ANNEX I
Project Plan

CarbFix project

Project ID:	09-02-001
Coordinator:	Sigurður Reynir Gíslason, University of Iceland
Start date:	January/2010
Duration:	3 years
Partners:	Orkuveita Reykjavíkur

1 Project description

The CarbFix Project was fortunate to be extended a full grant. Please find the project description below in Chapter 1.2.

1.1 Objectives and GEORG WP relevance

The overall objective of the CarbFix project is to develop an industrial solution for mineral sequestration of CO_2 in basalt, and to train young scientist to carry this knowledge into the future. The project consist of field injection of CO_2 charged water at the Hellisheidi power plant SW Iceland, laboratory experiments, computer modelling of fluid flow and gas-water-rock interactions, tracer tests, natural analogue- and cost analysis. GEORG has extended the project funding to be able to realise 1) CO_2 charged seawater-basalt experiments 2) monitoring of CO_2 gas and groundwater composition before and after injection 3) reactive transport computer modelling of water flow and composition before and after injection.

The CarbFix new technology will be tested and improved with the aid of monitoring and modelling, thereby increasing the usage of geothermal resources, diminishing environmental impact and helping GEORG achieving its main objectives

The relevance to GEORG WP is following:

WP 2	WP 3	WP 4	WP 5	WP 6	WP 7	WP 8
20%	5%	10%	35%	10%	10%	10%

WP 2.2.Eight PhD students and two MSc students have been and are working on their research within CarbFix, WP 3.1.1 hosting annual workshops, 3.1.2 maintains a webpage (carbfix.com) and organises seminars presenting the progress of the project and the possibilities of utilising its expected outcome. Modelling under WP 4.1. The main essence of CarbFix objective is CO2 sequestration, WP 5.4. WP 6, especially sub-tasks 6.2. and 6.3. Similarly it can be classified within WP7 Sustainability – economics – social, sub-task 7.6. cost-benefit analysis and environmental impact as a part of the CarbFix project is the economic assessment of the sequestration.

1.2 Project description

1.2.1 General description

The CarbFix project (carbfix.com; Sigurdardóttir 2008; Gislason et al., 2009) has been created to develop and optimize a practical and cost-effective technology for in-situ carbon mineralization in basalt and to train young scientist to carry this knowledge into the future. CarbFix is a combined program consisting of field scale injection of CO_2 charged waters into basaltic rocks, laboratory based experiments, study of natural CO_2 waters as natural analogue and state of the art geochemical modelling. The injection site is situated in SW Iceland, 3 km south of the Hellisheidi geothermal power plant. The plant currently produces up to 60,000 tons of CO_2 per year; this production will increase as the plant expands. This CO_2 gas is a by-product of the geothermal energy production. The gas stems from the geothermal system; magma is situated at few km depths.

The CO_2 will be fully dissolved in water during injection, resulting in a single fluid phase entering the rock. The CO_2 charged water is reactive and will dissolve divalent cations from the rock that will combine with the carbon and form solid minerals, carbonates that precipitate

in the free pore space within the rocks. The high water demand limits the general application of this method throughout the world. However, seawater might provide a solution.

The past 3 years several designs for the injection setup have been proposed and a final design is now in the last phase of construction at the site. This new technology will be tested and improved with the aid of monitoring and modelling, thereby increasing the usage of geothermal resources and diminishing environmental impact.

The CarbFix project has been operated since 2006 in the cooperation of the partners: Orkuveita Reykjavíkur (OR), the University of Iceland (UI), Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory (LDEO) and The Centre National de la Recherche Scientifique, France (CNRS). Each partner has collaborators or subcontractors within CarbFix, ÍSOR, Lawrence Berkeley National Laboratory (LBNL) USA and Mannvit Engineering are collaborators and sub-contractors of OR. The four partners have co-financed the project with own funds, funds from the European Union and contributions from different competitive research funds in each country. The total cost up till now is about 300 m.kr.

Here the two Icelandic CarbFix project members seek funds from GEORG to co-finance three parts of the project:

WP-1: CO_2 charged seawater-basalt experiments to find out whether seawater can be used for mineral sequestration of CO_2 from geothermal activities.
WP-2: The monitoring and analysis of gases and fluids in the bedrock.
WP-3: Modelling of the injected CO_2.

This funding is intended to cover the work and travel of 2 PhD students and part of the operating cost of the experiments, see page 7.

