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AN ENFORCEMENT PROJECT ON ENVIRONMENTAL IMPACT OF GEOTHERMAL EXPLOITATION IN ICELAND

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ABSTRACT

Orkustofnun (Icelandic Energy Authority) and all main exploiters of high-temperature geothermal energy in Iceland, producing the Reykjanes, Svartsengi, Nesjavellir, Námafjall and Krafla field, initiated an enforcement project to study the environmental impact of geothermal develpment in 1991. Several research institutes and agencies participated in the project, such as the Icelandic Meteorological Office of Iceland, The Science Institute and The Engineering Research Institute of the University of Iceland and the Environmental and Health Agency. The aim of the project was to establish and predict the environmental impact of geothermal utilization, and to suggest remedies.

A new environmental legislation for Iceland was in preparation when the project started. Due to the increased emphasis on the environmental viability of energy production assessment of environmental impact and comparison of alternative power production possibilities with regard to environmental effects is required by Icelandic law.

A status report was written about the present situation regarding environmental research in the utilized geothermal fields including suggestions for remedies and monitoring schemes. Methods were developed to measure the mass flow of steam in fumarole outlets and for the monitoring of geothermal fields by aerial thermography remote sensing methods. The concentration of sulfur gases and mercury in atmospheric air was measured in all the utilized fields and four non utilized geothermal fields and their dispersion and reaction in atmospheric air was modeled. Ground levelling and gravity mesurements were made in the utilized fields and future monitoring outlined.

One priority project was the assessment of the status of environmental knowledge for the non utilized high-temperature geothermal fields in Iceland. Subsequently background data were collected and monitoring schemes initiated in a few selected fields to evaluate changes in natural features and the development of research methods for that purpose. A schedule and a cost estimate were made for the work required to carry out an environmental impact assessment for a 20 MW power plant in each field.

The cooperative environmental research project was mostly concluded in 1997, but several sub-projects are still in progress and new projects have been initiated following the initial results. The course of the program and the main results are summarized in this paper. Papers and reports describing many of the largest individual sub-projects, approximately 100 titles in all, have either been published already or are in press.

1. INTRODUCTION

The first phase of the project was to define the environmental impact of geothermal development (Ármannsson and Kristmannsdóttir, 1992) and to assess the present status at the five main sites of high-temperature geothermal production in Iceland. The second phase was to define several priority projects to be carried out within the scope of the enforcement project (Kristmannsdóttir and Ármannsson, 1995).

The assessment of present status in the utilized fields (Fig.1) resulted in a report (Ármannsson et. al., 1993) containing detailed checklists of environmental concerns related to geothermal exploitation in the high-temperature areas Svartsengi and Reykjanes, Nesjavellir, Námafjall and Krafla. All available literature connected to the fields in question was compiled in the report.

The next phase of the project was to define several priority projects to be carried out within the frame of the enforcement project and to make project plans for each of them. There were ten defined priority programs:

* Studies of gas emissions from utilized geothermal fields, especially mercury and sulfurous gasses.

* Aerial thermal scanning as a means to monitor geothermal fields

* Ground levelling and gravity mesurements

* Studies of microseismisity in utilized high-temperature geothermal fields

* Studies of formation and pervasion of steam pillows in utilized geothermal fields.

* Studies of natural changes in non utilized geothermal fields

* Groundwater research

* Surveillance of methods to measure natural steam discharge

* Evaluation of methods for gas removal

* Reinjection of spent fluids and inhibition of silica precipitation

Work on the subprojects was commenced in 1993. The main emphasis was placed on the first four projects. Some of the others were later intergrated into other projects and are still pending after the closure of the enforcement program.

