Grant Submission Document

Project Title:

H_2S sequestration into geothermal systems

The number and name of the WP the proposal refers to

WP6 – Sustainability – Environment

Task 6.3: Mitigation of environmental impact

Project Coordinator/ Managing Entity

Organization: University of Iceland	
Name of Coordinator:	**Phone / email:**
Andri Stefánsson	+354-525 4252 /as@hi.is
Name of Finance Manager:	**Phone / email:**
Sigurður Guðnason	+354-525 4800 /sgud@raunvis.hi.is

Other Participants

Organization: Reykjavík Energy	
Name of contact person:	**Phone / email:**
Ingvi Gunnarsson	+354-516 6000/ingvi.gunnarsson@or.is
Organization: Landsvirkjun	
Name of contact person:	**Phone / email:**
Sigurður H. Markússon	+354-515 4000/sigurdurm@lv.is
Organization: MIT, USA	
Name of contact person:	**Phone / email:**
Shuhei Ono	+617-253 0474/sono@mit.edu

Project Key Words

H_2S, sequestration, feasibility, geochemistry

Project Abstract

H_2S is commonly emitted into the atmosphere from geothermal power plants, causing potential environmental problems. One possibility disposal method for H_2S is injection back into the geothermal systems whereas H_2S may mineralise forming sulphides. The project "H_2S sequestration into geothermal systems" aims at defining the geochemistry of geothermal H_2S sequestration and its geochemical feasibility. Emphasis will be made on studying the rate of H_2S mineralization, possible oxidation to sulphuric acid and together with geochemical modelling assess the optimal conditions of H_2S disposal. The project is a joint effort between scientists that have contributed to this subject in years passed.

Information to be filled in by GEORG
Application number: 11-04-003

Eligibility Rules

For application to be eligible the following points shall be kept in mind.

- ***The proposal needs to be submitted no later than 23:00 GMT on November 20th 2011***
- ***The Coordinator of the proposal needs to be GEORG participant.***
- ***The Grant submission document shall neither exceed 10 pages (including front page, this page, figures, tables and references, but excluding cv's) nor shall it exceed the maximum number of words for each section of the document.***
- ***The budget plan shall be prepared and demonstrated according to Section I- Chapter 6 of the "Proposal & Award Policies & Procedures Guide" for the 4th Call.***
- ***The proposal shall address clearly problems and questions of importance for development of the geothermal sector. For information on GEORGs objectives please find GEORG - WP description at www.georg.hi.is***

Eligibility check list:		
	Yes	*No*
Is the coordinator of the proposal a GEORG participant?		
Does the proposal follow all applied rules regarding format of the proposal?		
Does the proposal follow all applied rules regarding the budget		
Does the proposal address clearly problems and questions of importance for development of the geothermal sector?		
Is the proposal, incl. all required appendixes, submitted in due time?		

Proposal that do not fulfill the eligibility rules listed above will not be evaluated by the Review Committee.

Information to be filled in by GEORG
Application number: 11-04-003

Project description

General descriptions

Hydrogen sulphide (H_2S) is among the major components in geothermal fluids, with concentrations ranging from a few ppb to levels of hundreds of ppm (Arnórsson 1995a, 1995b). Hydrogen sulphide is volatile and is commonly emitted into the atmosphere from geothermal power plants, causing potential environmental problems.

Several methods are employed in cleaning H_2S emissions including oxidation to form elemental sulphur or sulphuric acid (Sanopoulos and Karabelas, 1997). One method includes injection of H_2S into geothermal systems where it may be mineralized into sulphides including pyrite. Reykjavík Energy and Landsvirkjun, Iceland, are currently considering such an injection into the geothermal system at Hellisheidi, Námafjall and Krafla, where geothermal gas (CO_2, H_2S, N_2 and H_2) will be separated in a gas abatement station and the H_2S (+CO_2) stream mixed at the surface with water prior to injection into the geothermal aquifer.

It is generally accepted that the major elemental composition including H_2S concentration of geothermal fluids is controlled by local equilibrium with common secondary minerals (e.g. Giggenbach, 1980, 1981; Arnórsson et al., 1983; Stefánsson and Arnórsson, 2000; Gudmundsson and Arnórsson, 2005) including pyrite, pyrrhotite, prehnite and epidote as well as possibly magnetite (Stefánsson and Arnórsson, 2002). Therefore, elevated H_2S concentrations may lead to sulphide mineralization as well as some iron oxide and aluminium silicate formation. However, the exact response of the system, including the rate and quantity of H_2S mineralization, redox reactions and the associated fluid chemistry, is somewhat unclear.

