is not expected to be serious.

9.6 Vegetation

The flora of Iceland consists of 438 species. In the Torfajökull area, vegetation in general is relatively scarce due to sand blowing, volcanism and overgrazing by sheep for centuries as well as its altitude of mostly >600 m a.s.l. Continuously vegetated areas are small, the largest and most lushly vegetated being close to rivers and lakes. In the "nature reserve" about 150 species of flower plants and bracken plants

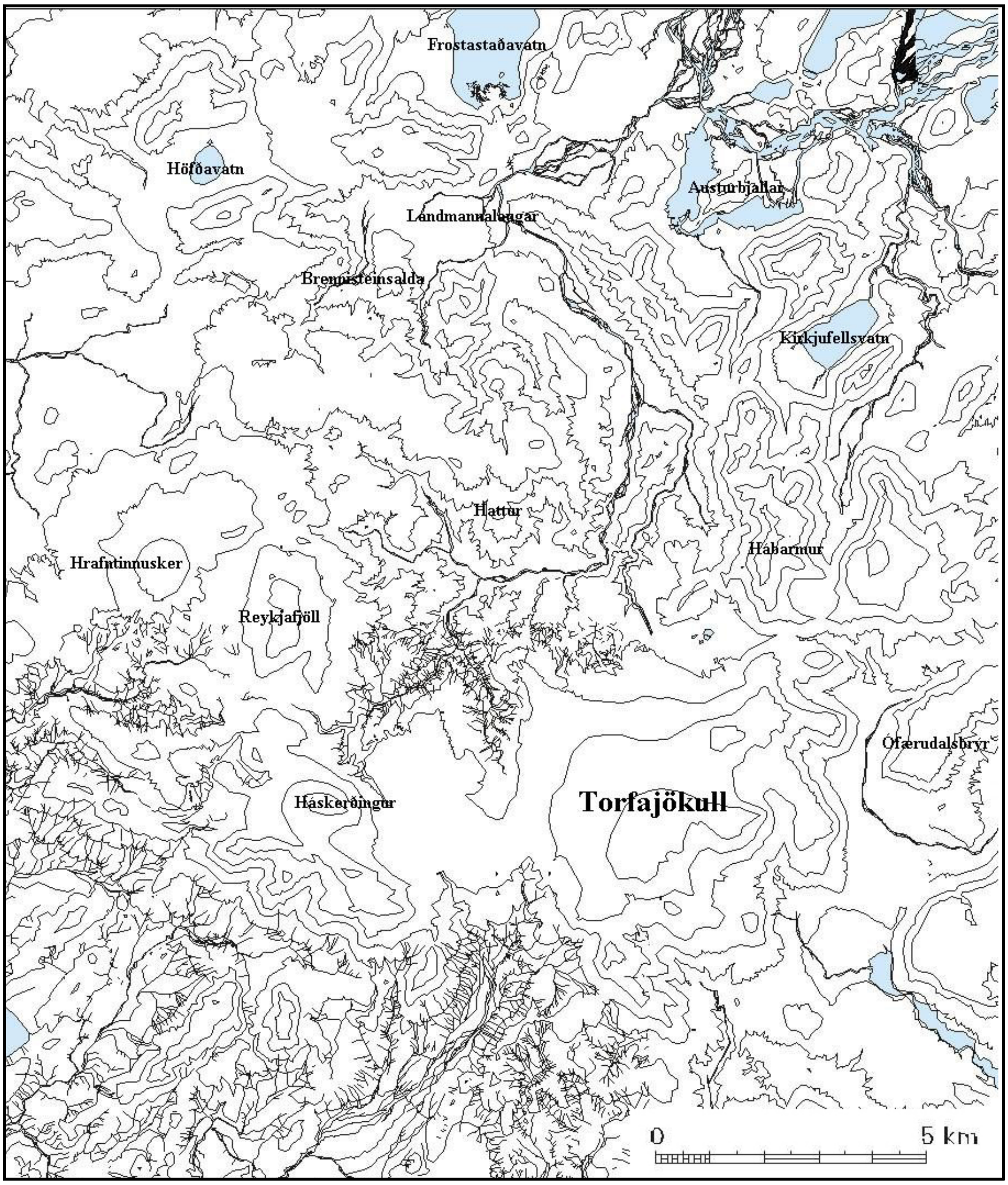

FIGURE 13: The area covered by squares 4961, 4962, 5061 and 5062 in the Iceland plant distribution grid system

