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H_2S AND CO_2 DISPERSION MODELLING FOR THE NESJAVELLIR GEOTHERMAL POWER PLANT, S-ICELAND AND PRELIMINARY GEOTHERMAL ENVIRONMENTAL IMPACT ASSESSMENT FOR THE THEISTAREYKIR AREA, NE-ICELAND

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ABSTRACT

A prediction of H_2S and CO_2 dispersion by the Industrial Source Complex Model (ISC3View) in Nesjavellir geothermal power plant is presented. The results from the model show that the H_2S and CO_2 concentrations are lower than those specified in workplace standards. The highest concentrations during the study were observed in July and August, but they were lower than specified in NIOSH and ACGIH standards for H_2S and CO_2. In all cases higher concentrations of both gases were predicted towards the north and northwest. In the second part of the report a preliminary environmental impact assessment for a geothermal project in the Theistareykir area, in northeast Iceland is presented. This area has been investigated for geothermal resources by various researchers in the past few years due to interest in using geothermal steam. A preliminary review is carried out on possible environmental effects due to the proposed project in order to decide whether 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. The result of this study suggests that detailed studies should 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 and operations, as well as a detailed assessment of the biology of the area.

1. INTRODUCTION

The environmental aspects of geothermal development are receiving increasing attention with the shift in attitudes towards the world's natural resources. There is a greater awareness of the effect of geothermal development on the surrounding ecosystems and landscape, and also a growing appreciation of the need for efficient and wide use of all natural resources. 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 effect of 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.

Well proven computer models for predicting dispersion of a gas plume in the atmosphere exist. Gas modelling studies have been widely used in environmental studies in many countries. In these studies, meteorological conditions and emission scenarios are used to predict the expected concentration and deposition rates. Modelling results are used to assess whether to employ pollution abatement technology, including stack height selection. The Industrial Source Complex Model ISC3View (Jesse and Cristiane, 1998) has been used for CO_2 and H_2S dispersion modelling in the power plant and surrounding areas. This model is a Gaussian puff dispersion model designed for two emission categories, continuous (steady state) or instantaneous (transient). In steady-state releases, source characteristics do not vary with time and the release duration is long compared to travel time. For transient release, the source characteristics do not vary with time but the duration of the release from the source is limited.

In recent years attention has been focussed on the utilization of high-temperature geothermal fields as alternatives to hydropower, and potential utilisers of the Theistareykir field include communities in Akureyri and Eyjafjördur with close to 20,000 inhabitants as well as the 6,000-7,000 inhabitants of Thingeyjarsýsla. These communities have also lost people and jobs in recent years. The council energy companies from these communities along with the National Drilling Company and the National Power Company have formed a conglomerate, Íslensk orka hf, with the aim of producing from the local geothermal areas. Drilling is already underway in Öxarfjördur, and spokesmen for the conglomerate have recently stated that they aim to produce electricity on the order of 250 MW from Öxarfjördur and Theistareykir to provide alternative energy for an aluminium smelter which could be situated in NE-Iceland or in Reydarfjördur, E-Iceland.

Before such projects are initiated, an environmental impact assessment is necessary. As regards the Theistareykir area, located in a formerly farmed area in NE-Iceland, it is necessary to predict the environmental effect of a geothermal project. In this report an attempt is made to describe the probable environmental effects of such a project on the area, and to give some recommendations on mitigation of those effects.

2. H_2S AND CO_2 DISPERSION MODELLING IN THE VICINITY OF THE NESJAVELLIR POWER PLANT

Over the past 30 years people have become progressively more anxious about the possible chemical contamination of their land, air and water. The effects of contamination on human health, domestic animals and wildlife are of particular concern, and this has led governments to introduce legislation to protect the environment. Consequently, industrial development in most countries is now subject to environmental legislation. The general responsibility to assess the impacts of, and monitor the chemical quality of their own discharges lies with individual industries. Gases are released from geothermal power plants to the atmosphere; the concentrations of carbon dioxide and hydrogen sulphide are relatively high and may cause air pollution. The amounts of CO_2 and H_2S from geothermal power plants are very low compared to many other types of power plants. Carbon dioxide and hydrogen sulphide emissions from some power plant types are shown in Table 1. Although chemical contamination of the environment may be caused by gas, steam and bore or cooling water discharge, impact can be minimised or even eliminated by careful management.

2.1 Geothermal power plant contamination

Geothermal discharges are generally of two types, gas emission and water discharge. The concentrations of components in steam and wastewater in the power plant are related to the concentration of components in fluid from wells. Important gas and wastewater contaminants in geothermal fluids are described below.

TABLE 1: Carbon dioxide and sulphur emission from some power plant types (Ármannsson and Kristmannsdóttir, 1992)

Plant type		**CO_2 (g/kWh)**	**S (g/kWh)**
Fossil	Coal	1000	11
	Oil	580	11
	Gas	550	0.005
Geothermal	Steam (Krafla, Iceland)	96	
	Hot dry rock	11	0
Solar	SEGS [1]	140	0
	Battery	0	0
Hydropower	------	0	0
Nuclear	------	< 1	0

[1] Solar Energy Generation system, based on "Rankine cycle steam turbine system" which employs gas for top loading.

2.1.1 Gas emission

Geothermal power generation using a standard steam cycle plant will result in the release of non-condensable gases and fine solid particles to the atmosphere. A summary of the discharge and main chemical contaminants from a steam-cycle geothermal power plant in a water-dominated geothermal field is shown in Figure 1. From vapour-dominated fields such as Larderello (Italy) and The Geysers (USA) and fields in which all waste fluids are injected, gas in steam will be the most important discharge from an environmental perspective. The most significant ongoing gas emission will be from the gas exhausters of the power station and sometimes discharge through a cooling tower. Although gas and particulates will also be discharged during well drilling, bleeding, and clean-outs and testing, as well as from line valve and waste bore water degassing, this is usually insignificant by comparison.

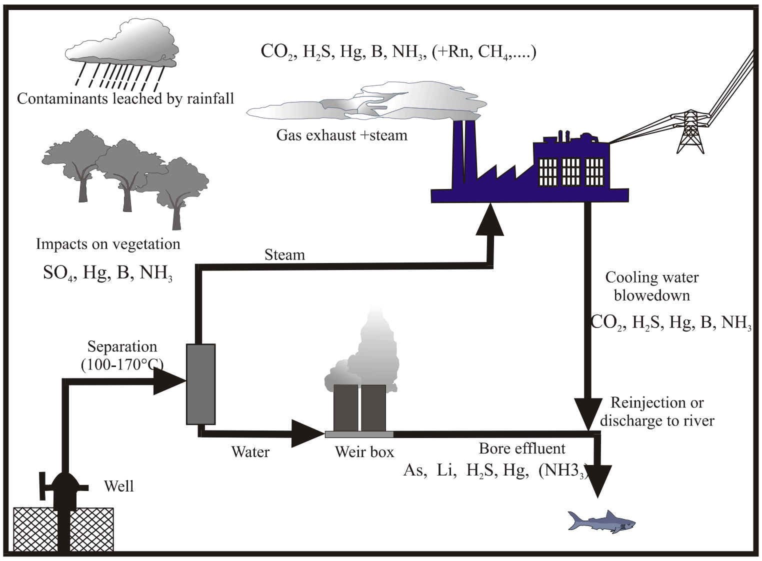

FIGURE 1: A summary of the discharges and main chemical contaminants from a steam-cycle geothermal power plant in a water-dominated geothermal field (Webster, 1995)

Geothermal gases are carbon dioxide (CO_2), hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N_2), ammonia (NH_3), hydrocarbons such as methane (CH_4) and ethane (C_2H_6), trace amounts of mercury (Hg), boron (B) vapour and helium (He) and radon (Rn). Carbon dioxide and hydrogen sulphide are the main hazardous chemical substances in geothermal fluids, and it is necessary to devise a monitoring programme for those in geothermal power plants. Short descriptions of both gases follow.

Hydrogen sulphide (H_2S) appears to be universally present in geothermal fields in quantities sufficient to be of environmental concern. The impact of H_2S discharge will depend on local topography, wind patterns and land use, but the effects include an unpleasant odour, equipment corrosion, eye irritation and respiratory damage in humans. Hydrogen sulphide is a heavy gas; it is extremely flammable and highly toxic. At low concentration the smell is very easily detectable but when concentration increases beyond a certain level, the smell senses are deadened and there is no detectable odour. There is no accumulation in the body, and the gas is excreted through urine, intestines and expired air. Hydrogen sulphide is likely to be of greater health significance in the work environment (e.g. a power plant) than in relatively distant areas. The "National Institute for Occupational Safety and Health" (NIOSH) (Webster, 1995), and the "American Conference of Governmental and Industrial Hygienists" (ACGIH) air quality standards for the protection of occupational health give limits of 10 ppm for H_2S in atmospheric air. The effects of hydrogen sulphide on humans are shown in Table 2.

TABLE 2: Hydrogen sulphide effects on humans (Sheu, 1984)

Concentration (ppm)	Effects
0.0007- 0.03	Odour threshold
0.33	Distinct odour; can cause nausea, headaches
2.7 - 5.3	Odour offensive and moderately intense
20 –33	Odour strong, not intolerable
100	Causes loss of sense of smell in a few minutes
210	Smell not as pungent, probably due to olfactory paralysis
667	Can cause death quickly due to respiratory paralysis
750	Virtually no odour sensation, death can occur rapidly upon very short exposure

Detection by smell is possible at a concentration of about 0.03 ppm. As the concentration increases, the odour becomes sweeter and finally the odour disappears at around 150 ppm, thus smell is not a reliable indicator of concentration. Because H_2S is a heavy gas, it accumulates in depressions and still, low lying areas. H_2S occurs near gas exhausters in power stations and in fumarolic geothermal areas. Continuous monitoring is required, and personnel required to enter risk areas should carry individual monitors. H_2S dissolved in water, such as fog, may react with atmospheric oxygen to form more oxidised sulphur compounds. Although some of these oxidised sulphur compounds have been identified as components of "Acid rain", a direct link between H_2S emission and acid rain has not been established. Results of recent studies suggest that only a small fraction of H_2S is oxidised in air (Kristmannsdóttir et al., 1999).

Carbon dioxide (CO_2) and hydrogen sulphide occur in similar environments. Carbon dioxide is also a heavy gas, and accumulates in pits and low depressions. It is most common in geothermal steam, at concentrations of 500 ppm to 20,000 ppm. Unlike H_2S it is not highly toxic, but a large intake can be fatal due to alteration of blood pH. CO_2 is odourless and has a slightly acid taste.

A 5 % concentration in air (500,000 ppm) can produce shortness of breath, dizziness, mental confusion, headache and possible loss of consciousness. At 10 % concentrations, the patient normally loses consciousness and will die unless removed. With little or no warning from taste or odour, it is possible to enter a tank or a pit, full of CO_2, be overcome and asphyxiated in a very short time. Long term exposure at concentrations of 1-2 % can cause increased calcium deposition in body tissue, and may cause mild stress and behavioural changes. Monitoring is normally accomplished by measuring oxygen levels. Many monitors record H_2S, O_2 and explosive gases simultaneously. The "National Institute for Occupational Safety and Health" (NIOSH) air quality standard for the protection of occupational health sets the limit for CO_2 at 10,000 ppm for 10 hours. The "Occupational Safety and Health Administration" (OSHA) air quality standards for the protection of occupational health sets the limit for CO_2 at 5,000 ppm (Webster, 1995).

2.1.2 Bore and waste waters

Unless all waste borewater and cooling water blowdown is reinjected, geothermal fluid discharge may have an impact on local and regional surface waters such as rivers, lakes and estuaries. The chemical composition of the fluid discharge is largely dependent on the geochemistry of the reservoir, and the operation conditions used for power generation. Reservoir chemistry will be different for different fields. For example, geothermal well fluids of the Salton Sea geothermal field in the USA, which is hosted by evaporite deposits, are acidic and highly saline (pH < 5, [Cl]=155,000 ppm). At the other extreme are the fields in Iceland that are alkaline and of very low salinity (pH >9, [Cl] <200 ppm). Most borewaters include high concentrations of hydrogen sulphide (H_2S), and possibly a significant concentration of at least one of the following chemical contaminants: lithium (Li), boron (B), arsenic (As), mercury (Hg) and sometimes ammonia (NH_3).

If these components are released into a river or a lake they can potentially damage aquatic life, terrestrial plants and human health. In natural geothermal features, the impact of such contaminants may be controlled by precipitation near the feature of fixation in soils and sediments. Hg and NH_3 are readily taken up by soils. Contamination of groundwater can be avoided by casing wells through the groundwater zone, avoiding uncontrolled flows containing fluids and mud.

2.2 Predicting and monitoring

Before a geothermal field is developed, the chemistry of the gas and water discharges needs to be predicted so that potential environmental impacts can be assessed. Discharge during both development and long term operation needs to be considered. The chemistry and relative importance of air and water discharge will depend on the nature of the field, the surrounding environment and on the operating procedures used during power generation.

For a power station with re-injection of wastewater and cooling water blowdown, or for stations in vapour-dominated fields such as the Geysers or Larderello, attention will focus on gas and steam emissions. Steam is released from wells during drilling, well cleanout and production testing, as well as from the power station during normal operation. The levels of H_2S, B and NH_3 in the steam emissions will depend on their concentrations in the geothermal fluid, the temperature of separation and, for power plant emissions, the efficiency of condensing systems.

