CO₂ Fixation into Basalts
Hellisheiði
Iceland

Annual Status Report 2010
Hólmfríður Sigurðardóttir
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**Prologue**

CarbFix, a combined industrial-academic pilot program, was developed in order to assess the feasibility of in situ CO$_2$ mineral sequestration in basaltic rocks. Unique to CarbFix is its connection to the Hellisheidi geothermal power plant in SW Iceland, allowing for capture of otherwise emitted CO$_2$ in addition to CO$_2$ transport and mineral sequestration.

The overall objective of the CarbFix project is to develop and optimize a practical and cost-effective technology for mineral storage of carbon dioxide in basaltic rock, 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, laboratory experiments, computer modelling of fluid flow and gas-water-rock interactions, tracer tests, natural analogue and cost analysis.

The CO$_2$ injection site is situated about 3 km south of the Hellisheidi geothermal power plant. The power plant currently produces 40,000 tons of CO$_2$ per year. The CO$_2$ gas is a by-product of the geothermal energy production and of magmatic origin. The produced geothermal gas mainly consists of CO$_2$ and H$_2$S. The two gases will be separated in a pilot gas separation plant, and CO$_2$ will be transported in a pipeline to the injection site. There, CO$_2$ will be fully dissolved in water during injection, resulting in a single fluid phase entering the storage formation. The CO$_2$ charged water is reactive and will dissolve divalent cations from the rock, which will combine with the dissolved carbon to form solid carbonate minerals. The injection test is designed to inject approximately 2,000 tons of CO$_2$ per year, but there is the potential to upscale if mineral carbonation proves to be successful.

In 2010 the CarbFix group has been working according to a monitoring and accounting program for the field injection, which consists of a surface, subsurface and atmospheric component. In early spring 2010 the construction of the CarbFix mechanism and equipments was finalised and in March 2010 CarbFix was ready for a few weeks test-run prior to being able to start injecting CO$_2$. Start-up of CarbFix needs the CO$_2$ gas produced in the pilot gas separation plant at Hellisheidi power plant. During its testing phase the pilot gas separation plant has been facing several incidences causing delay of CO$_2$ delivery to CarbFix now planned in 2011. In late November and beginning of December scientists from Columbia University arrived for testing the CarbFix system with the Icelandic groups. This test was a success. Furthermore, several scientific papers and abstracts on the laboratory experiments, developments of reactive transport computer models, natural analogue studies and cost analysis studies were submitted to international journals.

This report describes how the CarbFix pilot program has advanced during the year 2010.
Participants

The CarbFix project was formally launched on September 29th 2007. It is a consortium of the following four partners who signed a partnership agreement for the purpose of setting forth objectives, plans and undertakings with respect to the CarbFix project. Below is a short description of each partner and their responsibilities.

Figure 1 – CarbFix is connected to the Hellisheidi geothermal power plant in SW Iceland. The CarbFix injection site is located in the right part of the figure. Photo: Mats Wibe Lund.

Orkuveita Reykjavíkur (OR)

OR operates a geothermal district-heating system, an electricity distribution network and a water distribution system, serving 67% of Iceland’s population. OR is the main sponsor of the project being the owner of the Hellisheidi geothermal plant and the infrastructure used for the CarbFix pilot project at the injection site (Figure 1). OR provides the pilot gas separation plant (source of CO₂), pipelines, injection system, injection-and monitoring wells, management and logistics, geothermal science and technology as many of OR’s scientists, engineers and technicians work on this project. OR is responsible for communication with stakeholders and obtaining licences from local and environmental authorities. OR operates the Environmental and Energy Research Fund to support research, development and innovation in the field of environment and energy science. A considerable part of the annual budget has been granted to CarbFix.

Iceland Geosurvey (ISOR) is one of OR’s primary consultants. ISOR maintains a database of important geologic, geophysical and geochemical data of the Hengill area. ISOR plays an important role in monitoring and verifying of the CO₂ injection and is designing and conducting a soil gas monitoring program to detect possible CO₂ leakage to the surface before, during and after the injection.

Mannvit Engineering, Iceland (Mannvit) is one of OR’s primary consultants for the development of its power plants. Mannvit assists, the development, design and test of the CO₂ injection system.