2. PRIORITY PROJECTS

The enforcement project was officially terminated at the end of 1997, but work on many of the priority programs was continued for 1-2 years and some of them are still being pursued. The progress, results and present status of the priority projects are treated in the sub sections below:

2.1 Studies of gas emissions

This project started in the summer of 1992 by measuring of the concentration of various gases in atmospheric air within a few geothermal fields, utilized and non utilized. In 1993 this was followed by short term measurements of mercury, hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) concentrations in nine high-temperature geothermal fields. The aim of this first phase was to obtain range and reference values for further monitoring.

The gases (Kristmannsdóttir et. al., 2000, Ívarsson et al., 1993) were collected over 24-48 hours in 1-2 points in each area. Locations were based on the results of point measurements of hydrogen sulfide in a grid over the area of visible activity. The sites of highest concentration were selected for sampling. Sampling was performed by pumping measured quanities of air through an H_2O_2 solution, and filters wetted in $AgNO_3$ and KOH solutions respectively. The point measurements of H_2S were made by a hand-held Jerome 621 meter, based on the measurement of H_2S accumulated on a gold film. The detection limit of the meter is 1 ppb. Measurement were carried out from one up to seven times during the summer.

Long term mesurements of hydrogen sulfide and sulfur dioxide, extending over 4-6 months were started in Krafla and Svartsengi in 1994 and in Nesjavellir and Námafjall in 1995 and 1996. As the results of short term measurements were found to be extremely dependent on the weather, meteorological observations were performed concurrenty. Sampling sites were the same as for the short term measurements. Method testing during short term measurements showed that methods based on sampling on wetted filters were the most reliable and therefore were chosen for further work. Monitoring stations for hydrogen sulfide and sulfur dioxide were also operated for one year at two sites, 13 and 24 km outside of the Nesjavellir geothermal field. They were located at the two weather observation sites closest to Nesjavellir. These stations were used to monitor dispersion, decay and possible conversion with time of hydrogen sulfide to sulfur dioxide.

Air distribution modeling of the emitted H_2S from the Nesjavellir geothermal field indicates minor, or at least very slow, conversion of H_2S to SO_2. Furthermore, simple experiments performed suggest that the H_2S is converted so slowly to SO_2 that only a fraction of it could react within the geothermal fields or within a radius of 15-25 km from them. When H_2S dissolves into droplets solid sulfur will probably be precipitated due to the acidic environment. As precipitation will effectively wash H_2S from air, only a fraction of the H_2S dispersed away from the geothermal fields is believed to convert to SO_2 in the climatic conditions prevailing in Iceland.

A compilation of methods for the removal of gas from geothermal steam was also carried out within the framework of this program.

2.2 Aerial thermal scanning

In 1993 a three-year joint research program with the participation of Orkustofun and the Signal Processing Lab of the University of Iceland was initiated for the study of thermal remote sensing in geothermal areas. The main objectives of the program were to refine a newly designed lightweight thermal scanner to be carried on a small aircraft and provide high quality thermal images, and 2) to investigate whether repeated aerial surveys could be used to detect and map changes in surface temperature with time. Work on the refinement of the equipment and development of software was mainly carried out during the first year of the program, but continued throughout the project as several problems were encountered in conducting aerial surveys and processing and interpretation of the data.

Seven reports have been issued so far on the results of this priority project (Árnason, 1997). The spatial resolution of the airborne thermal scanner is typically 1–2 meters at flight altitudes of 1000–2000 feet and its radiometric resolution or dynamic range is 12 bits which makes it possible to detect relative temperature differences of less than 0.1 °C for the whole temperature range from 0 to 100 °C. Calibration of the thermal images to absolute temperature values is done using concurrent temperature measurements at several points on the ground. In the autumns of 1993, 1994 and 1995 aerial surveys were conducted over all the above mentioned utilized geothermal fields and Hveragerði as well as several non utilized ones; Theistareykir, Fremrinámar, Kverkfjöll, Brennisteinsfjöll, Krísuvík, Trölladyngja and Ölkelduháls. Ground temperature measurements and geological studies were carried out concurrently with the aerial surveys in some of these areas to calibrate the scanner data and interpret the thermal features depicted on the infrared imagery.