Well proven computer models for predicting dispersion of a gas plume in the atmosphere exist. These models use physical controls on air movement, such as wind patterns and topography, to predict contaminant gas movement and where plume contact with land is likely. Such programs include **ISC3View** developed by the U.S. Environmental Protection Agency (EPA), Industrial Source Complex Short-Term Model (ISCST3) (Jesse and Cristiane, 1998), and **AFTOX** (1991), The Air Force Toxic Chemical dispersion model that was developed by Trinity consultant company. Alternatively, for a power station discharging borewater and cooling water to a major river, the environmental impact of fluid discharge is of paramount importance. An average water-dominated field will produce of the order of 3-10 tonnes of saline borewater for every tonne of steam. There are also computer models, which are designed to model speciation in fresh and marine waters. Some of the more commonly used programs are: **MINTEQA2** developed by the USEPA (Felmy et al., 1984); the **EQ3NR** models developed by Wolery (1983) at Lawrence Livermore Laboratory in the USA; SOLVEQ**,** a computer program for computing aqueous-minerals-gas equilibria, by the University of Oregon (Reed and Spycher, 1984); **CHILLER,** a program for computing water-rock reactions, boiling, mixing and other reaction processes in aqueous-mineral-gas systems developed by the University of Oregon (Reed and Spycher, 1984); **WATCH**, Icelandic Water Chemistry Group, developed by the Science Institute, University of Iceland and Orkustofnun (Arnórsson et al., 1982, and Bjarnason, 1994). An understanding of contaminant chemistry is needed to reliably interpret the results of these models.

2.3 Nesjavellir geothermal area (study framework)

Once a plant is in operation, an ongoing monitoring program is required. If predictions are accurate and limits set for air and water discharge quality can be met, monitoring will become a routine procedure. If accurate and complete records are kept, there should be few problems for the duration of the discharge permit or consent (normally between 5 and 20 years).

Icelandic geothermal resources have traditionally been divided into two main groups depending on reservoir temperatures. The high-temperature reservoirs have temperatures exceeding 200°C and the low-temperature reservoirs have temperatures of less than 150°C at one km depth (Bödvarsson, 1961). Hengill is one of the largest high-temperature areas in Iceland. It is divided geologically into three separate volcanic systems. Each system has a volcanic centre and a SW-NE trending fissure swarm. This configuration is typical of active centres in the volcanic rift zones. The Hengill geothermal area covers about 100 km^2 as defined by geophysical measurements. It is divided into five geothermal fields on the basis of surface thermal activity and geological features. These five geothermal fields are Nesjavellir (northern Hengill), Ölkelduháls (eastern Hengill), Kolvidarhóll (western Hengill), Hveragerdi and Hengladalir.

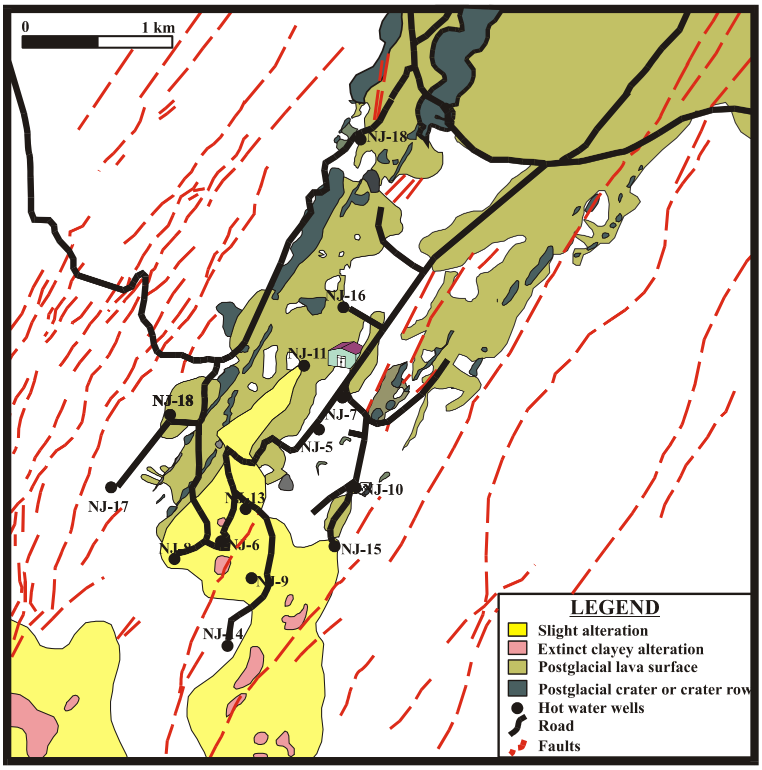

FIGURE 2: The Nesjavellir production field

The Nesjavellir geothermal reservoir is situated in the northern part of the Hengill geothermal system. The study area including the power plant, is about 25 km^2 (Figure 2). The exploration of the Nesjavellir field started in 1964, and drilling began in 1965 and has continued till now. Extensive geothermal exploration has been carried out in the Nesjavellir field, prior to, during and after geothermal drilling. These include geological mapping, geophysical surveys (resistivity, magnetic, gravity and seismic monitoring), field geochemistry, subsurface geology, borehole geophysics and reservoir modelling. A summary of a few of the results of these studies follows.

- The surface geology has confirmed that the main outflow channel of the geothermal system coincides with volcanic fissures along the Kýrdalshryggur ridge, which erupted 7000 and 2000 years ago.
- Resistivity surveys revealed a low resistivity in the Hengill volcano but increasing resistivity to the northeast, concomitant with decreasing temperature and deepening of the geothermal reservoir. It also points to the Kýrdalshryggur fissure as the main geothermal outflow channel, and a N-S geothermal structure crossing the Nesjavellir valley.
- Temperature and pressure logging in the wells have shown a three-dimensional variation in the reservoir, where the core of the reservoir is a two-phase boiling system, surrounded by a liquid-dominated system. The two-phase system is mainly found in the southern part of the reservoir. There is some evidence of a supercritical fluid deep within the reservoir (below 2-3 km) near the Kýrdalshryggur volcanic fissure (Gunnarsson et al., 1992).

2.3.1 Nesjavellir power plant

The geothermal power plant at Nesjavellir consists of the following five sub-systems all of which have separate functions:

- Geothermal fluid supply;
- Electricity co-generation;
- Cold water supply;
- Heating and treatment of cold groundwater;
- Transmission of water by pipeline to Reykjavík.

Co-generation of the power plant is 150 MWt for district heating and 60 MWe for electricity generation; the design is for two power stations of similar size. The development of the Nesjavellir power plant is summarised in Table 3.

TABLE 3: The development process of Nesjavellir power plant

Phase	Development	Year of development
Phase 1	100 MWt	1990
Phase 2	150 MWt	1992
Phase 3	150 MWt + 60 MWe	1998

The geothermal fluid supply system gathers the fluid from 10 production wells, and steam mixed with water is conveyed to the separating station where the water is separated from the steam. Excess steam and water are piped through a steam exhaust outside the separating station. From the separating station, 115 kg/s steam and 211 kg/s water proceed by separate pipes to the power plant at a pressure of about 12 bars and a temperature of 190°C. The steam is conveyed to two steam turbines, each turbine producing about 30 MWe, and the water goes to heat exchangers to heat the cold ground water.

Due to scaling, the geothermal fluid from the Nesjavellir field cannot be used directly in the space heating distribution network. In this system, cold groundwater at about 4°C is pumped from five shallow boreholes near Grámelur at nearby Lake Thingvallavatn to about 6200 m north of the powerhouse. From the wells, 1072 kg/s of 4°C temperature water is piped through a 900 mm diameter pipe to the 1000 m^3 storage tank by the power house. In this power plant there are five heat exchangers, and they use geothermal water at 90-188°C to heat cold groundwater. The heated water is pumped to a hot water storage tank and then piped to Reykjavík, about 32 km. The flow diagram for the Nesjavellir power plant is shown in Figure 3.

2.3.2 Discharges from the power plant

Gas emission. In the Nesjavellir power plant all spent geothermal fluid is discharged to the environment after use, and about 95% of the gas is released to the environment. Most of the gas is released from two points, the steam separator and the condenser. All the geothermal fluids from the wells are piped to the separating station and separated into liquid and steam (115 kg/s) that go directly to turbines and the heat exchangers, releasing most of the non-condensable gas to the atmosphere; dissolved gas is released to the atmosphere from the steam separator.

The annual emission of each gas from the Nesjavellir power plant can be calculated from the total fluid flow rate, gas fraction of fluid and the concentration of each gas in the fluid. H_2S and CO_2 are the main non-condensable gases that are released to the atmosphere. The annual release of CO_2 and H_2S is shown in Figure 4. The amount is directly linked to the flow of steam and water from boreholes, and a marked increase in gas release occurred after electricity production started. From 1994 to 1998 the annual release was about 7000 tonnes of CO_2 and 2000 tonnes of H_2S per annum, respectively, but will be close to 12000 tonnes and 3700 tonnes, respectively, in 1999.

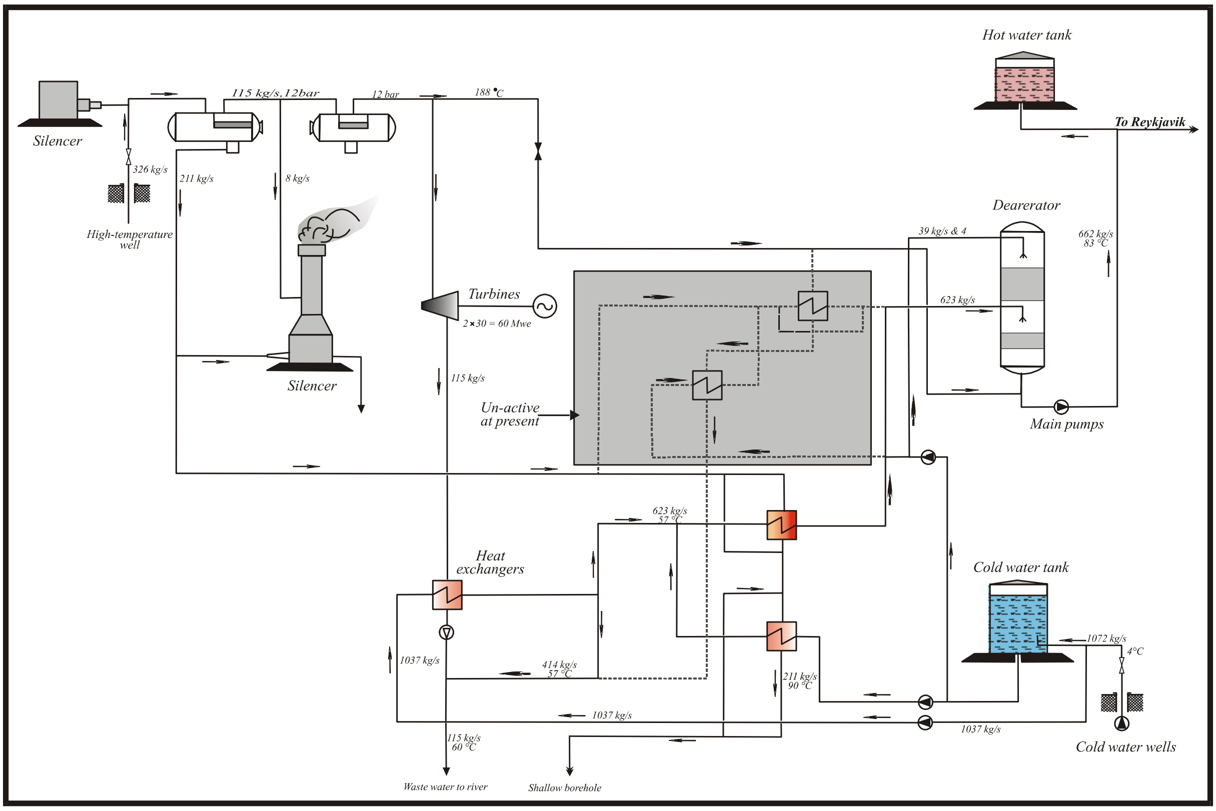

FIGURE 3: The flow diagram for the Nesjavellir power plant
(by permission of Reykjavík Energy Co.)

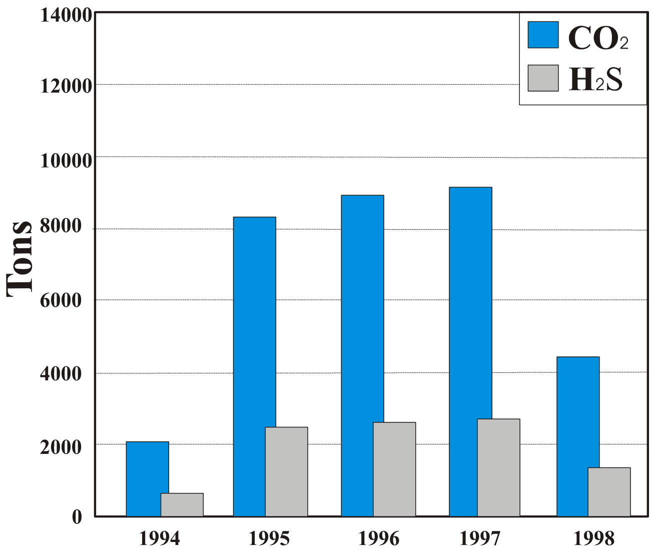

FIGURE 4: Total amount of CO_2 and H_2S released to the atmosphere from Nesjavellir power plant (mod. from Gíslason, in prep.)

Wastewater discharge and effects. In this power plant there are two important discharge routes for wastewater, injection into shallow wells and release to a stream. About 211 kg/s of 99°C water from heat exchangers used to heat cold water are injected into many shallow wells, and about 115 kg/s of 60°C water from turbines and two heat exchangers are discharged to the stream. All wastewater finally flows into Lake Thingvallavatn.

According to Ólafsson (1992) the chemical discharges from the power plant are diluted with groundwater flow in the Nesjavellir brook. Some components of the discharge may behave conservatively; the concentrations of others are likely to be modified by mineral reactions. The silica concentration of the drillhole water is high on account of high underground temperature. When cooled it becomes supersaturated with respect to amorphous silica which precipitates. Thus, only a fraction of the silica discharge is likely to reach Lake Thingvallavatn. Similarly, hydrogen sulphide is unstable in an oxygenated environment and groundwater, and the fraction, which does not escape to the atmosphere or precipitate as elemental sulphur, may be in sulphate form when it reaches Lake Thingvallavatn. Mercury in the gaseous emanations is in the form of elemental Hg, which is volatile. The speciation of Hg in the steam and in the drillhole water has not been investigated but both elemental Hg and $Hg(OH)_2$ are likely to be present.