Lawrence Berkeley National Laboratory USA (LBNL) is a long-term partner of OR for geothermal reservoir modelling. LBNL has adopted properties of Icelandic basalts into the reactive transport modelling code (TOUGHREACT), to predict the long-term success of CO₂ injection into basalts and to interpret field and experimental data.
The University of Iceland – Institute of Earth Sciences (IES)

IES develops and runs laboratory experiments and the plug flow reactor in collaboration with CNRS. The result of the laboratory experiments, kinetic and thermodynamic data are used for reaction and reactive transport modelling. The plug-flow reactor will be used to fine tune reactive transport models. IES in cooperation with LDEO, ISOR and OR administers the designing of the monitoring protocol and sampling equipment for the field injection at Hellisheidi. IES has a leading role in systematic collection and analysis of the groundwater in the injection and monitoring wells in cooperation with LDEO and OR.

Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory (LDEO)

LDEO has a leading role with OR and ISOR in monitoring and verifying the CO2 injection. The work includes pre-injection characterization of the basaltic rocks and ground waters with geochemical and geophysical tools to assess the CO2 storage capacity of the injection site, developing a monitoring program for the CO2-water-rock interactions in situ in the subsurface and validate the hydrological modelling with tracer studies in cooperation with IES and ISOR. LDEO develops a CO2-water mixing system in collaboration with OR and Mannvit Engineering.

The Centre National de la Recherche Scientifique, France (CNRS)

CNRS through the Laboratoire des Mécanismes et Transferts en Géologie (LMTG - UMR 5563) evaluates kinetic and thermodynamic data for basaltic rocks that will be used to further the CO2 storage process and reactive transport models. Laboratory efforts aim at characterizing the effect of surface coatings on mineral dissolution rates and the effect of solution compositions on precipitation rates, as well as the long-term evolution and consequences of these reactions on the porosity and permeability of the basaltic rocks.

IPGP in Paris is a collaborator of CNRS and has been working on performing a geo-microbiological monitoring on the Hellisheidi pilot site.

Leadership

The Scientific Steering Committee:

Sigurður Reynir Gíslason (Chairman). Research Professor at the Institute of Earth Sciences, University of Iceland. sigrg@raunvis.is

Wallace S. Broecker. Newberry Professor of Earth & Environmental Sciences, Lamont-Doherty Earth Observatory of Columbia University, USA. broecker@ldeo.columbia.edu

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Einar Gunnlaugsson. Research Director - Chemistry and Earth Science, Orkuveita Reykjavíkur, Iceland. einar.gunnaugsson@or.is

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Juerg M. Matter. Lamont Associate Research Professor. Lamont-Doherty Earth Observatory of Columbia University, USA. jmatter@ldeo.columbia.edu

Andri Stefánsson. Associated Professor at the Institute of Earth Sciences, University of Iceland. as@hi.is

Project Manager:

Hólmfríður Sigurðardóttir. Head of Innovation and Development, Orkuveita Reykjavíkur, Iceland. holmfridur.sigurdardottir@or.is
PhD Students
In 2010 eight PhD students were working on science projects, within the CarbFix project. One PhD student, Therese Flaathen, was the first one to finish in September 2009. In autumn 2010 one of the students had to quit the PhD thesis due to personal reasons.

