ANNUAL REPORT
YEAR 2

Biological Utilization of Geothermal Gas

Date of annual report: 25. March. 2012

Project ID: 09-01-017

Coordinator: Guðmundur Óli Hreggviðsson, University of Iceland

Start date: 1. June 2009

Duration: 2 years

Partners: University of Iceland, Prokatín ehf, Mannvit Engineering

1 General status of the project

As reported in the Annual report 1, the milestones 1.1., 1.2. & 1.3. were all completed by the end of 2010. Therefore all milestones and deliverables for year 1 have now been reached and completed according to the original plan. The overall project has been delayed in total of about 8 months. Also some modifications of the project plan and goals for the 2nd year have been necessary.

The main objective of the project is to develop a functional and economically viable solution to the problem of hydrogen sulphide exhaust from geothermal power plants. Biological utilisation of the geothermal gas (GEOGAS), has until now been the only proposed solution that could be economically feasible for the Icelandic situation. All other proposed or known methods would be too expensive for geothermal power plants in Iceland, due to the much lower electricity price than, for example in California and Europe.

A key element in the project has therefore been to do all experiments and development work directly on site, using real geothermal gas produced under industrial conditions from fully operating power plants. This will naturally bring in numerous problems and unexpected incidents that would not happen if similar experiments would be done under artificial laboratory conditions using controlled, synthetic gas. However, the value and applicability of the results from such experiments, when transferred to the real world, would be very limited. The downside, however of being on site is that the environment is corrosive due to H_2S, the power plant shuts down unexpectedly, due to mechanical failures, earthquakes or bad weather, causing frost damage or pipe flooding. Such experiences are the main causes of delays in the project, but at the same time, a valuable part of the learning process. This teaches us how to develop the process and the equipments to function successfully under the real conditions. Because of this many improvements in the original construction have been developed and tested. This has led to introduction of improved safety valves, condensate traps and more robust mechanisms for regulation of gas flow. Therefore the system for feeding the gas into the pilot plant, monitoring and regulating the gas flow and mixing of gas with air and dispersion/mass transfer into the bioreactor have improved and are now much more robust and therefore more dependable than before.

Because of measurements done during this project we have discovered that geothermal exhaust gas is even more difficult to handle than had been anticipated when the project was started, based on the existing knowledge at the time. The natural composition of the GEOGAS, as it enters the power plant on Hellisheiði and Nesjavellir, is about 20-40% H_2S, 20-40% H_2 and 30-60% CO_2. After the steam has gone through the turbines, it condenses but the non-condensable gas remains. To obtain the maximum energy from the steam, a mild vacuum is maintained on the exit-side of the turbines. This then leads to mixing of 10-30% air into to the GEOGAS, which is finally lead to exhaust or a gas-processing facility. Such a mixture is very difficult to handle mechanically, since it is highly toxic and explosive, it is highly corrosive and produces at the same time sulphuric acid and solid precipitates of sulphur and metal sulphides. This then can clog valves and narrow sampling pipes, making regulation and monitoring very difficult.

The above gas mixture and conditions is however part of the natural conditions of hot springs in the area and there are plenty of different bacteria that thrive under such conditions. In our case this wet, oxygen-containing GEOGAS at 20-60°C, is biologically treated by sulfide-oxidizing bacteria that grow in water and use oxygen at 50°C so this mixture is perfect for them. The problem therefore is not to find suitable bacteria, but rather how to handle and feed the gas in the most efficient way to the bioreactor, and this is in no way a trivial matter.

The results so far have shown that we have developed a workable and efficient system on a 10 L scale that can biologically treat this GEOGAS. We have managed to run this in a continuous mode for several weeks at a time, with good results. The transfer of this process results to the 1500 L scale has been delayed. The products produced are microbial biomass, or single cell protein and pure sulphure, both of good quality, according to analysis. Feeding experiments of fish are delayed and have been transferred to a new project, which is to take place during summer of 2012 under a new EuroStar project, in collaboration with Matis ohf, Sæbýli ehf and Swedish scientists. See further details of progress below.

1.1 Project progress/time schedule:

Our project "Biological Utilization of Geothermal Gas" has now come to an end as part of GEORG, but it will continue in other settings. The mains goals of the overall project are the same as before (see Subtasks 1-3 below , naturally with minor delays and modifications as is a normal part of such R&D projects. The description of Subtasks 2 & 3 below have been modified according to the current status and immediate goals.