2.4 Dispersion model description

Dispersion modelling in this power plant was carried out for six months, from March 1999 until August 1999. Due to the differing amounts of discharge from the power plant, in winter time and summer time a period including both winter and summer month discharges was used for monitoring, and dispersion of CO_2 and H_2S modelled.

Gaseous modelling studies have been widely used in environmental studies in many parts of the world. Gaseous puff models use an equation to describe the dispersion of a puff with time. In these studies, the meteorological conditions and emission scenarios are used to predict the expected dispersion rates. Modelling results are used to assess whether pollution abatement technology, including stack height selection, is needed. The Industrial Source Complex Model (ISC3View) has been used for CO_2 and H_2S dispersion modelling in the power plant and the surrounding area. This model is a Gaussian puff dispersion model designed for two emission categories, continuous (steady-state) and instantaneous (transient). In steady-state releases, source characteristics do not vary with time and release duration is long compared to travel time. For transient release, the source characteristics do not vary with time but the duration of the release from the source is limited. Some of the ISCView modelling capabilities are:

- ISCView model may be used to model primary pollutants and continuous releases of toxic and hazardous waste pollutants.
- ISCView model can handle multiple sources, including point, volume, area, and open pit source types. Line sources may also be modelled as a string of volume sources or as elongated area sources.
- Source emission rates can be treated as constant or may be varied by month, season, hour-of day, or other optional periods of variation. These variable emission rate factors may be specified for a single source or for a group of sources.
- The model can account for the effects of aerodynamics due to nearby building or point source emissions.
- The model contains algorithms for modelling the effects of settling and removal (through dry deposition) of large particulate and for modelling the effects of precipitation scavenging gases or particulate.
- Receptor locations can be specified as gridded and/or discrete receptors in Cartesian or polar coordinates.
- ISCView incorporates the COMPLEX1 screening model dispersion algorithms for receptors in complex terrain.
- ISCView model uses realtime meteorological data to account for the atmospheric conditions that affect the distribution of air pollutant impacts on the modelling area.
- Results can be output for concentration, total deposition flux, dry deposition flux, and/or wet deposition flux.

This chapter deals with a brief description of some of the mathematical formulations involved in this model.

2.4.1 The Gaussian diffusion equations

The ISC3View model for stacks uses the steady-state Gaussian plume equation for a continuous elevated source. For each source and each hour, the origin of the source's coordinate system is placed at ground surface at the base of the stack. The X-axis is positive in the downwind direction; the axis is crosswind (normal) to the Y-axis and the Z-axis extends vertically. The fixed receptor locations are converted to each source's co-ordinate system for each hourly concentration calculation. The hourly concentration that is calculated for each source at each receptor is summed up to obtain the total concentration produced at each receptor by the combined source emissions.

For the steady-state Gaussian plume, the hourly concentration at downwind distance X (m) and crosswind distance Y (m) is given by:

$$C = \frac{QKVD}{2\pi u_s \sigma_y \sigma_z} \exp[-\frac{1}{2}(\frac{y}{\sigma_y})^2] \qquad (1)$$

where Q = Pollutant emission rate (mass per unit time);
K = Scaling coefficient to convert calculated concentrations to desired units (default value for Q of 1×10^6 g/s and concentration in $\mu g/m^3$);
V = Vertical term;
D = Decay term;
σ_x σ_y = Standard deviation of lateral and vertical concentration distribution (m);
u_s = Wind speed at release height (m/s).

Cox and Sheppard (1980) and Cox and Sandalls (1974) have estimated average removal rates of hydrogen sulphide. Using an average reaction rate $5'10^{-12}$ cm^3/s and an average hydroxyl concentration of $3'10^6$ molecules/m^3, an average removal rate of hydrogen sulphide was estimated to be approximately 5% per hour. This will give an exponential decay rate of $1.425'10^{-5}$ s^{-1} when used in the ISC3View model.

Model runs with and without the decay showed very little difference over the grid for a study of the Olkaria field in Kenya (Sinclair Knight and ESA Pty Ltd, 1994). In the present study a similar removal rate of 5% per hour was used.

2.4.2 Atmospheric stability

Together with distance from source, the atmospheric stability affects the dispersion parameters (s_x, s_y). It is often defined by the Pasquill stability categories, which rank from category A for a stable atmosphere to E for an unstable atmosphere. In the model, the default wind speed parameter ranging from 1.54 m/s to 10.18 m/s is used in place of the discrete stability categories, and also wind speeds that are changeable by the user. The relationship between the Pasquill stability category and the wind speed parameters used in the model are shown in Table 4.

TABLE 4: The relationship between the Pasquill stability categories (SC) and the wind speed (m/s) parameter (WS)

SC	A	B	C	D	E
WS	1.54	3.09	5.14	8.23	10.18

To define the stability parameter, the model employs one of two methods, using wind speed and solar isolation or using the standard deviation of the wind direction to define the stability parameter. In the former case, Golder's nomogram (Golder, 1972) is used to determine stability, where the Monin-Obukhov length (L) and surface roughness are related to the stability categories. Since L is a function of friction velocity, u_* and sensible heat flux H, these two parameters must also be calculated. In the latter case, stability is obtained by calculation using the Modified Theta (MST) approach (Mitchell, 1982).

2.4.3 Calculating the solar elevation angle

The solar elevation angles for a given time and locations are calculated by the following method described by Woolf (1980):

$$\sin\phi = \sin LA \sin D + \cos LA \cos D \cos H \qquad (2)$$

where LA = Station latitude;
D = Solar declination angle, and;
H = Solar hour angle.

Solar declination angle is a sinusoidal function of time with maximum and minimum angles occurring during summer and winter, respectively. There is a slight asymmetry, due to the ellipticity of the earth's orbit, which is accounted for in the following expression for calculating declination:

$$\sin D = \sin 23.4438 \sin \sigma \tag{3}$$

where $\sigma(deg) = a + 179.9348 + 1.914827 \sin a - 0.079525 \cos a + 0.019938 \sin 2a - 0.001620 \cos 2a$

The angular fraction of a year, a, for a particular date is given by

$$a = 360(JO - 1)/365.242 \tag{4}$$

where JO = Julian date.

The solar hour angle, H, a measure of the longitudinal distance to the sun from the point for which the calculation is made, is given by

$$H(°) = 15(ZO - M) - LO \tag{5}$$

where ZO = Greenwich mean time (GMT) of the calculation (hour);
M = Time of the meridian passage, or true solar noon (hour), and;
LO = Station longitude, positive being west of Greenwich .

M is divided into

$$M = 12 + 0.12357 \sin a - 0.004289 \cos a + 0.15809 \sin 2a + 0.06078 \cos 2a \tag{6}$$

2.5 Meteorological parameters in the Nesjavellir area

The meteorological parameters required by both models are surface observation data and upper air observation data, which are obtained by sending a sensor attached to a balloon into the atmosphere. The sensor sends signals to the computer at the earth's surface. The models require surface data for temperature, dry bulb temperature, cloud cover percentage, cloud height, wind speed and direction of wind. The upper air data that is required is the mixing layer height. ISC3View can estimate the mixing layer height from the surface data. The meteorological information for the Nesjavellir area has been taken from the Reykjavik station, which is located 32 km west of the Nesjavellir area.

Wind patterns in the Nesjavellir area. Wind analysis was carried out for the period from March to August 1999, the period that H_2S and CO_2 measurements taken. It is evident that the dominant wind patterns for these months are different. In March and April the dominant wind directions are north and east, and this means that transport of H_2S and CO_2 in these months is to the south and west. In May and July the wind directions are very different, almost equal wind in all directions with a very slight dominance in a northeasterly direction. In June, the main wind direction is southeasterly and the transport of H_2S and CO_2 in this month is to the northwest. In August, the main wind directions are southwesterly and the transport of H_2S and CO_2 in this month is to the northeast. Month to month wind rose diagrams are shown in Figure 5.

2.6 H_2S and CO_2 sampling and measurement methods

2.6.1 Sampling method

To obtain H_2S and CO_2 concentrations in steam from the silencer and the condenser, gas samples were collected with vacuum flasks used for the collection. The flask is evacuated by a pump and boiling, dried

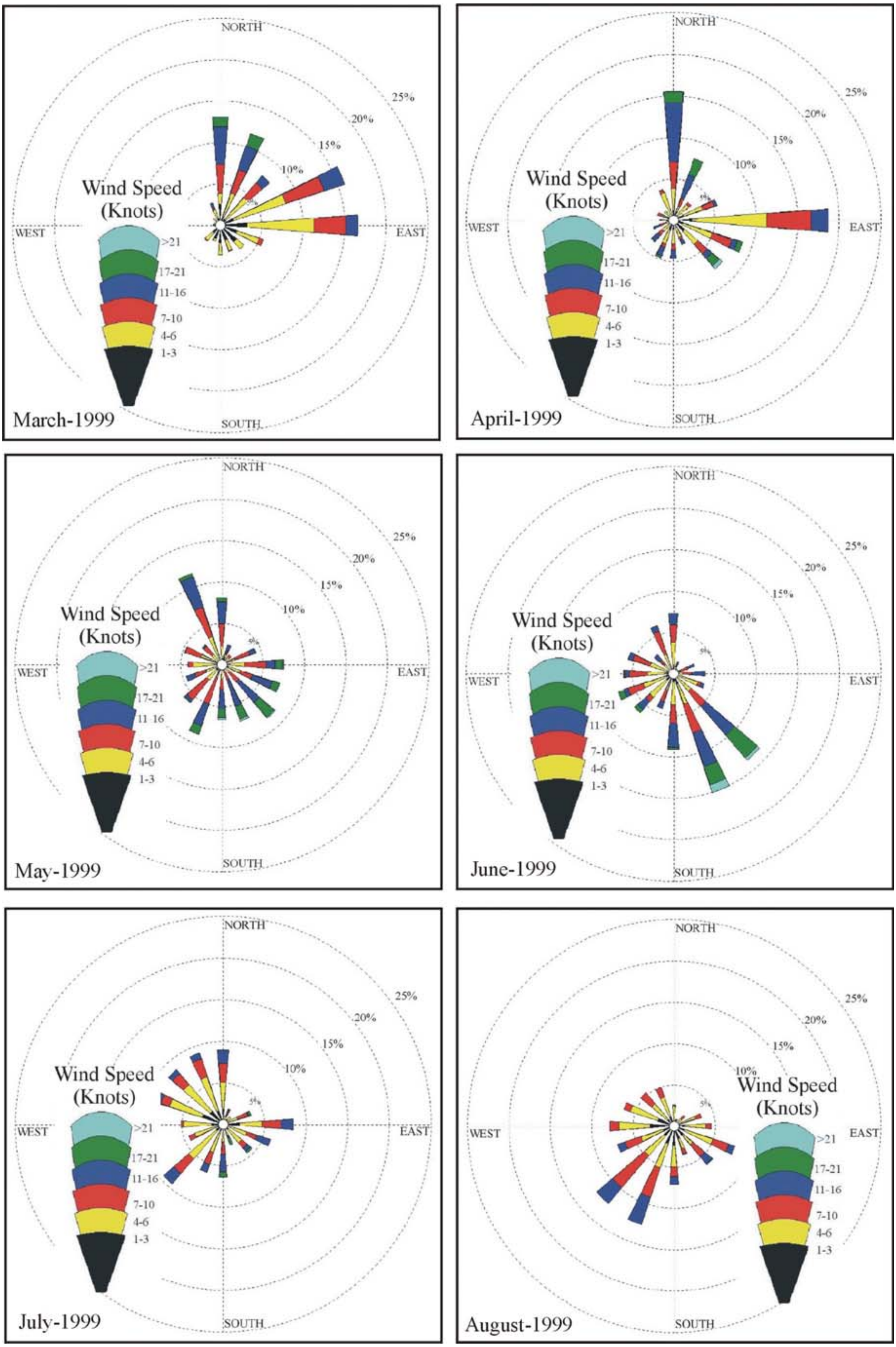

FIGURE 5: Windrose diagrams for March - August 1995 for the Nesjavellir area

and weighed (M_0). This flask consists of an evacuated 300 ml cylindrical, round bottomed flask equipped with a Rotaflo teflon stopcock, containing 50 ml of 4N NaOH. During sampling the condensate is added to the sodium hydroxide solution and the gaseous carbon dioxide and hydrogen sulphide are dissolved. The flask is shaken intermittently and the steam collected through the NaOH solution until bubbling stops. When the collection is finished, the flask is weighed again (M_s) and the total volume of the sample and the NaOH solution (V_s) is measured. Finally we can calculate the ratio (R), which is needed when analysing for CO_2 and H_2S.

2.6.2 Analytical methods

H_2S and CO_2 in the flask are absorbed by 4N NaOH. The alkaline samples, together with blanks for the 4N NaOH absorbent, are diluted to 200 ml with deoxygenated, distilled water, and analysed for CO_2 and H_2S.

To analyse for CO_2, a 2-10 ml oxidised sample is diluted with 50 ml distilled water. After adjusting, the pH of the solution, using a pH-meter first with 2 N HCl, then with 0.1N HCl to 8.2, the solution is titrated with 0.1N HCl to pH 3.8.

$$(\text{mg } CO_2 \text{ collected}) = 1760 \text{ (ml N/10 HCl)(ml sample)} - 1.182\ H_2S$$

To determine the concentration of H_2S, 0.1– 0.2 ml of the sample are combined with 5 ml of 5N NaOH solution, 10 ml of distilled water, 5 ml of acetone and a pinch of dithizone, and titrated with 0.001M $Hg(CH_3COO)_2$, the amount of $Hg(CH_3COO)_2$ is then recorded (Ólafsson, 1988).