Previous work on volatile gas disposal has mainly focused on reaction modelling and experiments regarding CO_2 (e.g. Gunter et al., 2000; Johnson et al., 2001; McPherson and Lichtner, 2001; Xu et al., 2004, 2005, 2006, 2007; Knauss et al., 2005; White et al., 2005; Zerai et al., 2006; Jacquemet et al., 2008; Palandri and Kharaka, 2008; Gessner et al., 2009; Crandell et al., 2010; Gysi and Stefánsson, 2011). Less is known about H_2S disposal under geothermal conditions. Based on geochemical modelling, Stefánsson et al. (2011) concluded that the optimal conditions for H_2S sequestration into geothermal systems are temperatures between 200-250°C whereas mineralization rates may be assumed fast and most of the Fe^{2+} goes into pyrite formation. Some key questions still need to be answered including the effect of H_2S supply (pH_2S) on the fluid–rock interaction, rate and mechanism of H_2S mineralization, and possible oxidation of H_2S to sulphuric acid under geothermal conditions.

The focus of the proposed project will be twofold. Firstly, laboratory experiments will be conducted to study the interaction of H_2S-rich water with basalt and rhyolite. Based on this, the reaction path, H_2S mineralization rate and possible H_2S oxidation rate will be studied. Secondly, using data obtained in the first part, data on fluid composition and secondary mineralogy from selected geothermal systems and geochemical modelling, the optimal conditions for H_2S sequestration into geothermal systems will be studied.

Here the group seeks funding from GEORG to co-finance the project including experimental running cost and salaries for a Ph.D. student and a young scientist.

Scientific – and/or Technical Merit

Environmental effects of power production constitute some of the most serious environmental problems of today. Geothermal energy production is generally regarded relatively environmentally friendly, yet the anthropogenic emissions from geothermal power plants cannot be regarded negligible. This includes emission of gases like H_2S (Axtmann, 1975a,b; Bargagli et al., 1997; Kristmannsdóttir and Ármansson, 2003; Rybach, 2003; Arnórsson, 2004; Ármannsson et al., 2005, 2008; Daysh and Chrisp, 2009).

In recent years considerable focus has been on making geothermal utilization more environmental friendly. Among the main tasks posed on the industry in Iceland are regulations regarding H_2S emission and atmospheric concentrations (www.idnadarraduneyti.is/ og www.umhverfisraduneyti.is/). Four main approaches have been suggested in order to clean H_2S emissions from geothermal power plants: (1) the Claus process, (2) liquid redox sulfur recovery (LRSR) processes, (3) the burn/scrub process and (4) water absorption and injection (Trimeric Corp., 2011). The first three processes are well established but expensive to set up and run resulting in increased energy prices. The last method involves mixing the H_2S with water at surface and injecting it into the geothermal system. This approach has never been tried before but preliminary studies indicate the cost to be considerably less compared to the other methods. However, the geochemical aspects of H_2S sequestration into geothermal systems are somewhat unclear.

Based on geochemical modelling, Stefánsson et al. (2011) concluded that the optimal geochemical conditions for H_2S sequestration into the Hellisheidi geothermal system, Iceland, are <250°C whereas injection into higher temperatures may result in insufficient mass of mineralization of sulfides. However, some basic questions are still unanswered including the rate (efficiency) of mineralization and possible oxidation of H_2S to sulphuric acid. The latter may result in the formation of acid reservoir fluids (pH<3) with serious consequences for production. To address these problems more knowledge is needed on the basic geochemistry of H_2S-water-rock interaction, such information obtained by performing controlled laboratory experiments.

One of the main focuses of the proposed project is to apply recently developed experimental methods that have been successfully applied for studying CO_2-water-rock interaction and CO_2 sequestration using batch and plug flow reactors. Using similar setup for studying H_2S-water-rock interaction information on reaction path, possible H_2S oxidation and H_2S mineralization rates may be obtained. The results obtained provide the fundamental input for geochemical modelling used to optimize H_2S sequestration conditions, i.e. pH_2S, temperature, injection water type (cold water, condensed steam or waste water) etc. The project is further intended to bring together experienced scientists working within the field of geothermal chemistry and the geothermal industry, a fruitful training environment for young scientists and students within the institutes of the applicants as well as providing a possible platform for future work and discussion on the chemical impact of geothermal power production in Iceland and elsewhere.