have been identified (squares 4961, 4962, 5061 and 5062 of the grid system for the study of plant distribution in Iceland; Kristinsson and Jóhannesson 1970, see Figure 13). During a recent visit to the geothermal field in Hólmsárbotnar, H. Kristinsson (pers. comm.) recorded those species that grow only around geothermal manifestations in that area. e.g. Botrychium lunaria - common moonwort, Calamagrostis stricta - narrow small reed, Eleocharis quinqueflora - few-flowered spiko-rush, Epilobium palustre - marsh willow nest, Hieracium islandicum - Icelandic hawkweed, Juncus alpinus - alpine rush, Juncus articulatus - jointed rush, Juncus bufonius - toad rush, Juncus filiformis - thread rush, Poa annua - annual meadow grass, Ranunculus hyperboreus - arctic butter cup, Sagina procumbens - procum bent pear/wort, Triglochin palustre - marsh arrowgrass.

In sandy parts lyme grass (Leymus arenarius), bladder campion (Silene uniflora) and thrift (Armeria maritima) are about the only species found. Where there is more moisture, sand vegetation is relatively continuous and also includes narrow small-reed (Calamagrostis stricta), Scheuchzer's cotton grass (Eriophorum scheuchzeri) and curved sedge (Carex maritima). On gravel beds the most important species are least willow (Salix herbecea), alpine mouse-ear (Cerastium alpinum), purple saxifrage (Saxifraga oppositifolia), thrift (Armeria maritima), northern rock-cress (Cardaminopsis petraea), northern fescue (Festuca vivipara), glaucous meadow-grass (Poa glauca) and alpine hair-grass (Deschampsia alpina).

Mosses are quite extensively distributed and the area is very much characterized by Racomitrium ericoides and its relative Racomitrium lanuginosum but higher plants occur intermittently and are mostly the same as those of the gravel beds but also including stiff sedge (Carex bigelowii).

The rhyolitic lavas are devoid of vegetation but the species that do occur are mostly the same as those of gravel beds and heathland although vegetation typical of snowy lows occurs in the deepest lows. On basaltic lavas there is more abundant vegetation, which is like that of the heathland but including some grass.

In flat areas and on the lower parts of slopes, grass species provide the most extensive coverage but borders of flatland, wetlands and heathland are not clear. The species that characterize the heathland are wooly willow (Salix lanata), broadleaved willow (Salix callicorpea) and least willow (Salix herbacea), especially wooly willow. Slopes are divided into three belts, i.e. meadows where the most important species are velvet bent (Agrostis vinealis), fescue grasses, alpine meadow-grass (Poa alpina) supplemented by some flowering plants. In the central belt Bellard's kobresia (Kobresia myosuroides) dominates with a sprinkling of stiff sedge (Carex bigelowii). In the top belt the kobresia heaths disappear and change to mossland.

The mountain slopes are in some cases grassy but several flowering plants are found in lows, e.g. alpine lady's mantle (Alchemilla alpina), common lady's mantle (Alchemilla vulgaris), meadow buttercup (Ranunculus acris), dandelion (Taraxacum), alpine vernal grass (Anthoxanthum odoratus) and more grass species, even wood cranesbill (Geranium sylvaticum) and angelica (Angelica archangelica) are found. There are unclear borders between the flowering plant land and snowy lows but the most important snowy low plants are creeping sibbaldia (Sibbaldia procumbens), dwarf cudweed (Omalotheca supina), least willow (Salix herbacea) and timothy (Phleum pratense) and the snowiest of them are gray with snow moss.

There are quite a few wetlands in the area. Kýlingar is a continuous marshy ground with pools and ponds. The main species there is common cotton grass (Eriophorum angustifolium) but mountain bog-sedge (Carex rariflora), Scheuchzer's cotton grass (Eriophorum scheuchzeri) and narrow small-reed (Calamagrostis stricta) are common, too. The latter two occur mostly on the borders of sand and wetlands and often form belts along brooks and ponds. In drier moorlands stiff sedge (Carex bigelowii) is the main species but in marshy spots in Laugar and Hattver common sedge (Carex nigra) is virtually the sole species.

In Landmannalaugar the vegetation is akin to lowland vegetation. Next to the lava border there is a swamp with common sedge (Carex nigra), Lyngbye's sedge (Carex lyngbyei) and some flowering plants such as marsh cinquefoil (Potentilla palustris), marsh willowherb (Epilobium palustre), butterwort (Pinguicula vulgaris) and others. By the lava's edge there are continuous sections of flowering plants where brittle bladder-fern (Cystopteris fragilis) grows as well. On the banks of the brook Laugalaekur vegetation is lush and field grasses, dandelions (Taraxacum), meadow buttercups (Ranunculum acris) grow in the geothermal warmth. There is a lot of autumnal hawkbit (Leontodon autumnalis) as well as widespread clover (Trifolium) which is rare in the highlands. There are however hardly any species that can be termed geothermal except for small adder's tongue (Ophioglossum azoricum) but in this area jointed rush (Juncus articulatus), frog rush (Juncus ranarius) and even silverweed (Potentilla anserina) may be classified as such. In the Laugalaekur brook there is plenty of vegetation, such as common water-starwort (Caliitriche stagnalis) and lesser pondweed (Potamogeton pusillus).