2.7 ISC3View predictions

The model was used to predict 1, 3, 8, and 24 hourly gas concentrations; monthly, and 5 monthly concentrations were also considered. In the ISC3View model the emission parameters shown in Table 5 were used.

TABLE 5: Emission parameters used in ISC3View model for dispersion modelling

Parameter	Silencer	Condenser
Stack height (m)	25	24.5
Stack exit diameter (m)	2.02	0.273
Gas exit temperature (°C)	192	105
Gas exit velocity (m/s)	2.76	3.87
Pressure (bar)	2	1.5
Total flow rate (kg/s)	8.25	0.476
CO_2 flow rate (g/s)	26	376
H_2S flow rate (g/s)	7	100

In this study a 1-hour average time was used for predicting H_2S and CO_2 concentrations. The power plant data and meteorological data obtained during the study and the ISCView dispersion modelling program have been used to make predictions about the dispersion of H_2S and CO_2. The program only takes account of the amount of gas released from the power plant source points, and the CO_2 naturally present in the atmosphere needs to be added to the results. The natural concentration of CO_2 in unexploited Icelandic geothermal fields such as the Theistareykir area in NE-Iceland is on average 450 ppm, and this concentration has been used to obtain a realistic distribution of CO_2 in the study area. Predicted dispersion of CO_2 from March to August 1999 is shown in Figure 6 and for H_2S in Figure 7.

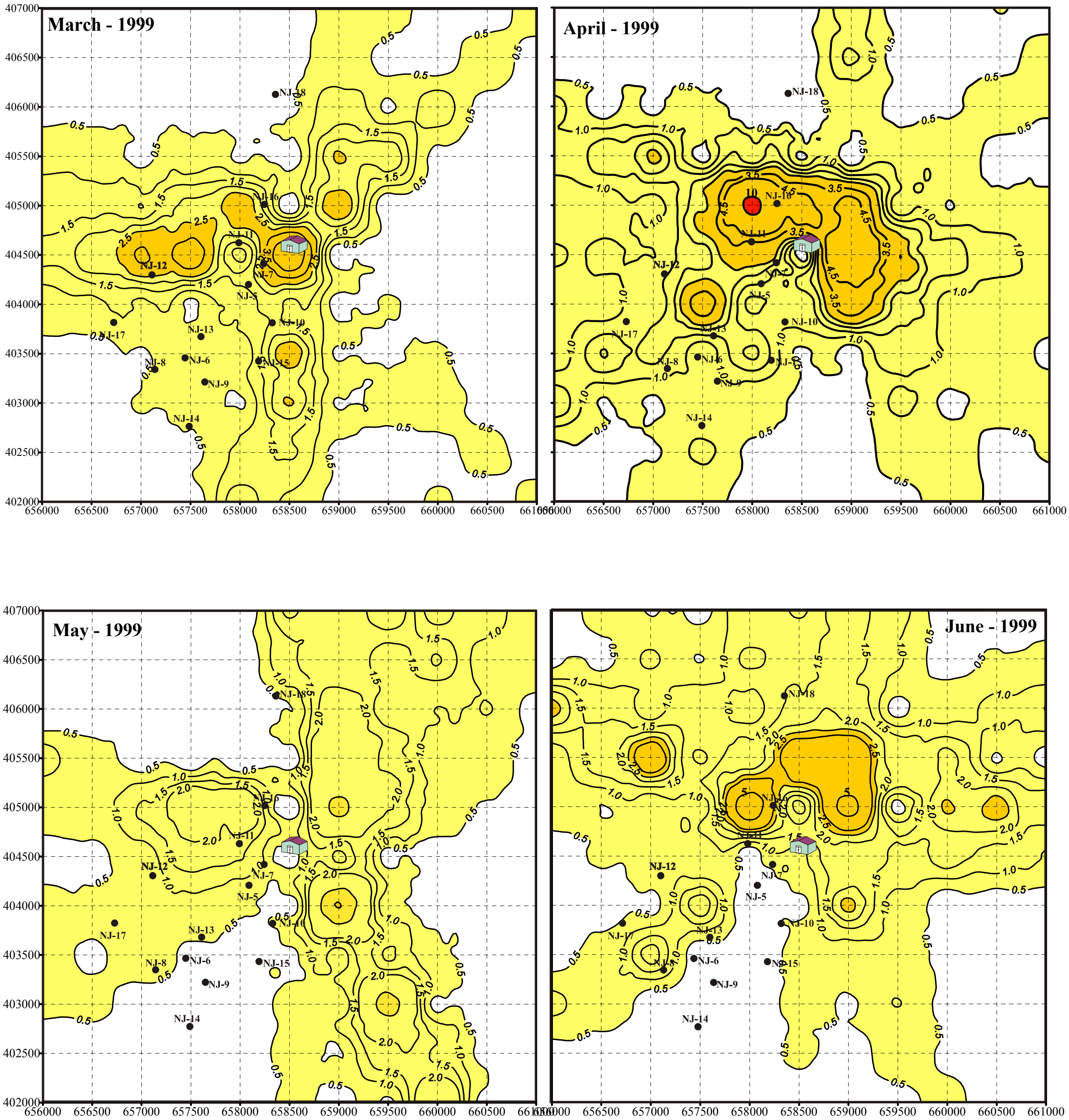

FIGURE 6: Predicted dispersion of CO_2 at Nesjavellir from March to August 1999

Results for H_2S distribution in March and May are almost the same, i.e. the gas from the power plant moves to north, west and southeast. The maximum concentration of H_2S, is about 4 ppm, close to the powerhouse, but the maximum concentration is lower than the levels set by the NIOSH and ACGIH as standards for workers. In April and June the distribution trend of H_2S is mainly to east and west. Only in a small part of the area close to wells NJ-11 and NJ-16 does the H_2S concentration reach 10 ppm, the threshold for workers. In July the maximum concentration of H_2S is around the powerhouse and to the north and northwest, but in this month the area where 10 ppm (threshold for workers) is exceeded is larger than that in March, May, April and June. In August, the area with relatively high H_2S concentration is the largest, and lies close to the east corner of the powerhouse.

The predicted results for CO_2 show mainly northeasterly and southeasterly distribution, but the movement directions in March, May and June are westerly, easterly and southeasterly, in April northerly and westerly, and mainly easterly in August.

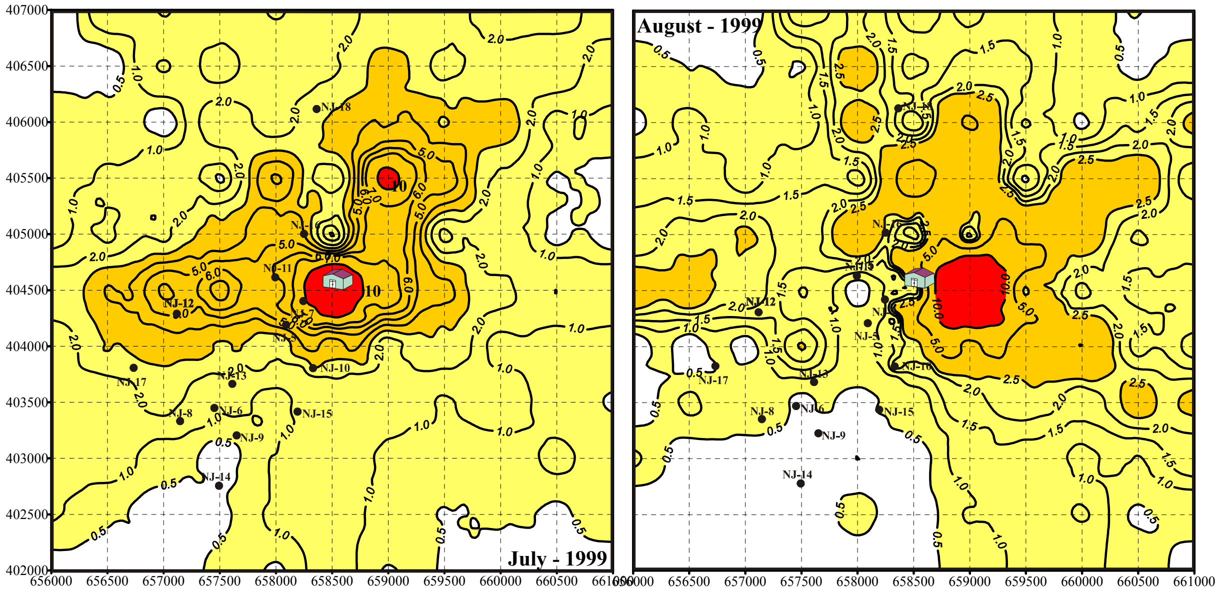

FIGURE 6: Continued

The results show that the concentration of CO_2 is, in all cases, less than 600 ppm, much lower than the level set by the "National Institute for Occupational Safety and Health" (NIOSH) air quality standard for the protection of occupational health for CO_2 which is 10,000 ppm for 10 hours, and the "Occupational Safety and Health Administration" (OSHA) air quality standards for the protection of occupational health for CO_2 which is 5,000 ppm. Thus, there is no CO_2 pollution in the Nesjavellir power plant and surrounding area.

2.8 Summary

The main objectives of the work were to model hydrogen sulphide and carbon dioxide dispersion in the area around the Nesjavellir geothermal power plant, to define the dispersion of H_2S and CO_2 in a 25 km^2 area surrounding it and compare the results with threshold values. The main conclusions are as follows:

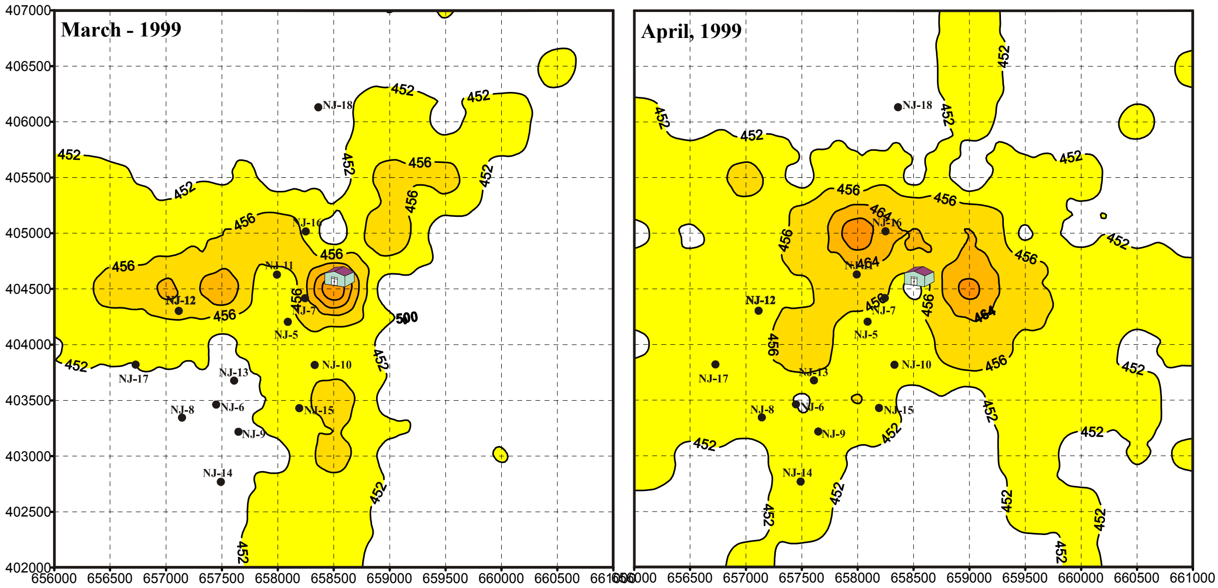

FIGURE 7: Predicted dispersion of H_2S at Nesjavellir from March to August 1999

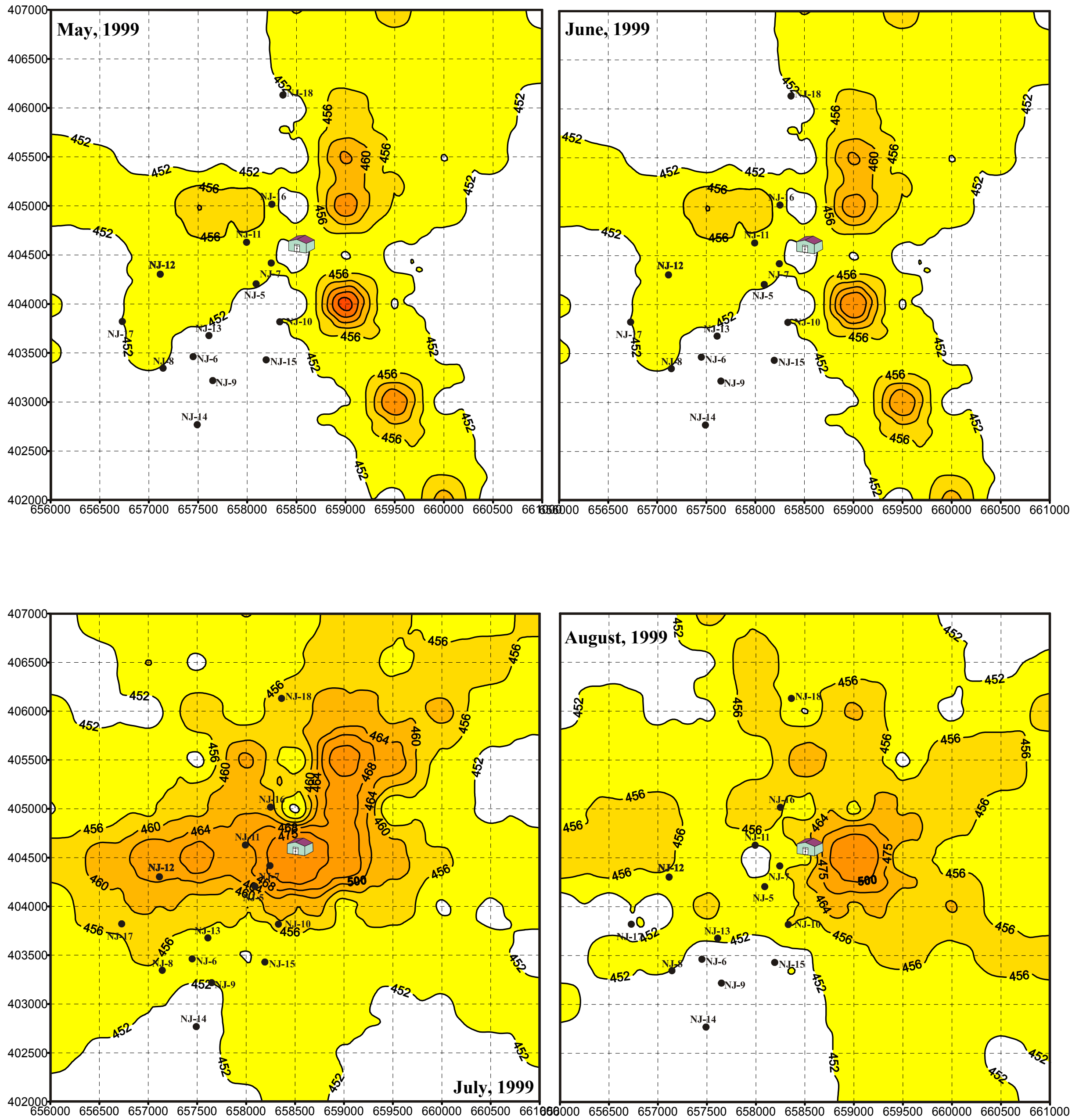

FIGURE 7: Continued

- The concentrations of H_2S in March, April, May and June are lower than the H_2S threshold values for workers published by the "National Institute for Occupational Safety and Health (NIOSH), and those of the "American Conference of Governmental and Industrial Hygienists (ACGIH)" air quality standards. Thus H_2S from the atmosphere is not expected to cause any damage to workers and tourists during these months.
- The concentration of H_2S only exceeds 10 ppm (the threshold value for workers) in a very small area around the powerhouse during July and August and is not expected to pose any danger.
- The concentration of CO_2 is, in all cases far below the quality standards of the "National Institute for Occupational Safety and Health (NIOSH), and those of the "American Conference of Governmental and Industrial Hygienists (ACGIH)" which are on the order of 5,000 to 10,000 ppm, whereas the maximum observed in the study area was 600 ppm.

3. PRELIMINARY ENVIRONMENTAL IMPACT ASSESSMENT FOR A GEOTHERMAL POWER PLANT IN THE THEISTAEYKIR AREA

3.1 Environmental impact of geothermal projects

Environmental impacts from geothermal development vary during the various phases of development. Geothermal development can be described as a three part process:

- Preliminary exploration
- Drilling
- Production and utilization

This section describes the typical activities for each phase of development and the nature of the effects that can be expected during each phase. The environmental effects of direct use geothermal projects are generally related to very minor surface disturbances required for one or two wells. The geothermal fluid is not emitted to the atmosphere or the surface during direct use applications such as space heating or food drying.

The operation of a geothermal power station, with major fluid withdrawal by wells, inevitably affects the natural thermal activity in the area. Changes occur, both in intensity and in the nature of activity. In this section of the report most impacts of geothermal activity are considered.

3.1.1 Impacts on geology and land

Preliminary exploration is the least expensive exploration activity with the least environmental effect. There are usually no environmental effects of geologic mapping as it only involves walking or aerial reconnaissance over the exploration area. Sampling procedures during this phase are also benign. Temperature gradient well drilling requires only small areas of surface disturbance to construct a level area for the drill rig.

In geothermal projects most land effects occur during drilling. Each drill site is usually between 200-2500 m^2 in area and the soil in these areas is compacted and changed, and close to the drill site there is also some deposition of waste soil and drill mud. To transport the drill rig and other instruments, road construction may be needed and this affects the land. Construction of roads, well pads, and power plant sites results in cut and fill slopes that reshape the topography, but this effect on the topography is not significant.

During installation there is some effect on the land from soil movement for construction of pipelines, power plant and other buildings. During operation, subsidence and induced seismicity are the main possible effects on the land around the power plant and surrounding areas. In areas of low rock strength, the withdrawal of massive quantities of fluid from the ground may cause subsidence of the ground surface. Withdrawal of geothermal water from any type of reservoir will normally result in a reduction of pressure in the formation pore space and this can lead to subsidence. 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 area as it can have serious consequences for the stability of the pipelines, drains and well casings in a geothermal field. If a field is close to a populated area it can lead to instability. In more remote areas, where there may be no habitation, the local surface water system may be affected. Before production, a baseline levelling survey and gravity measurements with the installation of levelling stations need be carried out at a number of separate survey stations to cover as long a time as possible before production so that the local tectonic change in level, if any, can be subtracted from those due to exploitation. While having a subsidence potential, hydrothermal reservoirs are not as greatly subject to subsidence as geopressured reservoirs, where subsidence is almost a certainty. Geopressured zones have such a high subsidence potential because the thick sedimentary sequences, in which they are found, are under-compacted and the water trapped in these sequences actually bears part of the lithostatic load. Withdrawing water from a geopressured reservoir leads to compaction of these rack units and results in subsidence. In geothermal fields the best known example is Wairakei, New Zealand, where subsidence rates of up to 40 cm/y have been reported. Geothermal resources are generally located in areas of high natural heat flow along thinning crustal zones. Thus, areas that are geothermally active are also very likely to be seismically active.

3.1.2 Impacts on air

Exploration (geological, geochemical and geophysical exploration) during geothermal projects does not affect atmospheric air. During drilling, air pollution can result from non-condensable gas emissions, exhaust smoke from generators, compressors and vehicles. Combustion of diesel fuel in the drilling rig produces NO_x, CO, SO_2 and hydrocarbons, but the amount of these gases is not significant. During well testing, steam and spray can have an adverse effect on the local vegetation with trees and grass being scalded. Some pollutant gases are emitted to the atmosphere during well testing from well pads, especially during multiple well flow tests in adverse meteorological conditions, but adverse effects of gases at this time are not likely. For example, although H_2S produces an unpleasant odour, eye irritation and respiratory damage, its concentration in air during drilling is not likely to be significant.

Fugitive dust is generated by several activities scheduled during construction, operation and decommissioning. The principal source is dust generated by travel on unpaved roads, dust generated by earthmoving activities during construction and reclamation on the power plant site and well pads, and dust carried by wind blowing across exposed surfaces. Most of the fugitive dust emissions occur as a part of construction and reclamation activities, and result only in short-term fugitive particulate matter less than 10 microns in diameter (PM_{10}).

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. The most significant ongoing gas emission will be from the gas exhausters of the power station that discharge through a cooling tower. Geothermal gases are carbon dioxide (CO_2), hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N), ammonia (NH_3), hydrocarbons such as methane (CH_4), and ethane (C_2H_6), trace amounts of mercury (Hg) and boron (B) vapour, and helium (He) and radon (Rn). The main hazardous chemical substances among possible airborne contaminants and are released during geothermal development are carbon dioxide and hydrogen sulphide, and the concentration of carbon dioxide is higher than that of hydrogen sulphide. A summary of geothermal project emission sources for some pollutants is shown in Table 6.

3.1.3 Impacts on water

Unless all waste borewater and cooling water is re-injected, geothermal fluid discharge may have an impact on local and regional surface waters such as rivers, lakes and estuaries. In wet fields the water phase sometimes contains toxic ingredients such as boron, arsenic, ammonia and mercury, which, if discharged, could contaminate downstream waters used for farming, fisheries or human water supplies.

During the operation phase, impacts on the water quality of surface water or groundwater in the shallow aquifer would not be expected during normal production and injection practices. The injected fluid would be released to the geothermal reservoir, which is not connected to the shallow ground water system. However, impacts could occur due to mixing of the geothermal fluid in the shallow groundwater aquifer through damaged well casings or accidental discharge to the surface. The local water quality could be affected if the well casing fails. Accidental discharge of geothermal liquids to surface drainage could occur due to blowouts during drilling, leaking pipes or wellheads, and overflow from well sumps.

Of greatest concern is the protection of public drinking water supplies. Spent geothermal liquids in the amounts expected to be discharged, could affect groundwater supplies in a disastrous way, because such contamination might well be impossible to correct. There are two ways of considering pollution effects

TABLE 6: Summary of geothermal project emission source and pollutants (Hauck and Phillips, 1997)

Sources	Pollutants					
	H_2S	PM_{10}	NO_x	SO_x	CO	Other
Construction						
Earth moving activities		✓				✓
Heavy equipment and vehicles		✓	✓	✓	✓	
Drill rig		✓	✓	✓	✓	
Emergency backup generator		✓	✓	✓	✓	
Well drilling and testing	✓	✓			✓	✓
Normal plant operation						
Plant vent silencer	✓	✓				
Cooling tower	✓	✓				
Drill rig engines		✓	✓	✓	✓	✓
Well flow testing	✓	✓				✓
Vehicles and mobile equipment		✓	✓	✓	✓	✓
Plant conditions						
Plant vent silencer	✓					✓
Emergency backup generator		✓	✓	✓	✓	✓
Decommissioning						
Earth moving activities		✓				✓
Demolition activities		✓				✓
Vehicles and mobile equipment		✓	✓	✓	✓	✓

and water quality criteria for agriculture commonly in use. These are livestock watering and irrigation. Critical laws for agricultural constituents that may be detrimental to agricultural use and quality criteria for water are listed in Table 7.

3.1.4 Noise impacts

Noise pollution is a sound which is unwanted or not desired, which may disrupt or degrade human activities. The air pressure variations are measured as the change in sound pressure is exerted on the diaphragm of a microphone attached to a sound level meter. During exploration of geothermal resources no environmentally significant noise is created.

Noise is one of the most ubiquitous disturbances to the environment from geothermal development, particularly during the construction and operation phases. Many geothermal developments are in remote areas where the natural level of noise is low and any additional noise is very noticeable. Residents in such areas 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. Instant noise is usually measured in decibels, denoted dB(A). The human ear is a remarkably sensitive device, which can detect sound intensities as low as 10^{-12} W/m^2 with the threshold of pain occurring at 10 W/m^2.

Development of a geothermal field creates considerable noise, particularly at the drilling and well-testing stages. Drilling operations, with noise from diesel engines and other heavy equipment, can create localised noise levels of 80-90 dB for 24 hours a day. The noise from the first discharge of wells is intense and can create annoyance at a distance of several kilometres. It may affect birds and animals in the district as well as concern local residents. Unsilenced geothermal wells may produce noise levels of up to 120 dB overall in their near vicinity, and to prevent damage to hearing, workers must wear ear protectors. Using cylindrical type silencers the noise can be brought down to about 85 dB. Thus, even with good designs for noise reduction, workers are recommended to use ear protectors both during drilling and discharge tests.

TABLE 7: The potential water pollutants and probable concentration ranges and agricultural use criteria for constituents in geothermal fluids (Kestin et al., 1980)

	Criteria for waters			Criteria for agricultural use	
Constituent	Criteria for fresh water	Criteria for marine water	Remarks	Crop irrigation	Remarks
Ammonia (un-ionized)	0.02 mg/l	---	Toxicity pH dependent	---	No criteria suggested
Arsenic	---	---	Daphnia impaired by 4.3 mg/l	0.1 mg/l	Toxicity of some crop at 0.5 mg/l
Barium	---	---	Toxicity level >50 mg/l	---	No criteria suggested
Beryllium	0.11 mg/l soft water 1.1 mg/l hard water	---	Toxicity hardness dependent	0.001–0.5 mg/l	Crop toxicity acidity dependent
Boron	---	---	Toxic to minnows at 19000 mg/l	0.75 mg/l	Toxic sensitive plants, e.g. Citrus at <1 mg/l
Cadmium	0.0004-0.004 mg/l soft water 0.0012-0.012 mg/l hard water	0.005 mg/l	Toxic at < 0.5 mg/l all tests	---	Reduced crop yield at 1 mg/l related to zinc concentration
Chromium	0.1 mg/l	---	Toxicity varies with pH and oxidation	---	No criteria suggested
Copper	0.1 96 hr LC_{50}	0.1 96 hr LC_{50}	Toxicity alkalinity- dependent	---	Toxicity for plants begins at 0.1 mg/l
Iron	1 mg/l	---	Toxicity variable	---	No criteria suggested
Lead	0.01 96 hr LC_{50}	---	Salmonoids most sensitive fish	---	Toxicity for plants at <30 mg/l
Manganese	---	0.1 mg/l	No problem for fish	0.2 mg/l	Toxicity for plants increases with decreased pH and Bio-accumulation
Mercury	0.0005 mg/l	0.0001 mg/l	High bio-accumulation and affects human food	---	
Phosphorus	---	0.0001 mg/l P	Eutrophication factor	---	No criteria suggested
Selenium	0.01 96 hr LC_{50}	0.01 96 hr LC_{50}	Toxic at > 2.5 mg/l	---	No criteria suggested
Silver	0.01 96 hr LC_{50}	0.01 96 hr LC_{50}	Toxicity dependent on compound	---	No criteria suggested
H_2S	0.0002 mg/l	0.0002 mg/l	Toxic at very low levels	---	No criteria suggested
Zinc	0.01 96 hr LC_{50}	---	Osmotic effects variable	---	Toxic to some crops at 0.4-25 mg/l

LC_{50} : Lethal concentration for 50%, the concentration needed to kill 50% of the organisms tested.