A concluding report describing the developement and testing of the equipment and the main achievements of the project was issued in 1997 (Árnason, 1997). However interpretation has not been concluded in all the studied areas due to lack of digital topographic maps for some of them. The results show that aerial thermal scanning is definitely a viable method to map changes in surface activity and to minimize time consuming ground work .

An example of the results obtained is shown in Figures 2 and 3 where thermal changes occurring in the Reykjanes geothermal field are displayed. The figures are differential images obtained by subtracting a thermal image from November 1994 from a coregistered thermal image from September 1995. Different colors indicate areas where warming has occurred in the one year time interval between the two acquisition dates with highest temperature difference values displayed in red and yellow (see accompanying color table). Areas of no thermal change are displayed in light grey and cooling is indicated with grey values from light grey (no change) to black (most substantial cooling). Note that the thermal images have not been calibrated so different colours are not assigned to absolute temperature values.

Figure 2 is an overview of the Reykjanes field with the plant and pond in the bottom right corner and the natural thermal expressions in the upper half of image. The temperature differences displayed at the plant site do not represent any natural changes but result from human activity and different intensity and directions of the vapour plumes.

On the other hand some definite changes in the natural expressions of the geothermal field have taken place during the one year between the acquisition of the two image datasets. In the steam field in the upper right quarter of Figure 2 a net substantial cooling is obvious as indicated with dark grey and black spots in the figure. Figure 3 is an enlargement of the steam field in the upper left quarter of Figure 2 and shows a general warming in this area by coloured pixels beeing much more abundant than dark grey and black ones. The overall picture thus indicates a shift of the fumarole activity from the one steam field to the other in the Reykjanes geothermal area. Unfortunately these observations have not been followed up by either mapping of the surface manifestations or sampling of fumaroles due to lack of funds.

Substantial changes in the geothermal field in Krýsuvík were also disovered and mapped by the aerial thermal scanning project (Ármannsson et al, 2000) and later verified by surface inspection.

2.3 Ground level and gravity measurements

Leveling and gravity measurements have been carried out in all the utilized areas since the start of development. However, consistent networks of points for monitoring have not been established and continuous data sets covering the whole survey areas do not exist and thus making it difficult to evaluate the data.

A 1992 survey of ground leveling and gravity measurements in the outer part of the Reykjanes peninsula (including Svartsengi-Eldvörp and Reykjanes) (Eysteinsson, 1993, 2000) revealed an inital subsidence rate of 14 mm/year (1975-1982) decreasing to 7 mm/year (1985-1992) in Svartsengi and a maximum subsidence rate of 5 mm/year at Reykjanes. Pressure at 900 m depth in Svartsengi boreholes is linearly related to subsidence. No gravity changes were observed in Svartsengi indicating that during production since 1976 the geothermal system has largely been recharged. A monitoring scheme on a routine basis was outlined at the end of the project and has already been activated (Eysteinsson, 2000). A similar survey was carried out at Nesjavellir in 1994 to establish network for future monitoring, production having started in 1991.

In Krafla and Námafjall an extensive survey was carried out in 1995 reavealing major changes in land elevation (Björnsson and Eysteinsson, 1998). The changes are however assumed to be mainly caused by volcanic activity in the area. A minor subsidence around the production field in Krafla is believed to be due to production.

The goal of this priority project to establish networks for monitoring for the major utilized areas has thus been fully obtained.