1.2.2 Scientific and Technical Merit

The reduction of industrial CO_2 emissions is one of the main challenges of this century (e.g., Broecker 2008; Oelkers and Cole, 2008). Among commonly proposed CO_2 storage techniques, the injection of anthropogenic CO_2 into deep geologic formations is quite promising due to their large potential storage capacity and geographic ubiquity (e.g., Metz et al., 2005; Oelkers and Cole, 2008; Benson and Cole, 2008). The effectiveness of this method of CO_2 storage and sequestration depends strongly on the retention time, reservoir stability, and the risk of leakage (e.g., Benson and Cole, 2008). One way to enhance the long term stability of injected CO_2 is through the formation of carbonate minerals as they provide a long lasting, thermodynamically stable and environmentally benign carbon storage host. Mineral carbonation is the fixation of CO_2 as stable carbonate minerals, such as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$), siderite ($FeCO_3$), and Mg-Fe carbonate solid solutions (Metz et al. 2005; Roger et al. 2006; Oelkers et al. 2008; Gislason et al. 2009). Mineral carbonation requires combining CO_2 with metals to form carbonate minerals. With few exceptions, the required metals are divalent cations, including Ca^{2+}, Mg^{2+} and Fe^{2+}. The most abundant cation sources on Earth are silicate minerals and glasses, that is, mineral trapping could be enhanced by injection of CO_2 into silicate rocks rich in divalent metal cations such as basalts and ultramafic rocks. Field and experimental evidence suggests that the slowest and thus rate limiting step in mineral fixation of carbon is the dissolution of the silicate minerals and glasses releasing the divalent cations. The lower the silica content of the

rocks and the higher the ligand concentration in the water solution the higher is the dissolution rate (Wolff-Boenisch et al., 2004a,b, 2006).

In coastal areas of Iceland and other basaltic terrains and on the ocean ridges, there is vast supply of seawater that could be used for mineral sequestration of CO_2 from geothermal activities. It is very important to perform laboratory experiments as soon as possible to determine the feasibility of using seawater for mineral carbon storage. This issue has not been addressed elsewhere and constitutes a creative and original contribution to the mineralization of CO_2 in basaltic subsurface. If the results from the laboratory experiments are positive, experiments could be scaled up in geothermal fields on the Reykjanes peninsula. If technology allows, CO_2 sequestration could be performed on the oceanic ridges. Goldberg et al. 2008 demonstrated large storage capacity of sub-oceanic basalt formations. Storage in basalts is considered to be among the most promising of the options for CO_2 storage (Oelkers et al., 2008). Being able to dispose of the large CO_2 amounts from geothermal energy extraction in such a straightforward and ecologically benign way has the additional appeal of avoiding potential CO_2 emission taxes.

Careful monitoring of subsurface impact of injected CO_2 gas is essential for the project's success and validation. It is important to be able to report that mineralization is actually taking place, whether improvements are needed during injection and for model calibration. Different monitoring methods in the project have already proven their value and will be continued. The monitoring involves the power plant gases, direct measurements on CO_2 capture by injecting tracers, systematic collection and analysis of groundwater downstream, monitoring soil CO_2 flux and monitoring of atmospheric CO_2.

Geochemical and hydrological modelling provides tools to predict and optimize long-term management of the injection site and to quantify the amount of CO_2 that can be mineralized. iTOUGH2 and TOUGHREACT have been used for developing reactive fluid flow models of the mineral CO_2 capture. As TOUGHREACT requires vast amounts of thermodynamic data for reactive transport simulations, effort was put into developing an internally consistent database suitable for mineral reactions of interest for this study. In the current second stage, field data is used to calibrate hydrological parameters. Reactive chemistry is then coupled to the model, which consequently can be used to simulate different scenarios for the CO_2 injection. The third and final stage of the model development will consist of validating simulated results by comparison to laboratory and field data. Reactive fluid flow models have already proven their value for the CarbFix project (Aradottir, 2009).

1.2.3 Innovation / Entrepreneurship

The innovative character of the project is its principal aim to show that carbon mineralization with water and seawater is a serious option to sequester and dispose CO_2 in the right terrain. The national and global implications of such endeavour are huge (e.g., reduction of greenhouse gases) and would include the promotion of geothermal activities as sustainable energy production and economic benefits through avoidance of CO_2 emission taxes. It is a valuable early experience, infrastructure and knowledge base that can be applied in future large scale CO_2 sequestration projects. The concept of CO_2 injection and mineralization encourages entrepreneurship and new business ventures because it requires the skill and know-how of engineers and scientists to turn the findings of the experimental studies into up-scaled applications for the industry. This is already done in part by the project but requires another approach when injection into the continental shelf is envisaged. On a mid-term,

successful CO_2 storage in Iceland would become a well acknowledged asset whose know-how could be exported abroad.

The project is carried out in international collaboration. Both partners have a network of international collaborators and subcontractors. Two European research Networks funded by the European Union (min-gro.com, and delta-min.com) have hosted 4 of the CarbFix PhD students. Each of these networks consists of 8 European partners.