Most of the noise from power plant operation results from three power plant components, the cooling tower, the transformer, and the turbine-generator building. Once the plant has started operation, noise mufflers can be made effective enough to keep the environmental noise even below the 65 dB limit set by the U.S. Geological Survey (D'Alessio and Hartly, 1978).

3.2 Existing environmental information on the Theistareykir geothermal area

3.2.1 Introduction and summary of the history of Theistareykir

The Theistareykir high-temperature geothermal field is located in the region Thingeyjarsýsla about 32 km from the coast and its principal town, Húsavik, in N-Iceland. The location of the study area and the active geothermal manifestations of the Theistareykir field are shown in Figure 8.

The Theistareykir land was farmed intermittently from early on, probably soon after the time of Iceland's settlement (about 870-900 A.D.). Another early farm was recorded at Maelifell but this was abandoned quite early. The farmland is recorded as good in early centuries, the only disadvantage being its remoteness. According to legends, the farm was twice abandoned due to polar bears attacking the inhabitants. The last inhabitants moved away in 1873 (Jónsson, 1945). Sulphur was mined but little is known about the work at Theistareykir. The first references to sulphur trade in Norway are from about 1200 in Bergen and historians agree that the Norwegians could not have had access to sulphur from anywhere but Iceland. In North Iceland three mining areas are recorded, i.e. Námafjall, Fremri námar and Theistareykir. The products from all of them were exported from Húsavik which is recorded as the major export port of sulphur from Iceland. The mines at Theistareykir are thought to have been depleted first of the three areas, the cause being that it is closest to Húsavik and transport of the product to port was easiest from there. In the nineteenth and twentieth century, numerous attempts were made to resume production but none of them were successful (Thórdarson, 1998).

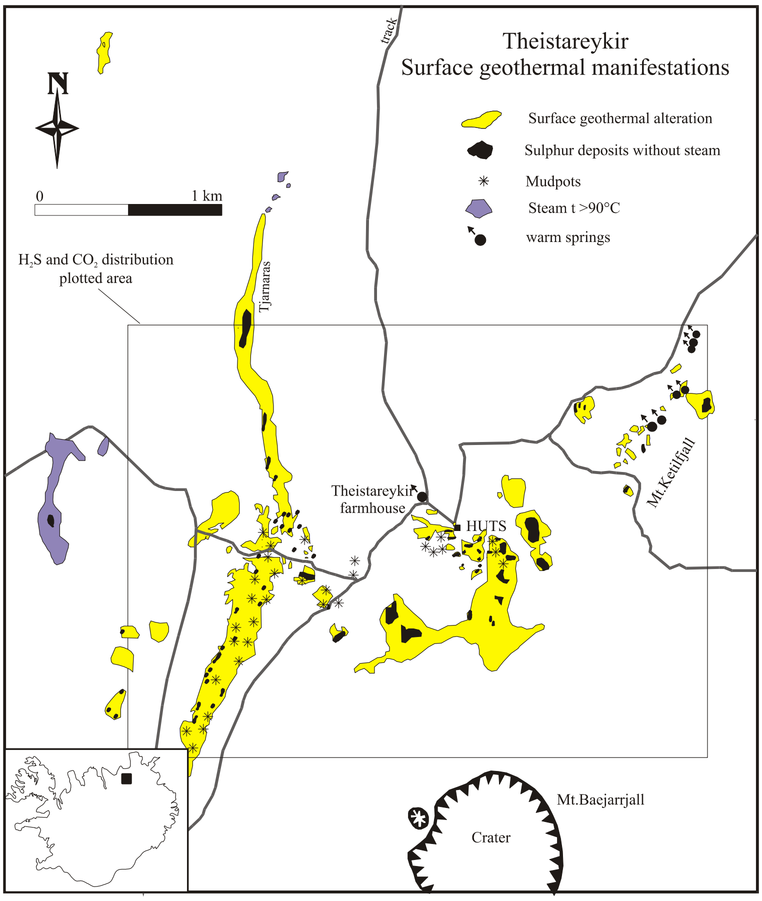

FIGURE 8: The Theistareykir geothermal field, N-Iceland

This study has been undertaken to determine information needed to establish baseline environmental conditions including surveys of geology and land, hydrology, weather conditions, noise conditions, ecology and socio-economic conditions.

3.2.2 Geology and land conditions

The Theistareykir high-temperature geothermal area lies in the Theistareykir volcanic system in NE-Iceland. The area was explored in the latter half of the 19^{th} century with the aim of resuming mining of native sulphur. Some studies were made, mainly on the geology of the mining area. The active part of the geothermal area lies in the eastern half of the Theistareykir fissure swarms. Hydrothermal alteration is also evident on the western side of the swarm, but thermal activity seems to have died out there about 1000 years ago. The active geothermal area covers nearly 10.5 km^2, and the most intense activity is on the northwestern and northern slopes of Mount Baejarfjall and in the pastures extending from there northwards to the western part of Mount Ketilfjall. If the old alteration in the western part of the swarm is considered to be a part of the active thermal area, its coverage is nearly 20 km^2.

The bedrock in the area is divided into breccias (hyaloclastites) from subglacial eruptions during the Ice Age, interglacial lava flows, and recent lava flows (younger than 10,000 years), all of, which are basaltic. Acid rocks are only found on the western side of the fissure swarm, from subglacial eruptions during the last glaciation or the second last. Rifting is still evident in this fissure swarm, and faults and fractures have been active in Postglacial time. One of the striking features of the fissure swarm is a bend where the thermal area is located. The structural meaning of the bend is not known, but its relation to the thermal area is evident.

Volcanic activity has been relatively infrequent in Postglacial time. Approximately 14 volcanic eruptions have occurred in the last 10,000 years, but none during the last 2500 years. Large earthquakes occur mainly just north of the area on the Tjörnes Fracture Zone, which is a right-lateral transfer fault zone. They also occur in the fissure swarm itself during rifting. The Tjörnes Fracture Zone strikes northwest, crosscutting the north-striking faults as it enters the fissure swarm about 5 km north of the thermal area. The volcanic activity ceases in the fissures swarm as it crosses the Tjörnes Fracture Zone, although its northern part remains seismically active. The most intense parts of the area are related to active fractures, giving rise to the permeability that enables the geothermal fluids to be conducted to the surface.

A survey indicates a low-resistivity area ($<10\ \Omega m$) elongated in an east-west direction from Mt. Baejarfjall in the east towards Mount Maelifell in the west. This low is located at a depth of 400-600 metres, but below this, the resistivity increases sharply. Gravity and magnetic field studies detected similar structures. This could be interpreted as an east-west trending heat source astride a north-south tectonic structure. Thus, the distribution of the surface manifestations reflects the direction of vertically permeable faults and fissures rather than of the heat source (Gíslason et al., 1984).

3.2.3 Gravity survey of the Theistareykir field

A gravity map of Theistareykir is shown in Figure 9. When making this map, the specific mass 2.3 g/cm^3 in surface layers (down to sea level) was used and landscape correction only made to 4.5 km. The gravity map is characterised by some lows in the gravity and rigs related to them. The distribution of measuring points is very variable. The greatest density in measurements is along profiles following existing paths but scarce between them (Gíslason et al., 1984).

What is most remarkable about the gravity map is a large gravity low to the northwest of Baejarfjall and east of the north part of Lambafjöll. This gravity low covers close to 25 km^2. Away from it, the gravity increases fast both to west and north but in other directions the gravity changes are very irregular. A closer look at the gravity map reveals clearly a deep low along the centre of Theistareykir fracture zone. This low is a few kilometres wide and extends in a N-S direction; similar lows can also be seen in the Krafla fissure swarm south of Krafla and also in the Hengill area. In the northeastern part there is another low with NW-SE direction, but the largest gravity low occurs just where these two lows meet. The

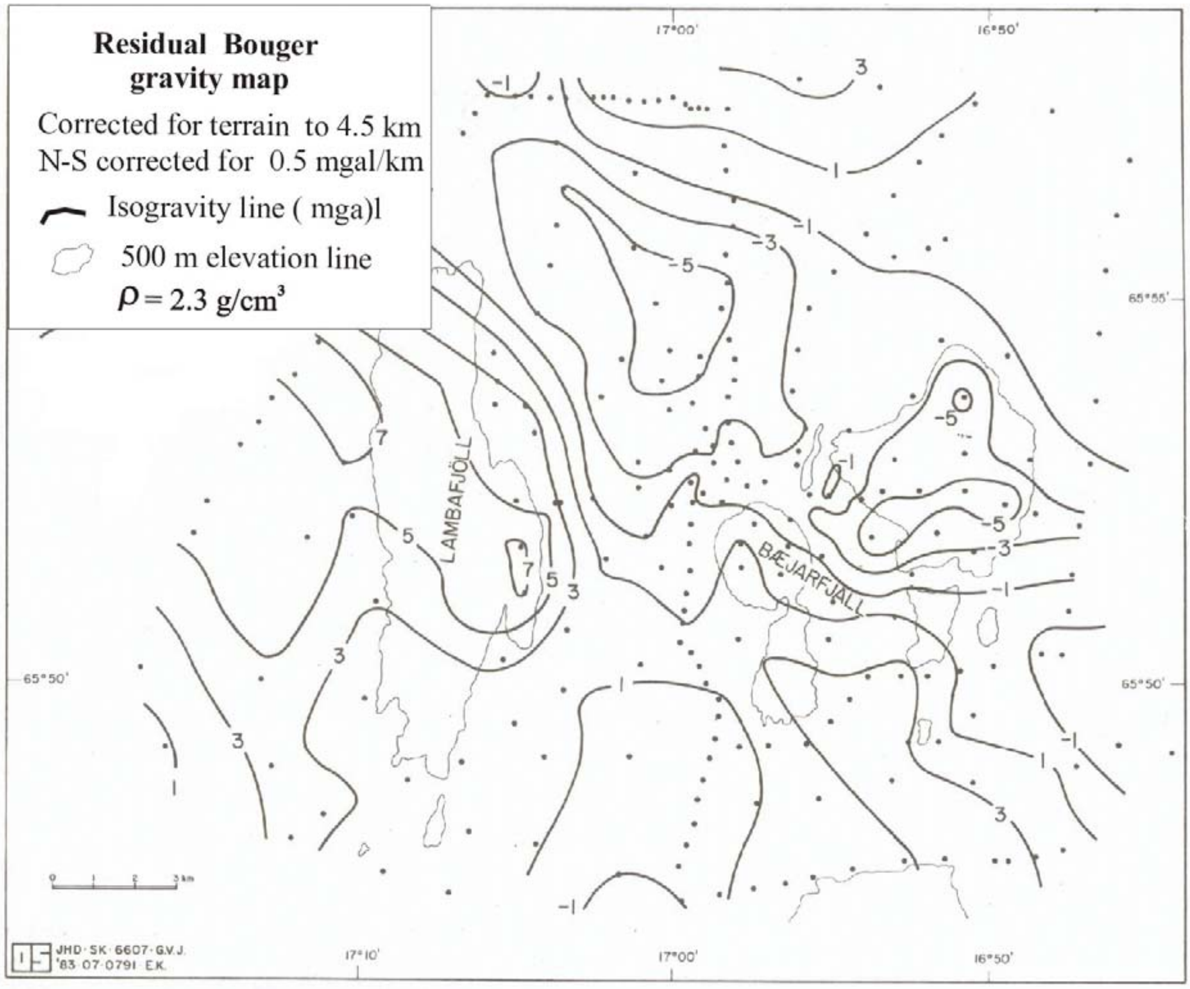

FIGURE 9: Residual Bouger gravity map of Theistareykir (Gíslason et al., 1984)

direction of this low seems to be caused by the Húsavik fault. It is not unlikely that manifestations on the surface are related to these lows. To the west a gravity high is seen in Lambafjöll mountains. Gravity changes in the east part of the map are much more irregular.

3.2.4 Hydrology

The Theistareykir high-temperature area lies north of Lake Mývatn. The terrain is mainly hyaloclastite mountains. The area is partly covered with extensive lava flows but is also dominated the by extensive open fissures, some of which formed in Postglacial time. The geothermal area lies approximately 300 m above sea level. The average precipitation in the area is 670 mm per year, but there is no river or surface water flow in the area. The precipitation (rain and melting snow) that percolates into open fissures flows from Lake Mývatn in the south and traverses the Theistareykir area, mixes with geothermal water and finally enters the ocean in the Öxarfjördur bay area in the north. By the ocean there are a lot of springs that are partially fed by geothermal waters. A total of about 20 m^3/s of 20°C water discharges into the ocean. A large heat source in the Theistareykir area is needed to heat this water volume. In the fissure swarm, in the geothermal area, the groundwater table is at 200 m above sea level. Thus, in Theistareykir the groundwater table lies approximately 100 m below the surface. The low groundwater table indicates high permeability, mostly because of the fissures. In the geothermal areas, hot water and steam penetrate the groundwater and the geothermal water is mixed with the cold groundwater. In 1998 three shallow observation wells to about 150 m depth were drilled in the Theistareykir area for hydrological investigations. These wells show the groundwater to be at 100 m depth. Aquifers are absent from the formation from surface down to 100 m, but in isolated pockets close to where geothermal water and steam rise from underground can there be found water above 100 m depth.

Well 2 is very close to the main geothermal area and the groundwater temperature there is more than 90°C at 100 m depth. Well 3 is approximately 1.5 km north of the geothermal area. The temperature at 100 m is about 68°C, but 88°C at 140 m depth. In well 1, drilled about 2.5 km north of the main geothermal area, the groundwater temperature at 130 m depth is 27°C. It shows that cold water coming from the south is heated by the Theistareykir geothermal system before flowing north.

3.2.5 Hot springs and fumaroles

In the Theistareykir geothermal area there are at least 35 active fumaroles, mainly distributed in the central part of area. Several warm streams are also found in the area, most are about 40°C, and come from Ketilfjall mountain. Another one about 23°C, is located near the old farmhouse. The distribution of fumaroles and hot springs is shown in Figure 8. Table 8 shows the concentration of components in some steam samples from fumaroles in the Theistareykir area.