2.4 Microearthquakes

Microearthquake activity was studied in one of the utilized areas, the Svartsengi field. Monitoring in the field was carried out during May to August 1993 with the object to study possible effects of water injection into a borehole. Refraction and seismic noise measurements were also made to gather information on the regional seismic structure of the crust to facilitate future seismographic siting (Brandsdóttir *et al*. 1994). Seismicity along the Reykjanes peninsula was low in 1993 and no detectable microearthquakes occurred within the geothermal field. It was concluded by application of criteria derived by Sherburn *et al*. (1990) and Davis and Frolich (1993) that the injection pressure into the Svartsengi field was far below that needed to induce seismicity. Pore pressure decreases by drawdown and in turn increases rock strength and reduces microseismic activity. The drawdown of 20 bar in Svartsengi and 10 bar in Eldvörp since the start of development may thus have reduced microseismic activity temporarily. Four suitable sites for future permanent seismic stations within 2 km distance from the Svartsengi power plant were located with reference to the results of refraction and seismic noise measurements. Three of these sites have been established and operated for about two years in cooperation with the power plant and the Meteorological Institute of Iceland.

2.5 Mapping of steam caps

Possible geophysical methods to map steam caps were reviewed within the project (Árnason, 1992). In order to delineate a steam zone that is known to exist in the Svartsengi field an attempt was made to use refraction and seismic velocity determined using several strategically placed explosions in the vicinity of Svartsengi (Árnason, 1994). The results were not conclusive and closer inspection and additional experiments are needed possibly in conjunction with TEM (Transient electro magnetic) resistivity soundings.

2.6 Non utilized areas

This priority project was considered one of the most urgent, but funding turned out to be hard to obtain. Four non utilized areas were selected as type localities for the project: Theistareykir, Krýsuvík, Kverkfjöll and Torfajökull (Fig. 1). According to the project plan the surface manifestations in the areas were to be mapped every year and compared to previous maps where available, the steam flow valued and samples for chemical analysis collected from 2-4 fumaroles in each area and possible changes noted (Kristmannsdóttir and Ármannsson, 1998, Ármannsson et al., 2000).

During 1991-1997 the Theistareykir area in NE Iceland was visited five times, surface expressions mapped and samples for chemical analysis collected from selected fumaroles. Remote sensing methods have also been used for thermal scanning, but due to the lack of digitized terrain models for the area interpretation has not been completed. Concentrations of sulphur gases and mercury in atmospheric air were determined. Considerable changes appear to have taken place in surface manifestations and gas geothermometers.

The geothermal area in Krísuvík was visited several times in 1991–1997 and a few fumaroles sampled repeatedly. The area was photographed by infrared remote sensing methods three times during these years. Extensive changes in surface expressions were seen during the six years of the enforcement project. Concentration of sulphur gases and mercury in atmospheric air was monitored within the geothermal area.

Little exploration has been carried out in the Kverkfjöll area. The main advantage of monitoring this area is that it is so remote from any potentially usable areas and so unlikely to be developed itself that it should be possible to observe natural changes alone. Mapping of surface expressions has been in progress from 1992 and samples for chemical analysis collected from fumaroles and particular fumaroles were selected for monitoring. The area has been photographed by infrared remote sensing methods two times during these years.

The Torfajökull geothermal area is one of the largest in Iceland and is likely to be developed in the next 10-20 years. Surface exploration has been in progress in the area from 1992, but little previous research had been conducted in the field and thus there are no reported changes in natural activity.

This priority project was concluded by making a preliminary project schedule and a cost estimate for the investigations necessary to carry out an environmental impact assessment for a 20 MW power plant in all non utilized Icelandic geothermal areas (Kristmannsdóttir et al., 1995). It was evident that there would not be funds available for such a project in the near future so a more realistic project plan was was made for the next five years to accquire the necessary background data on six selected non utilized areas. The start of environmental monitoring in the same fields was suggested (Kristmannsdóttir, 1997). So far the plan has not been initiated, but funding is being sought.

2.7 Cost of the enforcement project

The total cost of the project was about 1.1 mUSD over all the six years. This may not be considered a high cost by international standards but it is a huge program by Icelandic standards and actually of the same magnitude as the yearly budget of the Icelandic Science Fund. The funding was jointly provided by the associated power companies and Orkustofnun (approximately 60:40) with a smaller contribution from the Ministry of the Environment, the partcipating agencies and the Technical Science Fund of Iceland.