CarbFix promotes the position of Iceland as a productive source of expertise in the forefront of the technology of CO_2 sequestration in basalt.

1.2.4 Education / Dissemination

Currently 7 PhD students are working on CarbFix projects and 1 PhD and 2 MSc student have successfully finished their studies. The students are: PhD-students of UI (6), Columbia University (1) and combined studies at UI and CNRS in Toulouse (1). The MSc students are at REYST and UI. These students work in a creative environment that CarbFix as an international project has created. They have had several opportunities for presenting their research results; both their plans and results and had important comments and critique from experienced scientists. In this part, 2 PhD students are involved.

The contract agreement of the CarbFix project members includes an intention to explore the possibility of forming a separate corporate entity in the future. The students are thus a part of the end-user driven essence of the project.

The CarbFix project has received attention from industry, regulatory and research organizations in Iceland and overseas. Participants in the project and the students have held several lectures in international conferences and workshops. CarbFix organized an international conference on carbon sequestration in Iceland in September 2009, the project has been featured in BBC, Time Magazine, the Economist and on the cover of the September issue of Science (see carbfix.com).

OR has been preparing the CO_2 injection since 2006 and the plan until now has been to start the injection in April 2010. In the beginning of March it was discovered that the gas from the condensers in the Hellisheidi power plant contained air. Currently the engineers and chemists are going thoroughly through the possible cause and amendments. This incidence will impact the time schedule so the plan is to start injection May-July 2010. To be able to verify the success of the project, results from monitoring and analysis and from modelling are needed and will be published. It is expected that the results of the CarbFix project might impact the future policy of the government and industry regarding international trading schemes and future possible emissions tax.

2 Work plan and time schedule:

This project involves three major tasks within the CarbFix project. These are:

WP-1: CO_2 charged seawater-basalt experiments

This subtask aims at finding out if seawater can be used for mineral sequestration of CO_2 from geothermal activities. The relatively high water demand limits the general application of the mineral sequestration method where water supply is limited. The CarbFix project has built

a highly sophisticated laboratory to carry out the experiment. The mechanisms of rock hydrolysis in seawater in the presence of CO_2 will be studied. Results will be used to optimize mineral sequestration of CO_2 from geothermal activities in Iceland using seawater. The overall strategy of the workplan is to generate as much experimental data as possible under sufficiently varying experimental conditions including pressure, temperature, solution composition, and thermodynamics.

WP-2: Monitoring and analysis: Regular sampling of the injected gases from the power plant is essential and sampling of fluids from the subsurface in 9 monitoring wells to determine the CO_2 captured. Furthermore detection of major leakage of CO_2 from the surface and "bookkeeping" of key parameters like pressure, flow, temperature and conductivity is vital. Environmental authorities have granted licenses for the CO_2 injection based on a detailed monitoring plan of the injection facilities in the pilot project.

WP-3: Geochemical and hydrological modelling: The results from the monitoring data and analysis will be used to calibrate the model and to simulate different scenarios for the CO_2 injection, i.e. to find out whether improvements are needed during the injection and also to be able to predict and optimize long-term management of the injection site. Comparison to laboratory and field data in order to compare the actual and modelled behaviour of CO_2 is of utmost importance to be able to detect whether significant adverse effects for the surrounding environment occur. This is emphasised in the EU directive 2009/31/EC on the geological storage of CO_2.

Time schedule:

Subtask	Start	Finish	Deliverable/Milestone
Monitoring and analysis	01/2010	12/2011	Determination of injected CO_2, major surface leakage, key parameters, CO_2 capture.
Modelling	01/2010*	12/2011	Calibration of model for improvement of injection and management of the site
Experiments as a function of pH/pCO_2 and T in seawater (Phase I)	09/2010**	09/2011**	Fine tuning of equipment. Rate equations as a function of T, pCO_2 and pH
Reaction mechanism (Phase II)	09/2011**	09/2012**	Fundamental understanding of the driving forces of mineral sequestration in seawater
Experiments close to equilibrium (Phase III)	09/2012**	12/2013**	Knowledge on how mineral sequestration may be affected over long-tem injection

*Hellisheidi power plant is scheduled for maintenance this June and will therefore not operate for three weeks. The shutdown will affect the CarbFix project as experimental CO_2 injection could start earlier. In January the CarbFix reservoir model was used to simulate what effects a three weeks injection stop would have on CO_2 distribution and recovery. Therefore the start of modelling has been changed to 01/2010 instead of 04/2010.

** University of Iceland is not able to hire a PhD student earlier than in the fall 2010 (September 1st). All cost and time table are shifted accordingly.