Short description of the work plan

Subtask 1. Pilot plant at Hellisheiði
Main emphasis is put on building a several thousand liter pilot plant at the Hellisheiði power plant. The pilot plant will obtain geothermal gas directly from the power plant and the gas will be processed by a biological process for the production of biomass (single-cell protein) and solid sulfur and sulfuric acid. The pilot plant will be run for 1-2 years and is estimated that during the operation of the facility, up to 50 tones of biomass and 100-300 tones of sulfur / sulfuric acid will be produced. The operation will be a feasibility study for a future full-scale factory.

Subtask 2. Use of Biomass for Feed
There is much interest in the availability of new protein sources for feed due to shortage of fish meal for feed. Prices of protein-rich meals are high and rising. We have got a EuroStar-grant for the project Microfeed (formal start date was 1. oct. 2011) where we collaborate with Matís ohf and the Icelandic fish-farming company Sæbýli ehf for experiments using the single-cell protein for cultivation of the tropical Tilapia fish and Arctic trout, both of which are species with characteristics suitable for experiments of this kind.

Subtask 3. Utilization of Sulfur
The overall use of sulfur in industry increases 2-3% a year but use of sulfur in fertilizers is growing about 10% per year. Traditionally there has been an overproduction of sulfur and prices low, but for the last 4 years prices have been rising and are currently about $250 per ton. A biologically produced sulfur has different properties and has been shown to give better

yields of some plants than inorganic sulfur. Recent studies have shown that agricultural soils are increasingly deficient in sulfur and often a limiting factor in growing grass and vegetables. This is a particular problem in organic farming. We believe that a biological sulfur which we would produce in our process can be registered as allowed for use in organic farming. This would offer a huge market potential and possibly higher prices for our sulfur products. In collaboration with the Icelandic Forest Service and private growers we are planning both greenhouse and field experiments in the summers of 2012 and 2013.

Deliverables and Milestones indicating progress: Year 1. All completed.

The submission of a Progress & Annual report:

Milestone 1.1: Construction of 2000 L pilot bioreactor tank finished.

Milestone 1.2: Report on sulphur market situation and main uses of sulphur prepared.

Milestone 1.3: Bioreactor has been put in operation and at Hellisheiði power plant and tested with real GEOGAS on site.

Deliverables and Milestones indicating progress: Year 2.

The submission of an Annual report:

Milestone 2.1: Successful reproduction of 10 L operation from the Nesjavellir tests at Hellisheiði with similar level of biomass (3-5 g/L).

Results: Completed successfully. The main focus has been on improving the growth yield for thermophilic bacteria growing on GEOGAS. Changes were made in the media by increasing several of the essential minerals and iron. Also the buffer control was changed from NaOH to ammonia. This gave considerable improvements in the biomass density (up to 6-8 g/L) and oxidation rate of H_2S.

Milestone 2.2: Productivity in 10 L scale at Hellisheiði improved up to production scale of 8-10 g/L

Results: Completed successfully. The results from M2.1. above was hen taken to the next step and a continuous culture was started on the 10 L scale. With retention time of 1 day a stable system with good yields were obtained. The biomass density reached 6-8 g/L and the H_2S oxidation was 2-3 g/l/h.

Milestone 2.3. Successful operation of pilot plant at Hellisheiði for at least 1 month with biomass level of 3-5 g/L.

Results: Completed almost successfully. The operation of the 1500 L ALF with biomass yields up to 3-4 g/L have been reached but operation has not been stable due to technical difficulties that tended to result in premature shut-down. When restarted similar results could be obtained if no problems occurred. Therefore uninterrupted operation for 1 month has not been possible yet.

Milestone 2.4. Successful operation of pilot plant at Hellisheiði for at least 1 month with biomass level of 8-10 g/L.

Results: Not completed. It was decided to do some changes in the construction and control of the ALF in order to improve mass transfer of gas and change the level-control so the ALF can be operated in continuous culture mode. The changes have now been made and test operation without gas has been working well. Real experiments with this new setup will start in April 2012.

Milestone 2.5 Productivity in terms of kg/h of biomass and sulphur measured and documented.

Results: Partly completed. The yield of biomass that has been obtained on the 10 L scale (6-8 g/L) is sufficient to produce 60-100 g/day. That is enough so that we can produce what we need for the first fish feeding experiments. With same biomass yield in the ALF we can produce 10-15 kg/day which is enough to get commercial feed producers to test it.

Milestone 2.6: Certificate of analysis for representative samples in place.

Results: Completed successfully. Representative samples of biomass and sulphur have been produced on small scale and analysed. The biomass was about 80% protein and the sulphur was >99% pure. In both cases was the heavy metal content low and well within the allowed limit of biomass use for animal feed.

Milestone 2.7: Feed formulation and fish-feeding tests started.