3. CONCLUSIONS

- The status of environmental knowledge of the utilized high-temperature geothermal areas in Iceland has been compiled, background data collected in four non utilized areas selected as type localities and monitoring shemes initiated.
- Research has been initiated on microearthquake activity in geothermal areas and methods for mapping of steam caps. Basis has been laid for land elevation and gravity monitoring networks in all the utilized areas.
- The baseline values for the concentration of mercury and sulfur gases have been defined in all the utilized areas and a few non utilized ones. Studies on the dispersion and reaction of sulfur gases in the atmosphere has been initiated and it has been concluded that in the climatic conditions in Iceland only a small fraction of the H_2S emitted from geothermal fields will br converted to SO_2 a precursur to acid rain.
- Methods for aerial thermographic surveys have been refined and tested and their usefulness in detecting and mappping changes in surface manifestations with time have been demonstrated.
- A project schedule and a cost estimate have been made for the investigations necessary to carry out an environmental impact assessment for a 20 MW power plant in all non utilized Icelandic geothermal areas.
- Approximately 100 titles, reports and papers, have been published on the subjects covered by the enforcement project.
- The total cost of the enforcement project equals the yearly budget of the Icelandic Science Fund.

The main outcome of the project is better understanding and increased emphasis on environmental studies in the future. It is also believed to facilitate the implementation of the law on environmental impact assessment for geothermal exploitation and the comparison of alternative power production possibilities with regard to environmental effects.

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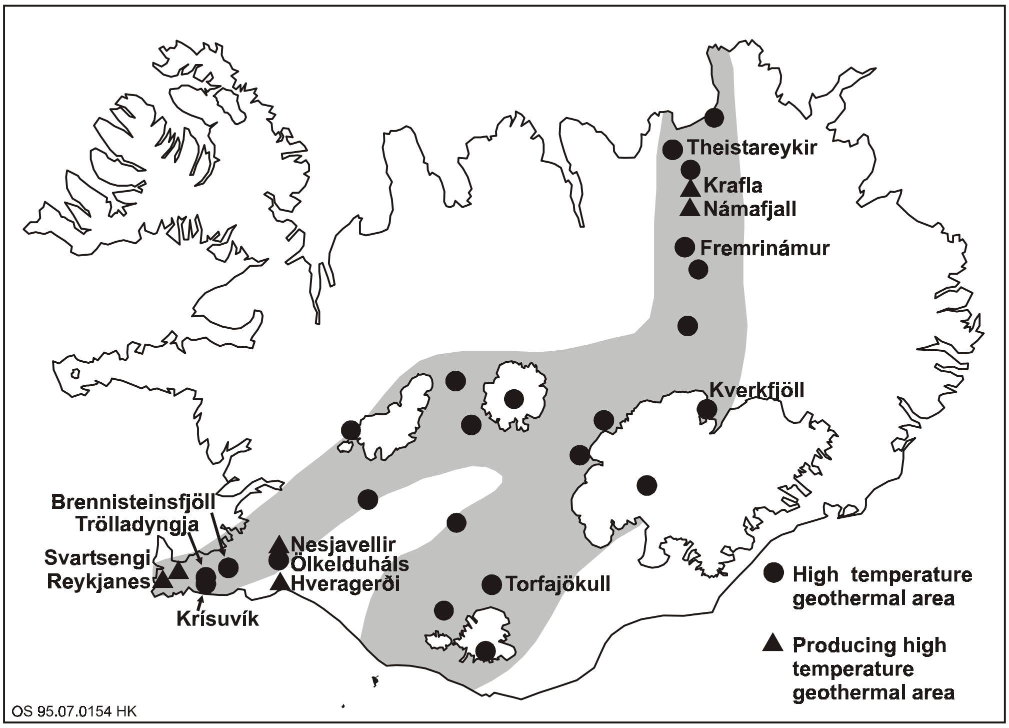
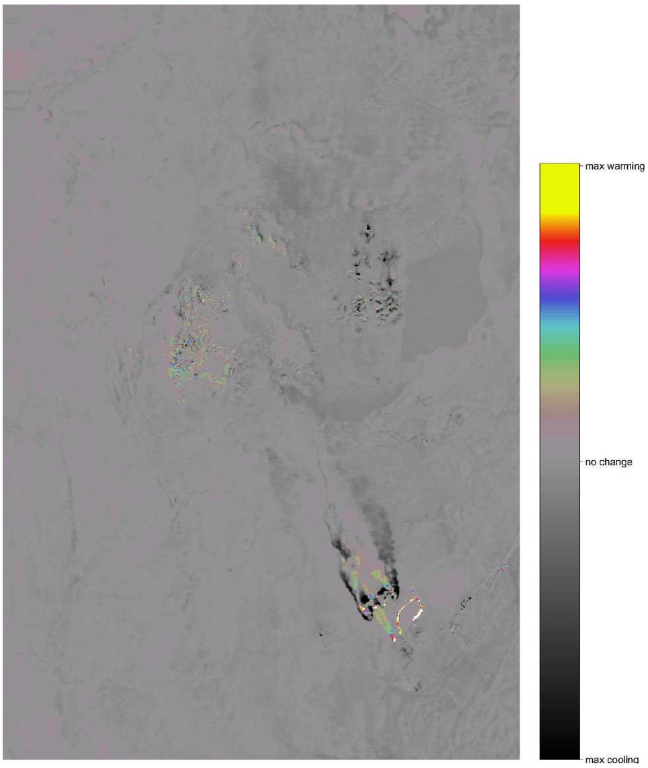