As mentioned above, in the beginning of March it was discovered that the gas from the condensers in the Hellisheidi power plant contained air. Currently the engineers and chemists

are going thoroughly through the possible cause and amendments. This incidence will impact the time schedule and might even delay it until July 2010 after the power plant stop in June.

3 Project Management

The CarbFix project is managed by Hólmfríður Sigurðardóttir, representing the management team. The Scientific Steering Committee (SSC) defines research tasks to be carried out by the management team. Sigurdur Reynir Gíslason is the chairman of the SSC and is leading WP-1. Hólmfríður has successfully managed CarbFix since 2007 and is leading WPs-2 and 3.

Seawater basalt experiment is to be carried out by a "new PhD student" at UI.

The monitoring and modeling part will be carried out by Bergur Sigfússon and Edda Sif Aradóttir OR. Bergur has a PhD from University of Aberdeen, October 2009 and Edda Sif is a PhD student at the UI in collaboration with LBNL in California. Technical assistant is Einar Örn Þrastarson OR. For the past two years he has been responsible for sampling and operation of submersible pumps and other sampling equipment for CarbFix.

Meetings will be held regularly before injection to ensure careful preparation. Meetings will be held at least every two weeks directly after the injection. This plan will be revised as experience is gained from collected data. CarbFix first annual report 2008 is available on the project website and the next annual report will be published early 2010. Results will be published in international journals and at conferences and workshops. Results have already been published in international journals, see the CarbFix website: http://www.or.is/English/Projects/CarbFix/Research/Publications/.

OR has stressed the importance of being able to publish whether the CO_2 injection will be proved successful or not within a year from the start of injection. The project has already delivered results and technical solution and is likely to deliver results according to its goals and work-time-cost plan.

The CarbFix project is and has been from the start in close cooperation with UI and ISOR. UI will participate actively in sampling of bedrock fluid and analysis and ISOR in monitoring with tracers, soil CO_2 flux measurements and modelling. This cooperation along with the cooperation of our participants at Columbia University and the CNRS in Toulouse France will praise GEORG as an organization.

4 Budget overview

	Cost item	Requested funding		Other financing		Total
2010/2011	Salaries					26.475
	Operational expenses					4.850
	Travel expenses					1.050
	Total 2010/2011:	8.000	25%	24.375	75%	32.375
2011/2012	Salaries					26.430
	Operational expenses					4.850
	Travel expenses					1.050
	Total 2011/2012:	8.000	25%	24.330	75%	32.330
2012/2013	Salaries					7.680
	Operational expenses					1.650
	Travel expenses					500
	Total 2012/2013:	3.500	36%	6.330	64%	9.830
Grand Total		**19.500**	**26%**	**55.035**	**74%**	**74.535**

Consortium: **OR, UI**

Name of Project: **CarbFix project**

ISK '000	Year		Year 1 2010/2011		Year 2 2011/2012		Year 3 2012/2013		Grand Total	
Salaries including overhead		**Unit cost**	Man-months	Total	Man-months	Total	Man-months	Total		
OR	BS	1.500	3	4.500	3	4.500		0	9.000	
OR	PhDstudent	265	3	795					795	
OR	ESA	1.500	3	4.500	3	4.500		0	9.000	
OR	EÖÞ	750	4	3.000	5	3.750		0	6.750	
OR	HS	1.500	3	4.500	3	4.500		0	9.000	
OR	EG	1.500	1	1.500	1	1.500		0	3.000	
UI	SRG	1.500	3	4.500	3	4.500	3	4.500	13.500	
UI	PhDstudent	265	12	3.180	12	3.180	12	3.180	9.540	
Total			32	26.475	30	26.430	15	7.680	60.585	
Operational exp.										
a. Chemical analysis				500		500			1.000	
b. CO2 flux measurements				2.500		2.500			5.000	
c. Monitoring station - operating cost				200		200			400	
d. Operating cost of mixed flow reactors				950		950		950	2.850	
e. Chemical analysis at UI				700		700		700	2.100	
Total				4.850		4.850		1.650	11.350	
Travel expenses										
a. Travel for monitoring in the field				550		550			1.100	
b. Conferences				500		500		500	1.500	
c									0	
Total				1.050		1.050		500	2.600	
Total cost				32.375		32.330		9.830	74.535	
Financing										
a. OR, UI, UOOR, Norðurál, Hitaveita Suðurnesja									0	
b.									0	
Total other financing				24.375	75%	24.330	75%	6.330	64%	55.035	74%
Requested funding from GEORG				8.000	25%	8.000	25%	3.500	36%	19.500	26%
Total financing				32.375		32.330		9.830		74.535	100%