By the sulfurous hot springs at the roots of Brennisteinsalda one more geothermal species, marsh cudweed (Filaginella uliginosa) grows. By the hot springs in Vestri-Reykjadalir there is quite lush vegetation too (Einarsson, 1985, H. Kristinsson, pers. comm.).

9.7 Microbiology

With regards to microbiology, the Torfajökull area (e.g. Landmannalaugar and Hrafntinnusker) has been investigated to some extent. J.K. Kristjánsson and his co-workers, as well as some foreign scientists, have collected samples and cultivated hot spring microorganisms from them. Some papers have been published on bacteria from the samples but it is not an easy task to find them. The area around Hrafntinnusker, for instance the ice caves and their surroundings, provide conditions for very rich ecosystems of hot spring microorganisms. Here is a great variety of hot springs, some of which are of a very special character, and are formed in a close interaction of a high-temperature area with ice and constant wetness (J.K. Kristjánsson, pers. comm.).

9.8 Animal life

There are plenty of tiny animals, such as blood-red planktonic crabs and small zooplankton in ponds and lakes. Skateworm has been found in Ljótipollur, Kýlingar and by Lake Lodmundarvatn. Water conches are common in Landmannalaugar. There is trout in most of the lakes, especially Ljótipollur, Dómadalsvatn and Frostastadavatn (Magnússon 1985). Recently trout has been bred in Álftavatn and Laufavatn where there was none before (Bödvarsson 1976). The most common wild mammal is fox and it is also likely that field mice live in the area. Mink has no doubt strayed there, too.

Close to Torfajökull, birdlife is scarce due to the high elevation. Snow bunting (Plectrophenax nivalis), ptarmigan (Lagopus mutus) and purple sandpiper (Calidris maritime) are the species most likely to nest there. The area is expected to take on added importance for the ptarmigans in autumn and early winter and pink-footed geese (Anser brachyrhynchus) will stop over in vegetated areas in the autumn. At that time other birds are rare visitors. The same applies to the whole area west to Reykjafjöll, Kaldaklofsfjöll and Hrafntinnusker. In the lower lying valleys to the north of Torfajökull birdlife is considerably more extensive especially where there are lushly vegetated patches such as in Landmannalaugar, Kirkjufellsvatn and Kýlingar, and there is also considerable birdlife on vegetated slopes such as Laugahlíd. The most common nesting birds in these parts are great northern diver (Gavia immer), whooper swan (Cygnus), pink-footed goose (Anser brachyrhynchus), mallard (Anas platyrhynchos), harlequin duck (Histrionicus histrionicus), ringed plover (Charadrius hiaticula), Eurasian golden plover (Pluvialis apricaria), purple sandpiper (Calidris maritima), dunlin (Calidris alpina), white wagtail (Motacilla alba), wheateater (Oenanthe oenanthe) and snow bunting (Plectrophenax nivalis). Meadow pipit (Anthus pratensis) and snipe (Gallinago gallinago) are probable nesting birds that are regularly spotted in the area but nesting has not been confirmed. Raven (Corvus corax) and lesser black-back (Larus fuscus) are regular visitors during the summer. The area is part of the migration route for migratory birds, which are numerous in the area in late summer, especially passerines in August. Birdlife in southern Fjallabak and Jökulgil has not been studied. There is considerable birdlife at Álftavatn and vegetated areas near by and the composition is similar to that north of Torfajökull even though the species are somewhat fewer. In addition gyrfalcon (Falco rusticolus) has nested in that area (E.Ó. Thorleifsson, pers. comm.).

9.9 Transportation

The transportation of the drill rig in the Torfajökull area could be rather difficult. A popular backpacking trail winds through the central part of this area, which is otherwise relatively inaccessible and almost devoid of vehicular tracks. New roads would have to be built, and great care taken that they distort views as little as possible.