Results: Not completed. This milestone has not been reached but as explained above this part of the project will continue in a newly funded EuroStar project.

2 Project Management

The project was managed by the coordinator and his cooperation partners, primarily Prokatin ehf, which mission is the same as the objectives of this project and concentrating all its efforts on this problem in close cooperation with Mannvit Engineering, Orkuveita Reykjavíkur and Landvirkjun.

The cooperation between Univ. of Iceland and the partners involved supervision by Dr. Guðmundur Ó. Hreggviðsson of the MSc student Guðný Inga Ófeigsdóttir. The student defended her thesis on 8. february 2012 and will formally graduate from Univeristy of Iceland next June. The daily operations of the pilot plant at Hellisheiði was under responsibility of Dr. Arnþór Ævarsson, CEO of Prokatin and Dr. Jakob Kristjánsson. The board of Prokatin, including representatives from Reykjavik Energy, Mannvit Engineering, Landvirkjun and Arkea, the mother company of Prokatin, take part in major decisions in the progress of the project. Chemical engineer Ásgeir Ívarsson at Mannvit Engineering supervised the operations of engineers in the projects. Progress in the project is regularly review by all involved parties for further decision making. Reykjavik Energy did allocated up to 50 millions ISK for construction of the pilot plant at Hellisheiði power plant and other share-holders of Prokatin have also contributed to the GEOGAS projects. Last summer Landsvirkjun contributed 15 million ISK to the project and has a conditional option to contribute additional 15 million. Cooperation has been started with Swedish researchers and efforts are being made to establish further international collaborations, especially aiming at EU funded programs.

Cooperative partners

University of Iceland,
Dr. Guðmundur Óli Hreggviðsson, Ph.D. in molecular biology from Edinburg Univ., UK. Docent in Microbiology at Univ. of Iceland. Department manager at Matís/Prokaria.
M.Sc. student: *Guðný Inga Ófeigsdóttir*, B.S. Biochemistry Univ. of Iceland.

Prokatin ehf
Dr. Arnþór Ævarsson CEO, Ph.D. educated in Biotechnology and Biophysics at Univ. of Lund, Sweden and Univ. of Washington, USA. Previously director of intellectual property and business development at Prokaria. Published about 20 scientific papers and a number of issued patents.
Dr. Jakob Kristjánsson, Chairman, Ph.D. in biochemistry from Brandeis Univ. USA. Previously docent and research professor at Univ. of Iceland. Founder and president of Prokaria. Published over 100 scientific papers and a number of issued patents.

Mannvit Engineering
Ásgeir Ívarsson, M.Sc. Chemical engineering, Chalmers Univ. of Technology, Sweden.
Rúnólfur Maack, M.Sc. Mechanical eng. Denmark Univ. Of Technology. Deputy CEO foreign operations.

Reykjavik Energy
Hólmfríður Sigurðardóttir, Cand Scient Soil Biology Univ. of Aarhus, MBA from Univ. of Reykjavik. Manager of innovation and development.

Landsvirkjun
Anna Guðný Hermannsdóttir, M.Sc. Biochemist, University of Iceland. Master of Project Management, University of Iceland. Project Manager.
Sigurður H. Markússon, M.Sc. Geochemistry, Univ. Iceland. Project Manager - Geothermal Energy.

3 Student involvement

One student has been directly participating in this project as part of her study. Guðný Inga Ófeigsdóttir did a Masters project as part of this project under the supervision of the coordinator. A matching grant was also awarded to the applicant from Reykjavik Energy Research fund (UOOR) for part of this work and supporting this student. The student defended her thesis on 8. Feb. 2012 and will formally graduate in June 2012.

4 Publications and disseminations

Michael Monit, 2009. **Bioprocess design: The GEOGAS Project – Bioremediation of geothermal gases and SCP production with HOX/SOX bacteria.** Lokaritgerð í MS námi við RES orkuskóla á Akureyri og HÍ.

Andri Stefánsson, 2009. **Blöndun brennisteinssýru við niðurrennslisvatn frá Hellisheiðarvirkjun** – Skýrsla Raunvísindastofnunar RH-01-2009.

Arnþór Ævarsson 2009, **The GEOGAS Project: Life based on geothermal gas**. Presentation at University of Lund, Prof. Anders Liljas symposium, Lund, Sweden.

Hildur Vésteinsdóttir og Jóhann Örlygsson. 2009. **Nýting jarðhita í líftækni - brennisteinsoxandi bakteríur**. Rit auðlindadeildar RA09:10. Háskólinn á Akureyri.