Innovation / Entrepreneurship

The innovative character of the proposed project is to define the geochemical aspects and geochemical feasibility of H_2S sequestration into high-temperature geothermal systems. This in turn can be combined with chemical engineering and knowledge of the structure, temperature and hydrology of a given geothermal system to facilitate H_2S disposal. The detailed knowledge and methods on H_2S sequestration into geothermal systems will hopefully become acknowledged and if proven to be successful may provide the bases of possibly the easiest and cheapest way in the future for H_2S disposal from geothermal.

The main entrepreneurship involves the geochemical assessment and feasibility of H_2S sequestration into geothermal systems. Such a disposal method for H_2S, if successful, is likely to be relatively simple and inexpensive than more common methods applied in geothermal with possible important influences on energy prices.

It is our hope that the results of the project will promote the position of geothermal power production worldwide as a green energy alternative as well as placing Icelandic companies and scientists in forefront in environmental issues related to geothermal power production.

Education / Dissemination

Currently one graduate student at the M.Sc. level and one postdoctoral researcher are working on the geochemistry of H_2S in geothermal systems. This includes Jóhann Gunnarsson Robin (M.Sc student, H_2S chemistry in geothermal fluids at Krafla, University of Iceland) and Nicole S. Keller (Postdoctoral Source and fade of sulfur in geothermal systems traced by sulphur isotopes, University of Iceland).

Here the group seeks funding from GEORG to co-finance the project including salaries for a new Ph.D. student, postdoctoral researcher and running cost for direct study of the geochemistry of H_2S and geochemical feasibility of H_2S sequestration in geothermal systems.

Managerial

The participating group of institutions comprises University of Iceland (UI), MIT, USA (MIT), Reykjavik Energy (OR), and Landsvirkjun (LV). Access to sampling and instrumental facilities (UI, MIT), data on fluid composition (UI, OR, LV) and access to geothermal power plants and sites (OR, LV) is guaranteed. The research group consists of highly experienced scientists within the field of geothermal fluid geochemistry that is currently working on H_2S sequestration into geothermal systems at Hellisheidi and Námafjall. The Science Institute, University of Iceland (UI) head office will be responsible for the financial management of the project.

The main leaders of the research project are: from UI: Andri Stefansson, associated professor in geothermal geochemistry; from MIT: Shuhei Ono, professor of isotope and sulphur geochemistry; from OR: Ingvi Gunnarsson, scientist; from LV: Sigurdur H. Markússon, project manager. The group will have access to other scientists and technical help within their institutions. The students and postdoctoral scientists involved in the project include Jóhann Gunnarsson Robin (UI) and Nicole Keller (UI). In addition a young scientist will be incorporated into the project.

It is our believe that there is good opportunity at the moment to continue working on H_2S sequestration into geothermal systems as a possible method for H_2S disposal. Reykjavik Energy has worked on this problem for several years and Landsvirkjun has made the first steps as well. However, there are still unanswered questions particularly related to the geochemistry of H_2S sequestration. In addition, the proposed project will involve a joint effort of researchers and students and hopefully result in well trained geothermal geochemists for the future.

Financing:

Cost item		Requested funding		Other financing		Total
2012/2013	Salaries					14'250
	Operational expenses					1'500
	Travel expenses					0
	Total 2012/2013:	7'150	45%	8'600	55%	15'750
2013/2014	Salaries					14'250
	Operational expenses					1'500
	Travel expenses					350
	Total 2013/2014:	7'500	47%	8'600	53%	16'100
2014/2015	Salaries					14'250
	Operational expenses					1'500
	Travel expenses					350
	Total 2014/2015:	7'500	47%	8'600	53%	16'100
Grand Total		**22'150**	**46%**	**25'800**	**54%**	**47'950**