10. CONCLUSIONS AND RECOMMENDATIONS

1. Careful planning is needed to reduce impacts of access and site development in the Torfajökull area, as it is a very popular nature reserve area in Iceland.
2. Care has to be taken to obtain good drilling fluids, as relatively acid carbonate fluids are known in the area, e.g. in the stream "Ölstallur" described by G.Ó. Fridleifsson (pers.comm.) where the pH of the water was 5.6 which renders it unsuitable as a drilling fluid.
3. Long-term monitoring of changes in geothermal manifestations water level should be put into effect.
4. The permeability of the lava formations suggests that it should not be difficult to dispose of effluent water. As there is always a danger of over-exploitation of the fluid, the best solution economically and environmentally is re-injection; it must be considered in the Torfajökull area.
5. The greatest damage to the vegetation of the area has, up to now, been due to sheep grazing; limiting this activity would improve the flora of the area. A careful recording of rare plants, especially those that normally only grow near hot springs, should be undertaken.
6. Production from the area would open it up with new roads. Increased tourism would be expected and might even call for some services in the area. Due to the increased number of travellers, easier access would be expected to increase hunting, a danger to the natural reserve area, and measures might be needed to protect it.

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APPENDIX I: Environmental impact checklist for drilling in the Torfajökull geothermal field

Subjects	*Exploration*			*Drilling*			*Operation*		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
1. Earth. Will the proposal result in:									
a. Unstable earth conditions or in changes in geologic substructures ?	✓			✓					✓
b. Disruptions, displacements, compaction or over covering of the soil ?			✓			✓			✓
c. Change in topography or ground surface relief features ?			✓			✓			✓
d. The destruction, covering or modification of any unique geologic or physical features ?			✓		✓			✓	
e. Any increase in wind or water erosion of soils, either on or off the site ?			✓			✓			✓
f. Changes in deposition or erosion of beach sands, or changes in siltation, deposition or erosion which may modify the channel of a river or stream or the bed of the ocean or any bay, inlet or lake ?			✓			✓			✓
g. Exposure of people or property to geologic hazards such as earthquakes, landslides, mudslides, ground failure, or similar hazards ?			✓			✓			✓
2. Air. Will the proposal result in:									
a. Substantial air emissions or deterioration of ambient air quality ?			✓		✓			✓	
b. The creation of objectionable odours ?			✓	✓			✓		
c. Alteration of air movement, moisture, or temperature, or any change in climate, either locally or regionally ?			✓			✓			✓
3. Water. Will the proposal result in:									
a. Changes in currents, or the course of direction of water movements, in either marine or fresh waters ?			✓			✓			✓
b. Changes in absorption rates, drainage patterns, or the rate and amount of surface runoff ?			✓		✓			✓	
c. Alteration to the course or flow of flood waters ?			✓			✓			✓
d. Change in the amount of surface water in any water body ?			✓	✓			✓		
e. Discharge into surface waters, or in any alteration of surface water quality, including but not limited to temperature, dissolved oxygen or turbidity ?			✓	✓					✓
f. Alteration of the direction or rate of flow of ground waters ?			✓		✓			✓	
g. Changes in the quantity or quality of ground water, either through direct additions or withdrawals, or through interception of an aquifer by cuts or excavations ?			✓	✓			✓		
h. Substantial reduction in the amount of water otherwise available for public water supplies ?			✓			✓			✓
i. Exposure of people or property to water related hazards such as flooding or tidal waves ?			✓			✓			✓

Subjects	*Exploration*			*Drilling*			*Operation*		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
4. Plant life. Will the proposal result in:									
a. Changes in the diversity of species, or number of any species of plants (including trees, shrubs, grass, crops, and aquatic plants) ?			✓			✓		✓	
b. Reduction of the numbers of any unique, rare or endangered species of plants ?			✓		✓			✓	
c. Introduction of new species of plants into an area, or in a barrier to the normal replenishment of existing species ?			✓			✓		✓	
d. Reduction in acreage of any agricultural crop ?			✓			✓			✓
5. Animal life. Will the proposal result in:									
a. Change in the diversity of species, or number of any species of animals (birds, land animals such as reptiles, fish and shellfish, benthic organism or insects) ?			✓			✓		✓	
b. Reduction of the numbers of any unique, rare or endangered species of animals			✓			✓		✓	
c. Introduction of new species of animals into an area, or a barrier to the migration or movement of animals ?			✓			✓		✓	
d. Deterioration to existing fish or wildlife habitat ?			✓			✓			✓
6. Noise. Will the proposal result in:									
a. Increases in existing noise levels ?			✓	✓			✓		
b. Exposure of people to severe noise levels ?			✓			✓			✓
7. Light and glare. Will the proposal produce new light or glare ?			✓	✓			✓		
8. Land use. Will the proposal result in a substantial alteration of the present or planned land use of an area ?									
Present :			✓			✓	✓		
Planned :			✓			✓	✓		
9. Natural resources. Will the proposal result in:									
a. Increases in rate of use of any natural resources ?			✓	✓			✓		
b. Substantial depletion of any nonrenewable natural resources ?			✓			✓			✓
10. Risk of upset. Will the proposal involve:									
a. A risk of an explosion or the release of hazardous substance (including, but not limited to, oil accident, chemical or radiation) in the event of an accident or upset conditions ?			✓			✓			✓
b. Possible interference with an emergency response plan or emergency evacuation plan			✓			✓			✓
11. Population. Will the proposal alter the location, distribution, density, or growth rate of the human population of an area ?			✓	✓			✓		