Guðný Inga Ófeigsdóttir. 2009. **Production and utilization of biomass with microbes.** Rannsóknaverkefni MS nema (12 ein) við Líf – og umhverfisvísindadeild. Háskóli Íslands. Ritgerð, 31 bls.

Guðmundur Óli Hreggviðsson. 2010. **Nýting efna í jarðhitagasi**. Erindi á Ráðstefnu Umhverfis- og orkurannsóknasjóðs OR, 14. maí.

Guðmundur Óli Hreggviðsson. 2010. **Biological Utilization of Geothermal Gas**. Erindi á ársfundi GEORG - GENERAL ASSEMBLY, 21. maí.

Arnþór Ævarsson 2010, **Líffræðileg nýting á afgasi frá jarðvarmavirkjunum**. Presentation at Reykjavik Energy, May 2010.

Arnþór Ævarsson 2010, **The GEOGAS Project: Life based on geothermal gas**. Presentation at The Nordic Achaeal Network Meeting, Stockholm, Sweden, May 2010.

Guðný Inga Ófeigsdóttir, Arnþór Ævarsson, Jakob K. Kristjánsson og Guðmundur Óli Hreggviðsson. 2010. **Nýting brennisteins í lífrænni ræktun**. Áfangaskýrsla til Umhverfis- og orkurannsóknasjóðs OR, 11 bls.

Arnþór Ævarsson 2010, **Líffræðileg nýting á afgasi frá jarðvarmavirkjunum**. Presentation at the CleanTech Iceland Consortium, Federation of Icelandic Industries. Reykjavik, September 2010.

Arnþór Ævarsson 2011, **Örverur til fóðurframleiðslu**. Presentation at Icelandic Feed Conference, Matis, Reykjavik, April.

Jakob K. Kristjánsson. 2011. **Use of Geothermal bacteria: From Discovery to Applications**. Lecture at the CAREX Forum: Biotechnological explorations of extremophiles to valuable products. Copenhagen, 8-9 May.

Jakob K. Kristjánsson. 2011. **New thermophiles from Icelandic hot springs for biotechnological applications.** Lecture at the Symposium of the Danish Microbiological Society, Copenhagen, 7. Nov.

Arnþór Ævarsson 2011, **Hvernig við búum til prótein úr brennisteinsvetni**. Presentation at University of Reykjavik, International activity week, November.

Jakob K. Kristjánsson. 2012. **Fóður úr brennisteinsvetni, MICROFEED verkefnið.** Eurostar presentation, Icelandic Research Council, Reykjavik, Jan.

Guðný Inga Ófeigsdóttir. 2012. **Líffræðileg nýting á jarðhitagasi**. M.Sc. thesis, University of Iceland.

Guðný Inga Ófeigsdóttir. 2012. **Líffræðileg nýting á jarðhitagasi**. M.Sc. examination lecture, University of Iceland. 8. February.

Arnþór Ævarsson 2012, **How to make protein from geothermal gas**. Presentation at University of Iceland, Department of Chemistry lecture series, March.

5 Cost statement

Name of Project: **Biological Utilization of Geothermal Gas**

ISK '000	Year					Year 1 2009/2010								
	Month	1	2	3	4	5	6	7	8	9	10	11	12	Total Y1	
Financing															
GEORG funding			350									600	300	1.250	3%
Participants own contributions		500	500	500	500	500	500	500	500	500	500	500	500	6.000	
Participants, in kind costs		107	100	150	150	150	150	150	150	150	150	150	150	1.707	
Facilites, equipm. & other resources												1.000		1.000	
Other national compet. grants		933	600	933	933	933	933	833	833	833	833	833	833	10.263	
Other intern. Grants, e.g. FP7														0	
Other sources (e.g. Philanthropic)			2.500	2.500	2.500		2.500	2.500	2.500	2.500	2.500	2.500	2.500	25.000	
Total other financing		1540	3700	4083	4083	1583	4083	3983	3983	3983	3983	4983	3983	43.970	97%
Total financing														45.220	