TABLE 8: Concentration of components of steam samples in mg/kg from the Theistareykir area (Ármannsson et al., 1986)

Sample no.	Sampling date	pH	Na	Cl	CO_2	H_2S	H_2	CH_4	N_2	Hg
G3	1981	--	1	13	6062	2137	36.77	7.64	185.1	330
G5	1981	--	1	19	1579	1200	30.43	8.74	52.8	<30
G31	1982	4.18	1	5	2852	13.42	11.18	5.48	41.5	<500
G10	1981	--	118	203	4370	681	4.69	11.84	982.2	670
G19	1981	3.55	36	60	7729	1830	10.39	0.00	0.00	3000
G28	1982	4.75	1	9	3381	9.1	0.00	0.00	0.00	300
G33	1982	5.20	1518	--	1530	448	0.00	0.00	0.00	<400

3.2.6 Weather conditions

Precipitation for the area was measured at Stadarhóll meteorological station, located approximately 17 km west-southwest of the Theistareykir area. Annual precipitation is 671.4 mm, with maximum precipitation in October about 125 mm, and minimum in May and June, about 10 mm. Figure 10 shows precipitation for each month in 1998.

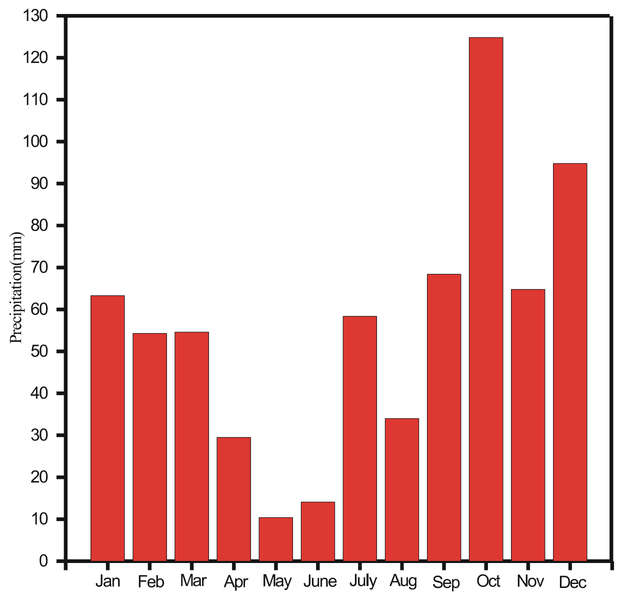

FIGURE 10: Monthly precipitation in 1998 at the Stadarhóll meteorological station

Temperature and humidity. Temperature data for the Stadarhóll station for 1998 are shown as monthly average temperatures in Figure 11, with maximum temperature in August, about 9°C, and minimum in February and March, about -7°C.

Humidity in Iceland is generally high due to high precipitation. Humidity data was collected in

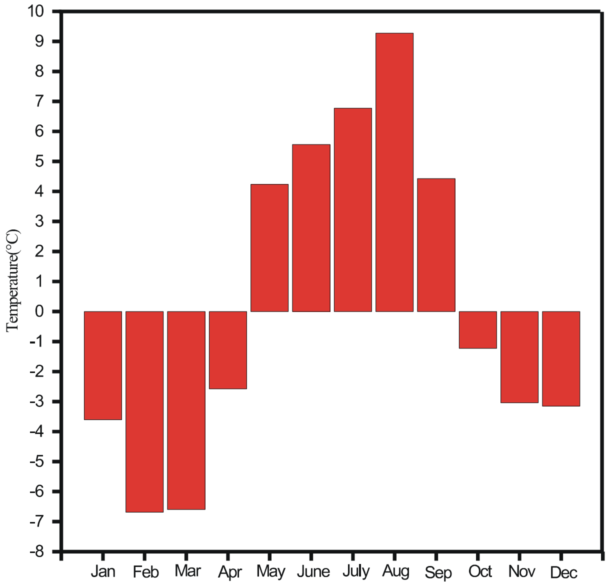

FIGURE 11: Average air temperatures at Stadarhóll for each month in 1998

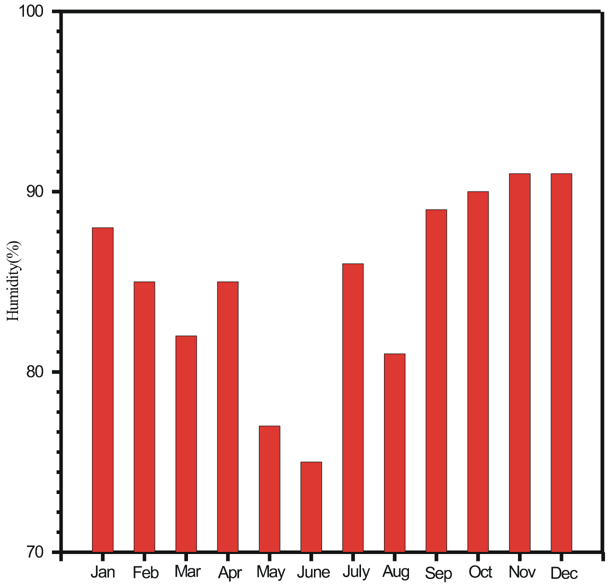

FIGURE 12: Month by month humidity at Lake Mývatn in 1998

1998 at Lake Mývatn meteorological station, located approximately 25 km south-southeast of the Theistareykir. Maximum humidity was recorded in November and December, about 91%, but minimum for August, about 80%. Month by month humidity at the Lake Mývatn station is shown in Figure 12.

Air quality. Theistareykir is an unexploited natural area without any industrial or other air polluting activities. Only gases from geothermal manifestations escape to the atmosphere. The concentrations of some of the components in the steam are shown in Table 8. The concentrations of H_2S and CO_2 are higher than others, and it seems necessary to monitor these in the area.

H_2S and CO_2 concentrations in air have been measured in the central part of the area where most of the geothermal manifestations are located. The concentration of gases in this part of the area should be high because most of the gas released to the atmosphere from the fumaroles. H_2S in atmospheric air was measured in August 1993 (Ívarsson et al., 1993), and H_2S and CO_2 concentrations in atmospheric air were measured by the author in September 1999. The results of these measurements were used to prepare H_2S and CO_2 distribution contour maps for the central part of the Theistareykir area (Figure 13).

Wind patterns. Wind conditions were measured in 1998 at a site (Kísilvegur), located approximately 14 km southwest of the Theistareykir area. Hourly wind direction and wind speed were noted to make a wind rose plot. It is seen that the most common wind directions are northeasterly and southeasterly. Figure 14 shows the yearly wind pattern in 1998.

3.2.7 Noise conditions

Most geothermal developments are in remote areas where the natural level of noise is low and a slight change in noise level is detectable. The Theistareykir area is an uninhabited place, without any industrial or human activities, thus there is no noise pollution found at present.

3.2.8 Social and economic conditions

The region Thingeyiarsýsla in N-Iceland has a population of approximately 6,900. Its principal town, Húsavík, has 2,500 inhabitants. The main industries are community services such as teaching, health care,

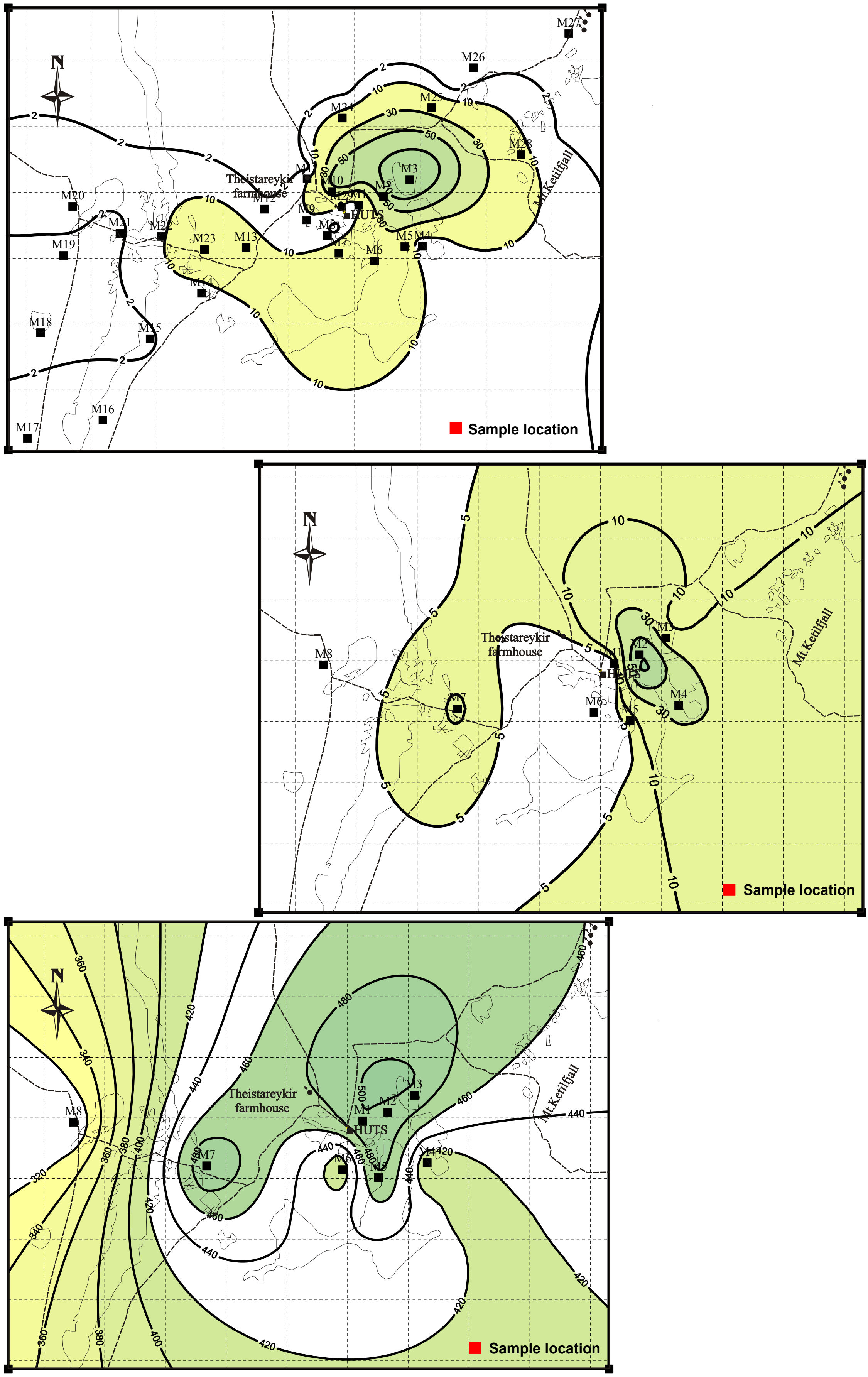

FIGURE 13: The Theistareykir area, distribution of a) H_2S in August 1993; b) H_2S in September 1999; c) CO_2 in September 1999

banking and trading, farming and fishing and industrial activities including fish processing, slaughtering, meat processing, diatomite production and construction. For several decades this region has suffered a brain drain because there have been few jobs for well educated people, much lower than the national average. Thingeyjarsýsla has been economically stagnant for two decades and unemployment is quite high. A survey was recently carried out on the resources available in Thingeyjarsýsla to analyse which type of activity might be of interest. The survey showed principally four areas where the region had an internationally competitive potential:

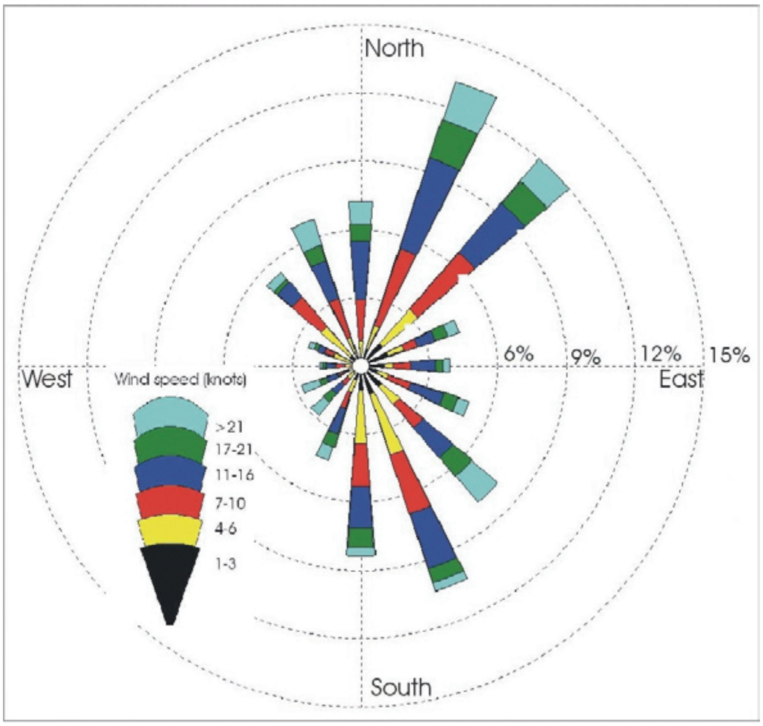

FIGURE 14: Annual wind pattern at the Kísilvegur site in 1998

- Tourism related activities;
- Food production (fish and farm products);
- Mining and minerals, the area has a good potential in scoria, pumice and diatomaceous earth;
- Utilization of high-temperature geothermal fields (Leifsson, 1992).

In recent years attention has focussed on the utilization of the high-temperature geothermal fields, and potential utilisers are not confined to Thingeyjarsýsla, but also the neighbouring communities in Akureyri and Eyjafjördur, with close to 20,000 inhabitants. These communities have also lost people and jobs in recent years. The council energy companies from these communities along with The National Power Company and The National Drilling Company have formed a conglomerate, Íslensk Orka Ltd, with the aim of utilizing the geothermal areas. Drilling is already underway in Öxarfjördur, and spokesmen for the conglomerate have recently told the media that they aim at producing electricity on the order of 250 MW, from Öxarfjördur and Theistareykir for industrial use.