<table>
<thead>
<tr>
<th>Name</th>
<th>Title of Ph.D. thesis</th>
<th>University</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexander Gysi</td>
<td>CO₂-water-basalt interaction: experiments and geochemical modelling</td>
<td>University of Iceland</td>
<td>Sept 2007</td>
<td>Aug 2011</td>
</tr>
<tr>
<td>Diana Fernandez de la Reguera</td>
<td>Monitoring and verification of geologic CO₂ storage using tracer techniques</td>
<td>Columbia University</td>
<td>Sept 2008</td>
<td>Quit Sept 2010</td>
</tr>
<tr>
<td>Edda S. P. Aradóttir</td>
<td>Reactive transport approach to studying CO₂-water-basalt interaction: Modeling, designing and optimizing mineral CO₂ sequestration in basaltic rocks</td>
<td>University of Iceland</td>
<td>Jan 2007</td>
<td>Sept 2011</td>
</tr>
<tr>
<td>Gabriella Stockmann</td>
<td>Experimental determination of the effect of precipitated mineral coatings on the rates of basaltic glass and minerals; effect of bacteria on the dissolution of basaltic glass</td>
<td>University of Iceland</td>
<td>Sept 2007</td>
<td>Nov 2011</td>
</tr>
<tr>
<td>Helgi Arnar Alfreðsson</td>
<td>CO₂ sequestration in basaltic rock: Pre-injection studies of the injection field and development of a piston-type down hole sampler for CO₂ rich fluids and tracers</td>
<td>University of Iceland</td>
<td>Sept 2007</td>
<td>April 2012</td>
</tr>
<tr>
<td>Iwona Galeczka</td>
<td>Experimental studies on CO₂ sequestration in basaltic rocks with the plug flow reactor</td>
<td>University of Iceland</td>
<td>Sept 2009</td>
<td>Sept 2012</td>
</tr>
<tr>
<td>Snorri Guðbrandsson</td>
<td>Dissolution rates of crystalline basalt as a function of temperature and solution composition</td>
<td>University of Iceland</td>
<td>Sept 2007</td>
<td>March 2012</td>
</tr>
<tr>
<td>Kiflom Gebrehiwot Mesfin</td>
<td>Dissolution of basaltic glass in seawater at 100°C and 70 bars CO₂ pressure. Implications for CO₂ mineral sequestration</td>
<td>University of Iceland</td>
<td>June 2010</td>
<td>June 2013</td>
</tr>
</tbody>
</table>

Following is the main research focus of the PhD students:

Alexander Gysi: Laboratory batch experiments at pCO₂ of 0-40 bar and 40-250 °C. Analysis of secondary precipitates using x-ray diffraction (XRD), scanning electron microscope (SEM/EDS) and electron microprobe (EMPA). Geochemical modeling using PHREEQC and update of the thermodynamic dataset relevant for low temperature CO₂-water-basalt interaction.

Diana Fernandez de la Reguera: Laboratory experiments to study the dissolution of carbon dioxide (CO₂) in fresh and salt water. The objectives of these experiments were to simulate a representative scaled down version of the planned CarbFix CO₂ injection scenario, and to test different ways to maximize the percentage of dissolved CO₂. Results from these experiments were used to optimize the design of the CarbFix CO₂ injection system. The student had to quit in September 2010.

Edda S. P. Aradóttir: TOUGHREACT and iTOUGH2 are used to develop reactive transport models that simulate hydrology and mineral alteration associated with injecting dissolved CO₂ into basalts. The mineral reactions database in TOUGHREACT has been revised and extended, providing an internally consistent database suitable for mineral reactions of interest for this study. Hydrological parameters of the model were calibrated using iTOUGH2 to simulate tracer tests that have been ongoing since 2007. Reactive chemistry was coupled to the model and TOUGHREACT used for reactive transport simulations, which are ongoing.

Gabriella Jarvik Stockmann: Experiments performed partly in Iceland and partly in Toulouse, France: Long-term calcite precipitation on basaltic glass and diopside crystal surfaces. Calcite coatings on different
silicates - to investigate if crystal structure plays a role in calcite precipitation. Bacteria effect on the dissolution rate of basaltic glass.

Helgi Arnar Alfredsson: Pre-injection study of the injection site at Hellisheidi. Water sampling and analysis from the boreholes. Development of a piston-type down-hole sampler for CO$_2$ rich fluids and tracers.

Iwona Monika Galeczka: Crushing, sieving and cleaning basaltic material which will fill up a plug flow reactor. Assembling the plug with attached equipment and conducted mixed flow experiments in the laboratory. Iwona was also involved with Helgi, Domenik and Kiflom in testing the piston sampler.

Snorri Guðbrandsson: Continued experiments on the dissolution rates of crystalline basalt and plagioclases of variable composition, and submitted a paper to GCA on the dissolution rate of crystalline basalt. Snorri spent several months in the CNRS laboratory in Toulouse, France conducting precipitation rate experiments.