Operational Costs

Average Personnel Costs		**Unit**														**Man-**
Participant:		**cost**	1	2	3	4	5	6	7	8	9	10	11	12	Total Y1	**months**
Univ. Icel. Applicant	GÓH	500				250					250				500	1,0
Univ. Icel. M.Sc.Student	GIÓ	266	260	260	270	270	270	270	270	270	270	270	260	260	3.200	12,0
Prokatín ehf - Partner	AÆ	530	265	415	530	530	530	530	265	265	265	530	530	265	4.920	9,3
Prokatín ehf - Partner	JKK	470	150	150	150	150	200	150	150	200	300	300	300	300	2.500	5,3
Mannvit Eng. - Partner	ÁÍ	750	500	500	500	500	500	500	800	800	800	800	800	800	7.800	10,4
															0	0,0
Total			1.175	1.325	1.450	1.700	1.500	1.450	1.485	1.535	1.885	1.900	1.890	1.625	18.920	38
Operational exp.																
			900	1.000	1.000	1.000	1.000	1.000	2.000	2.000	2.800	2.000	2.000	2.000	18.700	
															0	
Total			900	1.000	1.000	1.000	1.000	1.000	2.000	2.000	2.800	2.000	2.000	2.000	18.700	
Contracted services																
															0	
Total			0	0	0	0	0	0	0	0	0	0	0	0	0	
Travel expenses																
															0	
															0	
Total			0	0	0	0	0	0	0	0	0	0	0	0	0	
Others																
															0	
Total			0	0	0	0	0	0	0	0	0	0	0	0	0	
Overhead																
			500	600	600	600	600	600	600	700	700	700	700	700	7.600	
															0	
Total			500	600	600	600	600	600	600	700	700	700	700	700	7.600	17%
Total operational cost			2.575	2.925	3.050	3.300	3.100	3.050	4.085	4.235	5.385	4.600	4.590	4.325	45.220	

Justification & explanations

The main project her is really the only operational activity of Prokatin and therefore the GEORG project is not booked separately in the companie´s accounting system.

The total operating costs of Prokatin in 2009 was ISK 32.640.000. Half or from 1.june is counted here as cost of GEORG project

The total operating costs of Prokatin for 2010 was ISK 17.253.234 + ISK 40.000.000 invested in tangible assets (=equipments & pilot plant) - all is counted here as cost of GEORG project

The total operating costs of Prokatin for 2011 was ISK 29.768.350 - all is counted here as cost of GEORG project

The salary costs are listed as close to real paid salary and time-input.

Other operational costs are estimates as part associated to the student´s part of the project.

Name of Project: Biological Utilization of Geothermal Gas

ISK '000			Year / Month	1	2	3	4	5	6	7	8	9	10	11	12	Total Y2	
			Year 2 2010/2011														
Financing																	
GEORG funding														500	750	1.250	4%
Participants own contributions				600	600	600	600	600	600	600	600	600	600	600	800	7.400	
Participants, in kind costs				150	200	150	150	150	150	150	150	150	150	150	150	1.850	
Facilites, equipm. & other resources														500		500	
Other national compet. grants				600	600	600	600	600	600	600	600	600	600	600	600	7.200	
Other intern. Grants, e.g. FP7																0	
Other sources (e.g. Philanthropic)				500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	11.500	
Total other financing				1850	2400	2350	2350	2350	2350	2350	2350	2350	2350	2850	2550	28.450	96%
Total financing																29.700	
Operational Costs																	
Average Personnel Costs		Unit															Man-
Participant:		cost															months
Univ. Icel. Applicant	GÓH	600					250					250				500	0,8
Univ. Icel. M.Sc.Student	GIÓ	280		260	260	270	270	270	270	270	270	270	270	260	260	3.200	11,4
Prokatín ehf - Partner	AÆ	550		530	530	530	530	530	530	265	265	265	530	530	265	5.300	9,6
Prokatín ehf - Partner	JKK	500		300	300	300	300	300	300	300	300	300	300	300	300	3.600	7,2
Mannvit Eng. - Partner	ÁÍ	800		300	300	300	300	300	300	300	300	300	300	300	300	3.600	4,5
																0	0,0
Total				1.390	1.390	1.400	1.650	1.400	1.400	1.135	1.135	1.385	1.400	1.390	1.125	16.200	34
Operational exp.																	
				400	400	400	400	400	400	400	400	400	400	400	400	4.800	
																0	
Total				400	400	400	400	400	400	400	400	400	400	400	400	4.800	
Contracted services				100	100	100	100	100		100		100	100	100	100	1.000	
																0	
Total				0	0	0	0	0	0	0	0	0	0	0	0	1.000	
Travel expenses						250						250				500	
																0	
																0	
Total				0	0	0	0	0	0	0	0	0	0	0	0	500	
Others																	
																0	
Total				0	0	0	0	0	0	0	0	0	0	0	0	0	
Overhead																	
				600	600	600	600	600	600	600	600	600	600	600	600	7.200	
																0	
Total				600	600	600	600	600	600	600	600	600	600	600	600	7.200	24%
Total operational cost				2.390	2.390	2.400	2.650	2.400	2.400	2.135	2.135	2.385	2.400	2.390	2.125	29.700	

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