Consortium: **UI, RE, LV, MIT**

Name of Project: **H_2S sequestration into geothermal systems**

ISK '000	Year		Year 1 2012/2013		Year 2 2013/2014		Year 3 2014/2015			**Grand Total**	
Salaries including overhead		**Unit cost**	Man-months	Total	Man-months	Total	Man-months	Total			
UI	PhD student	450	12	5'400	12	5'400	12	5'400		16'200	
UI	Postdoc	550	12	6'600	12	6'600	12	6'600		19'800	
UI	AS	900	1	900	1	900	1	900		2'700	
RE	IG	900	1	450	1	450	1	450		1'350	
LV	SHM	900	1	450	1	450	1	450		1'350	
MIT	SO	900	1	450	1	450	1	450		1'350	
Total			27	14'250	27	14'250	27	14'250		42'750	
Operational exp.											
a Experimental apparatus maintainance				500		500		500		1'500	
b Chemical analysis				1'000		1'000		1'000		3'000	
c										0	
Total				1'500		1'500		1'500		4'500	
Travel expenses											
a Conferences						350		350		700	
b										0	
c										0	
Total				0		350		350		700	
Total cost				15'750		16'100		16'100		47'950	
Financing											
a Rannís, LV-grant and UI-grant				6'350		6'350		6'350		19'050	
b UI, RE, LV, MIT				2'250		2'250		2'250		6'750	
Total other financing				8'600	55%	8'600	53%	8'600	53%	25'800	54%
Requested funding from GEORG				7'150	45%	7'500	47%	7'500	47%	22'150	46%
Total financing				15'750		16'100		16'100		47'950	100%

Explanation of cost:

Salaries: The salaries of participants' contribution more than half a month per year are incorporated into the proposed project. Here we apply for covering salaries, including overhead cost, of a PhD student and a young scientist for 3 years.

Operational expenses: The experimental apparatus maintenance and chemical analysis include all running cost for experiments and shipment for analysis to MIT, USA. It should be pointed out that the value of the equipment itself is estimated >25 m.kr, not included here.

Travel expenses: The travel expenses include two conferences in 2013 and 2014.

Work plan and time schedule:

The project involves three major tasks. These are

WP 6.3 – H_2S oxidation under geothermal conditions

This subtask will involve experimental work on the oxidation rate of H_2S during water-rock interaction under geothermal conditions (150-300°C) as a function of pH_2S and pH_2. It is intended to perform experiments using a mixed-flow reactor on the interaction of H_2S-rich fluids with basalts and rhyolites. From the results, the stability and possible oxidation rates of H_2S may be assessed

WP 6.3 H_2S-water-rock interaction and H_2S mineralization rate

This subtask will involve experimental work on the interaction of H_2S-rich fluids with basalts and rhyolites as a function of pH_2S and pH_2 and under geothermal conditions (150-300°C). The experiments will be carried out in batch type reactors and the secondary mineralogy and fluid chemistry studied as a function of time. From the results, the reaction path of H_2S-water-rock interaction and H_2S mineralization rates may be assessed. The experimental work will be complemented with geochemical simulations.

WP6.3 – H_2S geochemistry and sequestration into geothermal systems

This subtask aims at gathering data on fluid composition and secondary mineralogy in selected geothermal systems in Iceland, Krafla, Námafjall and Hellisheidi. Combined with the results on H_2S-water-rock interaction and H_2S oxidation rates obtained in the first two tasks of this study the geochemical behaviour and feasibility of H_2S sequestration into geothermal systems will be evaluated.

Time schedule:

Subtask	Start	Finish	Deliverable/Milestone
H_2S oxidation under geothermal conditions	01/01/12	01/01/14	Rate of H_2S oxidation
H_2S-water-rock interaction and H_2S mineralization rate	01/01/12	01/01/14	Rate of H_2S mineralization
H_2S geochemistry and sequestration into geothermal systems	01/01/12	01/01/15	Geochemical feasibility of H_2S sequestration into geothermal systems
Writing and introduction of the results	01/01/13	01/01/15	Introduction and publication of the results

Appendix I Applicant CV

Name: **Andri Stefánsson**
Date of birth: 22.12.1972
Nationality: Icelandic
Work address: Institute of Earth Sciences, University of Iceland
Sturlugata 7, 101 Reykjavík, Iceland
Work Tel: +354-525 4252
E-mail: as@hi.is

Higher education

1992-1994	University of Glasgow. Major in Geography and Chemistry
1994-1996	University of Iceland. B.Sc. with major in Geology.
1996-1998	University of Iceland. M.Sc. in Geochemistry.
1998-2002	ETH Zurich, Switzerland. Ph.D. in Geochemistry.