3.2.9 Vegetation

There is no vegetation map available that covers the immediate Theistareykir area. A vegetation map of the nearby Gaesafjöll area shows about 5% moss heaths, 60% other drained land vegetation, 0.01% bogs and fens and about 35% without vegetation (Agricultural Research Institute, 1982). The permanent flora of Iceland has been recorded as consisting of 438 species. At least half of them are found in Theistareykir and vicinity (Kristinsson 1986). The immediate Theistareykir area is relatively fecund due to geothermal manifestations and the water from Ketilfjall mountain. *Prunella vulgaris* and *Veronica officinalis,* rare in North-Iceland, are quite abundant in the meadows and the mountain slopes. *Ophioglossum azoricum* and *Plantago major* which are plants that grow almost exclusively in geothermal areas, are quite widespread, too. *Thelypteris phegopteris,* which is common around hot pools but quite rare in North Iceland, has been found (Kristinsson, H., pers. comm., Hallgrímsson, H., pers. comm*). Blechum spicant* has been recorded at Stóra víti, a crater near Theistareykir but it is very unlikely that this is the *Phallax variant* that grows around hot springs and is a protected species (Kristinsson, H., pers. comm.; Kristinsson, 1986).

3.2.10 Fauna

In the Theistareykir area field mice are well known and foxes are quite common. Stray minks are likely to travel the area, but there is not enough water to sustain a mink population. Reindeer used to live in the area but became extinct in the late 1930s and stray polar bears have been reported in previous centuries.

A great number of migrating birds cross the area, especially in spring, but the only ones that are known to stop over to rest are geese. A special feature is the mass movement of ptarmigans, which are common nesting birds, into the area in autumn and winter, making it a haven for bird hunters. One of the most important consequences of geothermal exploitation would be the opening up of the area to the public by way of new improved roads. This would increase the number of hunters and might endanger the ptarmigan stock. The birds that are characteristic of the area are upland birds, especially Eurasian golden plover, meadow pipit, snow bunting and ptarmigan. The habitat is also suitable for some birds of prey, e.g. gyrfalcon, merlin and raven. Table 9 shows which birds nest in the area (Nielsen, O.K., pers. comm).

TABLE 9: Nesting birds in the Theistareykir area

Name	Zoological name	Notes
Eurasian golden plover	*Pluvialis opricaria*	Common nesting bird
Whimbrel	*Numenius phaeopus*	Scattered nesting bird
Purple sandpiper	*Calidris maritima*	Scattered nesting bird
Dunlin	*Calidris alpina*	Scattered nesting bird
Redshank	*Tringa totanus*	Nests on farm grassland
Common snipe	*Galinago galinago*	Scattered nesting bird
Gyrfalcon	*Falco rusticolus*	2 territories
Raven	*Corvus corax*	2-3 territories
Merlin	*Falco columbarius*	At least 5 territories
Arctic skua	*Sterocarius parasiticus*	A very likely nesting bird
Meadow pipit	*Arthus pratensis*	Common nesting bird
Snow bunting	*Plectrophenax nivalis*	Common nesting bird
Wheatear	*Oenanthe oenanthe*	Scattered nesting bird
Redwing	*Turdus iliacus*	Scattered nesting bird
Ptarmigan	*Lagopus mutus*	Common nesting bird, autumn, winter visitor in great numbers

3.2.11 Tourism

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. Theistareykir 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.

3.3 Environmental impact assessment

Baseline environmental conditions have been estimated with further analysis suggested to determine the impacts of a geothermal project for all relevant phases of development and to propose mitigating measures to reduce impacts. The objective of environmental impact assessment is to determine the potential environmental, social and health effects of a proposed development. It attempts to assess the physical, biological and socio-economic effects of the proposed project in a form that permits a logical and rational decision to be made. Attempts can be made to reduce or mitigate any potentially adverse impacts through the identification of possible alternative sites and/or processes. There is, however, no general and universal accepted definition of EIA and there never can be.

3.3.1 Checklist

The key elements of the project are all included in the checklist. Impacts that could result if the project were implemented are also discussed where appropriate. Only those elements of the environment which may be impacted, or might be considered as producing cumulative effects, are included in the discussion. The checklist that has been used for assessment of environmental impacts of geothermal projects is taken, (with some modification) from Webster (1995), and an assessment of a geothermal project of average size and lifetime has been attempted. The filled in checklist is shown in Appendix I.

3.3.2 Geology and land

During exploration there is no significant impact on geology and land, only in geophysical exploration such as the drilling of shallow wells for a geothermal gradient measurements, can there be some effects on land and soil from disposal.

During drilling, road construction and drill site preparation, unstable earth conditions and changes in geological substructure can occur. For drilling in the steep parts of the area, the solution to erosion and landslides can 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 situated on stable land at the surface. During well testing, care should be taken not to discharge the waste water directly to steep areas. Sumps should be made to contain this waste water, to avoid serious gullying.

Each drill site in Iceland is, on average, about 1000 m^2 in land area. Thus, by drilling 10 wells during the first phase of the project about 10,000 m^2 of land, that is currently used for sheep farming, will be affected during drilling and for many years after that. The soil in these areas will become compacted and changed, and close to the drill site there will be some deposition of waste soils. The construction of pipeline, powerhouse and workers' quarters will affect several hundred square meters of land. During operation, subsidence and induced seismicity are the main possible effects on the land around the power plant and surrounding areas. A monitoring programme for subsidence is recommended.

3.3.3 Effects on air quality

Gas emission to the air takes place during all phases of such a project. During the construction and decommissioning phases, fugitive dust (i.e. airborne particulate matter) would result from surface disturbance and vehicle travel on unpaved roads. Non-condensable gases including hydrogen sulphide (H_2S) and carbon dioxide (CO_2) will be released from the geothermal fluid during well drilling and testing and during power plant operation. Oxides of nitrogen, carbon monoxide, and oxides from sulphur emissions (critical air pollutants or their precursors) from internal combustion engines are released during all phases of the project. A summary of the effects on air during such a project follows:

- Fugitive dusts are generated from travel on unpaved roads, earth moving activities during construction and decommissioning activities, especially when there is no precipitation and the surface is dry.
- Small quantities of critical air pollutants are released from mobile construction equipment and other vehicles, but this impact is below the level of significance.
- Large quantities of critical air pollutants, in particular oxides of nitrogen (NO_x), are released from drilling rig engines during well drilling operations, but this impact is not significant if wells are drilled one by one, and only one active drill rig is operated at any one time.

- Hydrogen sulphide is released during well flow testing from well pads. It is necessary to control the concentration of H_2S in the atmosphere and keep it below levels specified by international standards.
- Hydrogen sulphide is released to the atmosphere during power plant operation. As regards H_2S concentrations in steam samples from the area, these are not dangerously high, and are similar to the concentrations of H_2S in steam flow in other geothermal fields in Iceland (e.g. Reykjanes). Thus, the H_2S concentrations in the atmosphere in this field are acceptable as in other fields.
- The project releases "greenhouse gases" which contribute to global warming. These gases consist mainly of carbon dioxide (CO_2) and some methane (CH_4). But a prediction of the amount of carbon dioxide released to the atmosphere per kilowatt of electricity shows it as approximately 20 times smaller than the amount of "greenhouse gases" released from a fossil-fuel power plant for an equivalent amount of electricity.
- The concentration of other gases is generally very small in Icelandic geothermal fluids. This field is no exception.
- It is concluded that for most sites, odour impact will remain more or less at present levels, in terms of the number of times the odour threshold is exceeded.

3.3.4 Water effects

The wells drilled in this area for high-temperature geothermal fluid will be deep and may require up to 3000 m^3/day of water for a period of several months depending on the number of wells to be drilled. For completion well testing and injection testing, up to 10,000 m^3/day of water may be needed. This water will create a stream in the valley nearest to the drill rig and can lead to siltation and deposition from the stream, which may have some impact on the vegetation. 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 could affect the quality of the groundwater in the area.

Hydrological studies show that the groundwater flow in the Theistareykir area is from south to north and the water is finally discharged to the ocean. Some warm springs, about 10-20°C, are close to the ocean and it seems that these warm springs are fed by geothermal water from the Theistareykir area. After drilling and geothermal fluid production from the field, the temperature of springs in the Öxarfjördur bay area may be affected. Groundwater level depends on geothermal fluid production, and with an increase in the production of geothermal fluid in the geothermal field, the groundwater level will drop.

Spent geothermal fluid from the power plant will be discharged to the environment. The concentration of dissolved solids and gases in geothermal water and steam are greater than in surface water. It is necessary to survey the effect of geothermal fluid on surface water and shallow groundwater after the installation of a power plant.

3.3.5 Noise effects

In the Theistareykir geothermal field there will be no serious noise impact during geothermal project activity such as drilling, well testing and operation. Only during well testing will there be some temporary noise impact which will affect wildlife in the vicinity of the drill rig, and workers on-site. During drilling and well testing, the wearing of appropriate hearing protection is a necessary safety consideration. The noise impact will decline when all wells have been drilled and tested.

The most pronounced noise effects during power plant operation are from the cooling tower, transformer, and turbine-generator building. When power plant operation starts, noise mufflers must be used to keep the environmental noise level below the 65 dB limit set by the U.S. Geological survey (Kestin et al., 1980). With a reduced level of noise, the impact on wildlife, workers and tourists will not be serious.

3.3.6 Flora

For vegetation in the Theistareykir area, very little disturbance is expected except during drill site preparation and road construction, but this effect is not significant because the drill site can be re-vegetated with the same species of plants after drilling and well testing. During operation, a monitoring programme including the monitoring of pollutant gases such as H_2S in the atmosphere, should be run, and if the concentration of these becomes higher than limits set by standards, measures must be taken to reduce their amount in the atmosphere.

Sheep in this area affect the vegetation profoundly. During drilling and well testing, care should be taken to avoid damage to the grass when disposing of drilling effluents and operational waste waters with reference to the sheep. A detailed study should also include the potential effect of changes in the thermal area, such as increased steam flow due to production, to changes in the distribution of the thermally adapted plants, and to whether some of the species could be rendered extinct. Some rare bacteria species have been found in Icelandic geothermal fields (Pétursdóttir, 1995) but no investigation of bacteria has been carried out in Theistareykir (Kristjánsson, J.K., pers. comm). Therefore, it is recommended to take bacterial counts and monitor the bacteria if interesting results are obtained. Rare species or strains of bacteria may be found and possibly utilized in bio-technology in future

3.3.7 Animal life

During exploration for geothermal energy, damage to sheep, mice, foxes and minks is unlikely. During drilling, the effect of noise from the drill rig and well testing will cause most of the animals to move from the vicinity of the drill rig. Birds will especially be affected by the road construction and the preparation of drill sites will affect mice.

The most important effect of geothermal power plant operation on the environment is air pollution. Care should be to taken that concentrations of pollutant gases, such as H_2S are kept at bay. The sensitivity threshold of animals to gas smell is the same as that of humans. Up to now, there is no reported damage from air pollution from Icelandic geothermal operations. Thus, in the Theistareykir field there is not likely to be any significant air pollution effect. A detailed study to identify all animals and a survey of the probable effects on them by a long term geothermal operation is required.

3.3.8 Transportation

There is an extremely poor road connection with Theistareykir, with paths that are only usable for 3-4 months each year and cannot possibly be used for the transport of a drill rig. The shortest distance by road to Húsavík is 25 km, 11 of them being the above paths but the rest a dirt road, the Reykjaheidi road. The shortest distance to the Kísilvegur road, which is the main transportation road from Húsavík to the Lake Mývatn diatomite plant, is 21 km and this has been recommended as a better choice for a road site than the shorter road via Reykjaheidi (Gíslason et al. 1984). The construction of such a road will obviously create some disturbances and cause increased traffic to the area, in addition to the subsequent transportation of drill rigs.

3.3.9 Visual effects

Visual quality may be diminished due to the loss of naturalness and the imposition of man-made structures like drill sites, drilling rig, and accessories creating artificial landscape elements in the project area but all these are temporary and will disappear when drilling is completed. All natural geothermal manifestations such as hot springs, fumaroles, mud pools and boiling pools are attractive to tourists and should be protected. A detailed study should be conducted in the Theistareykir area to find out whether these unique features will or will not decline when drilling takes place.

3.4 Conclusions and recommendations

- Studies on prospective drilling water for the area need to be continued as a proper cold water reservoir has not yet been identified. Drilling up to now has revealed extremely permeable formations and water at about 90°C at 100 m depth.
- The extreme 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.
- 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.
- Production from the area would open it up with the construction of new roads. Increased tourism would be expected and might even call for some services to the area. Due to the dense populations of ptarmigan in the winter, easier access would be expected to increase hunting, a danger to the ptarmigan stock, and measures might be needed to protect it.

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APPENDIX I: Environmental impact checklist for the Theistareykir 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, in let 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 of ground waters, 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 in a barrier to the mitigation 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 alter the location, distribution, density, or growth rate of the human population of an area ?			✓	✓			✓		
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 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. 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 ?		✓		✓			✓		

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	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 recreational opportunities ?			✓	✓			✓		
20. Cultural Resources.									
a. Will the proposal result in the alteration of or the destruction of a prehistoric or historic archaeological site ?			✓			✓			✓
b. Will the proposal result in adverse physical or aesthetic effects to a prehistoric or historic building structure, or object ?			✓			✓			✓
c. Does the proposal have the potential to cause a physical change which would effect unique ethnic cultural values ?			✓			✓			✓
d. Will the proposal 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 (California) 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 impact on each resource is relatively small, but where the effect of the total of those impacts on the environmental 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 ?			✓			✓			✓