Kiflom Gebrehiwot Mesfin: Batch experiments at pCO$_2$ of 70,100 bar and 100°-150°C. Analyse the evolution of the solute chemistry as well as the precipitation of secondary phases using XRD (X-ray diffraction), SEM (Scanning Electron Microprobe) and EMPA (Electron Microprobe). He was involved in developing the piston sampler to be used to monitor the high pressure solution at Hellisheidi.

MSc Students
Friday 20th January, Elisabet Vilborg Ragnheiðardóttir defended her MSc thesis. The MSc is a joint degree between the University of Iceland and Reykjavik University.

<table>
<thead>
<tr>
<th>Name</th>
<th>Title of MSc thesis</th>
<th>University Programme</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elisabet Vilborg Ragnheiðardóttir</td>
<td>Costs, Profitability and Potential Gains of the CarbFix Program</td>
<td>Reykjavik Energy Graduate School of Sustainable Systems</td>
<td>Jan 2009</td>
<td>Jan 2010</td>
</tr>
</tbody>
</table>

Following is the main research focus of the MSc student:

Elisabet Vilborg Ragnheiðardóttir: Review the costs associated with the CarbFix pilot CO$_2$ injection program and identify avenues for improvement. The CarbFix costs are reviewed both for the current pilot project, as well as for two larger scenarios involving greater sequestration at the Hellisheidi geothermal power plant in SW Iceland and a hypothetical pulverized coal plant.

Related projects

CO$_2$-charged seawaters-basalt experiments. Domenik Wolff-Boenisch, Project Director for the University of Iceland’s contribution to CarbFix has been working on buffer capacities of seawater solutions equilibrated with different partial pressure of CO$_2$ are presented, under open and closed conditions.

<table>
<thead>
<tr>
<th>Name</th>
<th>Title of Project</th>
<th>University</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domenik Wolff-Boenisch</td>
<td>On the buffer capacity of CO$_2$-charged waters used for mineral sequestration</td>
<td>University of Iceland</td>
<td>Jan 2010</td>
<td>Dec 2010</td>
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</tbody>
</table>

Successful mineral trapping of carbon dioxide faces the challenge of effectively titrating a CO$_2$-charged acidic injection solution to pH conditions favourable to carbonate precipitation -using the rock as primary alkalinity source. To illustrate the magnitude of this task work has been done on buffer capacities of seawater solutions equilibrated with different partial pressure of CO$_2$ are presented, under open and closed conditions.

Impact of CO$_2$ injection on deep biota. Since 2008 a group of French scientist at IPGP, Paris has been working on performing a geo-microbiological monitoring on the Hellisheidi pilot site.

<table>
<thead>
<tr>
<th>Name</th>
<th>Title of Project</th>
<th>Organisation</th>
<th>Start</th>
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<tbody>
<tr>
<td>Bénédicte Menez</td>
<td>CO$_2$FIX (French ANR project - LMTG Toulouse, IPGP Paris, Géosciences Montpellier, ICMCB Bordeaux)</td>
<td>IPGP, Paris, France</td>
<td>October 2008</td>
</tr>
</tbody>
</table>
The Status of the CarbFix Project 2010

The CarbFix Field Site

The Hellisheiði geothermal power plant is the source of the CO₂. The plant produces electricity and thermal energy by harnessing geothermal steam. The produced steam contains geothermal gases, mainly CO₂ and H₂S. The targeted field site for the injection of CO₂-charged water is close (3 km distance) to the Hellisheiði geothermal plant in SW Iceland (Figure 2). The well field had already been developed by Reykjavík Energy to serve as a deep reinjection system for separated water from Hellisheiði geothermal power plant, currently generating 213 MWₑ and 133 MWₜₜ. The power plant annually produces some 40,000 tons CO₂ of volcanic origin as a by-product of the geothermal energy production.

The Hellisheiði natural laboratory comprises ideal conditions for studying the long-term effect of mineral CO₂ sequestration in basaltic rocks. Connection to the power plant provides access to a concentrated source of CO₂. Additionally, field data, such as calcite rich cap rocks overlying the high-temperature reservoir, suggest that mineral CO₂ sequestration already plays an important role in the evolution of the Hellisheiði geothermal system. Injecting and precipitating CO₂ into nearby formations with the objective of imitating and accelerating this natural CO₂ sequestration process should therefore be considered as an environmentally benign process.