Professional and research experience

2010-	Visiting Research Professor, LMTG, CNRS/Univ. Toulouse/Obs. Midi-Pyr., France.
2009-	Associated Professor, Institute of Earth Sciences, University of Iceland
2002-	Research scientist, Institute of Earth Sciences, University of Iceland.
2002-	Geothermal Geochemistry Consulting
2006-	Teacher of geothermal geochemistry at University of Akureyri, RES Iceland, UNU.

Selected recent publications

Stefánsson, A., Arnorsson, S., Gunnarsson, I., Kaasalainen, H., Gunnlaugsson, E. (2011) The geochemistry and sequestration of H_2S into the geothermal system at Hellisheidi, Iceland. J. Volc. Geotherm. Res. 202, 179-188.

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Stefánsson, A., Gíslason, S.R., and Arnórsson, S. (2001) Dissolution of primary minerals of basalt in natural waters II. Mineral saturation state. Chemical Geology 172, 251-276.

Curriculum Vitae

Personal information

Name:	Ingvi Gunnarsson
Date of birth:	12.08.1971
Home address:	Þrastarhöfði 59 270 Mosfellsbær Iceland
Work address:	Reykjavík Energy Bæjarhálsi 1 110 Reykjavík Iceland
Work Tel:	+354-5166000
Fax:	+354-5166008
E-mail:	ingvi.gunnarsson@or.is

Higher education

1993-1997	University of Iceland. B.Sc. in Geology
1997-1999	University of Iceland. M.Sc in Geochemistry

Professional and research experience

2008-present	Geochemist at Reykjavík Energy
1999-2008	Research scientists and teacher at Science Institute University of Iceland.
1996-1999	Research assistant, Science institute, University of Iceland, for Prof. Stefán Arnórsson and Dr. Sigurður R. Gíslason.

Selected Publications

Gunnarsson I, Sigfússon B, Stefánsson A, Arnórsson S, Scott SW and Gunnlaugsson, E (2011) Injection of H_2S from Hellisheiði power plant, Iceland. Proceedings Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford.

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CV

Sigurður H. Markússon
Landsvirkjun, Project manager - Geothermal
Date of birth 7. May 1980
Address: Þórðarsveigur 32, 113 Reykjavík
e-mail: sigurdurm@lv.is

Higher Education

2009 - 2010	Geochemistry – PhD program, Toulouse France
2007- 2009	Geochemistry – M.Sc. University of Iceland
2002-2006	Geology – B.Sc. University of Iceland

Professional Experience

2011	Landsvirkjun, Project manager - Geothermal
2010-2011	Efla, Geothermal
2006-2008	Efla, structural geology

Selected publications

Markússon, S. H. and Stefánsson, A. (2011) Geothermal surface alteration of basalts, Krysuvik Iceland-Alteration mineralogy, water chemistry and the effects of acid supply on the alteration process. *Journal of Volcanology and Geothermal Research, v 206*, p. 46–59.

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Shuhei Ono
Assistant Professor of Geochemistry
Earth, atmospheric and planetary sciences
Massachusetts Institute of Technology
E-34-254, 42-44 Carleton Street
Cambridge MA 02139-4307, USA
+617-253 0474
e-mail: sono@mit.edu

Professional Preparation

Waseda University (Tokyo) Geology B.S.,1994
Waseda University (Tokyo) Economic Geology M.E., 1996
Pennsylvania State University Geochemistry Ph.D., 2001
Carnegie Institution of WashingtonGeochemistry Postdoc, 2002 -07

Appointments

2007 -	Assistant Professor, Earth, Atmospheric and Planetary Sciences-MIT
2005 – 07	Agouron Geobiology Fellow
2002 – 05	Carnegie Postdoctoral Fellow, Carnegie Institution of Washington

Selected recent publications

Bosak, T., Bush, J., Flynn, M., Liang, B., Ono, S., Petroff, A. P., and M.S. Sim (2010), Formation and stability of oxygen-rich bubbles that shape photosynthetic mats, Geobiology 8, 1-11

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