Figure 1. A location map of geothermal areas cited. On the map the outlines of the active volcanic zones in Iceland and all the utilized and non utilized high-temperature geothermal fields in Iceland are shown.



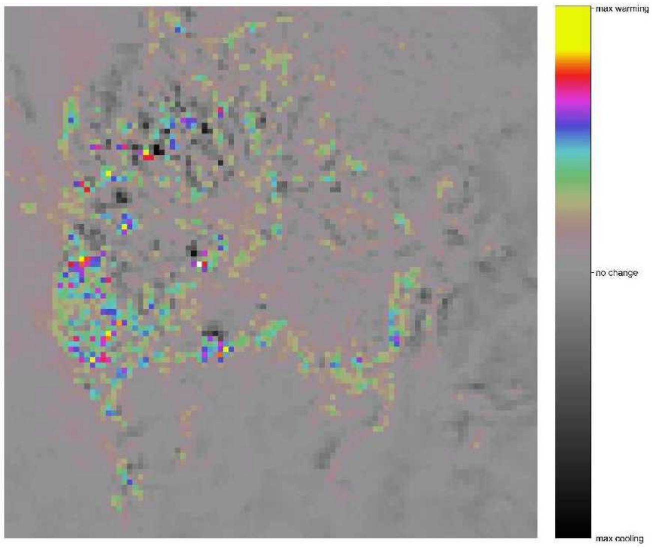


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Figure 2. A differential thermal image of the Reykjanes utilized geothermal field. The figure is obtained by subtracting a thermal image from November 1994 from a coregistered thermal image from September 1995. Areas of no thermal change are displayed in light grey, colours indicate spots where warming up has occurred and cooling is indicated with dark grey to black (most substantial cooling). Note the two steam fields in the upper half of the image. The steam field on the right has become colder but the steam field on the left has warmed up during the time interval between the two survey dates.

Figure 3. An enlarged part of the differential thermal image in figure 2, showing the natural steam field area in the upper left quarter of figure 2. Substantial warming up has occurred in this steam field between autumn 1994 and 1995