Subjects	Exploration			Drilling			Operation		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
12. Housing. Will the proposal affect the existing housing, or create a demand for additional housing ?			✓	✓			✓		
13. Transportation/circulation. Will the proposal result in:									
a. Generation of substantial additional vehicular movement ?		✓		✓			✓		
b. Effects on existing parking facilities, or demand for new parking ?			✓	✓			✓		
c. Substantial impact upon existing transportation systems ?			✓	✓			✓		
d. Alteration to present patterns of circulation or movement of people and/or goods ?			✓	✓			✓		
e. Alteration to waterborne, rail or air traffic ?			✓			✓			✓
f. Increase in traffic hazards to motor vehicle, bicyclists or pedestrians ?			✓	✓			✓		
14. Public services. Will the proposal have an effect upon, or result in a need for new or altered governmental services in any of the following areas:									
a. Fire protection ?			✓			✓			✓
b. Police protection ?			✓			✓			✓
c. Schools ?			✓			✓			✓
d. Parks or other recreational facilities ?			✓			✓			✓
e. Maintenance of public facilities, including roads ?			✓	✓			✓		
f. Other governmental services ?			✓			✓		✓	
15. Energy. Will the proposal result in:									
a. Use of substantial amounts of fuel or energy ?			✓	✓			✓		
b. Substantial increase in demand upon existing sources of energy, or require the development of new sources of energy ?			✓			✓			✓
16. Utilities and service systems. Will the proposal result in a need for new systems, or substantial alterations to the following utilities:									
a. Power or natural gas ?			✓			✓	✓		
b. Communications systems ?			✓			✓			✓
c. Water ?			✓	✓			✓		
d. Sewer or septic tanks ?			✓		✓		✓		
e. Solid waste and disposal ?			✓	✓			✓		
17. Human health. Will the proposal result in:									
a. Creation of any health hazard or potential health hazard (excluding mental health)			✓	✓			✓		
b. Exposure of people to potential health hazards ?	✓			✓			✓		

Subjects	***Exploration***			***Drilling***			***Operation***		
	Yes	Maybe	No	Yes	Maybe	No	Yes	Maybe	No
18. Aesthetics. Will the proposal result in the obstruction of any scenic vista or view open to the public, or will the proposal result in the creation of an aesthetically offensive site open to public view ?			✓			✓		✓	
19. Recreation. Will the proposal result in an impact upon the quality or quantity of existing recreational opportunities ?			✓	✓			✓		
20. Cultural resources. Will the proposal:									
a. Result in the alteration of or the destruction of a prehistoric or historic archaeological site ?			✓			✓			✓
b. Result in adverse physical or aesthetic effects to a prehistoric or historic building structure, or object ?			✓			✓			✓
c. Have the potential to cause a physical change which would effect unique ethnic cultural values ?			✓			✓			✓
d. Restrict existing religious or sacred use within the potential impact area ?			✓			✓			✓
21. Mandatory finding of significance.									
a. Does the project have the potential to degrade the quality of the environment, substantially reduce the habitat of a fish or wildlife species, cause a fish or wildlife population to drop below self-sustaining levels, threaten to eliminate a plant or animal community, reduce the number or restrict the range of a rate or endangered plant or animal or eliminate important examples of the major periods of history or prehistory ?			✓			✓			✓
b. Does the project have the potential to achieve short-term, to the disadvantage of long-term, environmental goals ? (A short-term impact on the environment is one which occurs in a relatively brief, definitive period of time while long-term impacts will endure well into the future.)			✓			✓			✓
c. Does the project have impacts which are individually limited, but cumulatively considerable ? (A project may have a relatively small impact on each resource, but the effect of the total of those impacts on the environment is significant.)			✓			✓			✓
d. Does the project have environmental effects which will cause substantial adverse effects on human beings, either directly or indirectly ?			✓			✓			✓