The CO₂ gas. In spring 2010 the construction of the pilot gas separation station was finalised at the Hellisheiði geothermal power plant. The pilot station separates CO₂ from the geothermal gas coming from the condensers of the power plant by sequential extraction. First, a scrubber washes CO₂ and H₂S out from less soluble gas species (H₂, N₂, Ar and CH₄). A deaerator then removes CO₂ and H₂S from the washing water, followed by separation of CO₂ and H₂S in a distillation column. The H₂S will be re-injected with brine to the deep geothermal reservoir and the CO₂ will be available for the CarbFix project.

In early March it was discovered that the gas from the condensers in the Hellisheiði power plant contained air. After thorough examination necessary amendments were dealt with. This incidence did however cause delays in the time schedule and it was not possible to start the pilot gas separation plant until after the power plant stop in late June.

In July the pilot plant started operation along with a planned three week testing phase prior to delivery of gas to CarbFix. Experiments with the distillation column commenced and liquid gas was produced. However, after a short period of experiments a device that condenses H₂S broke down. In August, September and October there were delays of shipping of device for the pilot plant, more components and small equipments broke down almost every day. Therefore, the time plan of delivery of CO₂ for CarbFix and injection of the gas needed constant revision. In late October samples consisting of 80% clean CO₂ for the CarbFix project had been produced and analyzed. However, reinitiation of the gas separation plant did not go according to plan and delivery of CO₂ to CarbFix is planned in 2011.

In the pilot study, approximately 5% of the total geothermal gas coming from the power station will be separated in the pilot station. Thus, about 2,200 tons CO₂ are to be captured and made available for CarbFix on an annual basis.

The CarbFix wells. After its capture, CO₂ will be transported in a 3 km pipeline to the pilot injection site as pressurized gas. There, CO₂ will be injected at depth into well HN-2 (Figure 2). Co-injected water will divert injected CO₂ further downward, resulting in a single fluid phase entering the sequestration formation. Wells HN-4, HK-34, HK-31 and HK-26 are deep monitoring wells and wells HK-12, HK-25, HK-7 and HK-13 are shallow monitoring wells. Long-term CO₂ pilot injection is scheduled to start in the first half of 2011. Environmental authorities in Iceland have granted licenses for the injection. The injection well (1,997 m) was drilled in 2005, the four shallow monitoring wells were drilled in the period 2001-2005 and their depth is 80-140 m. The five deep monitoring wells were drilled in the period 2004-2008 and they are 800-1,300 m deep.
Figure 2 – Aerial map of the CarbFix pilot injection site at Hellisheidi, SW Iceland. Fresh groundwater, used for dissolving CO₂, is pumped from well HN-01 and transported to well HN-02 in a pipeline (blue line). CO₂ captured at the pilot gas separation plant is transported in a pipeline (yellow line) to well HN-02 where it is injected along with water from HN-01. Deviation of wells HN-04 and HK-34 is depicted by red lines. Combed lines represent faults. Figure: ISOR.

Resource Characterisation

Prior to the planned CO₂ injection in 2011, a background field characterization study at the injection site and in the target reservoir has been ongoing since 2006. Different monitoring methods in the project have already proven their value and will be continued after CO₂ injection.

Tracer tests have been launched in 2007 (using sodium fluorescein) and 2008 (using sulfur hexafluoride (SF₆) and sodium fluorescein) in collaboration with scientists at LDEO and ISOR to understand and characterise the regional groundwater flow and to estimate the volume of the reservoir available for CO₂ injection. In addition the tracer tests are intended to ensure that there is no loss of injected CO₂ to the surface, see more information in the Annual Status Report 2008 and 2009 at the CarbFix website: www.carbfix.com.

All year 2010, samples were taken from wells HN-4 and HK-34 once a week and the rest of the wells once a month. In early January it was not possible to take samples from the deep wells HN-4 and HK-34 due to construction on the site and heavy frost. In August no samples were taken due to a motor failure in the fixed submersible pump. The pump needed to be lifted to the surface. In February it was not possible to take samples from the shallow wells HK-13, HK-7, and HK-25 due to heavy frost. This was also the case in October as a trailer for the portable pump was under construction. The SF₆ samples were shipped to LDEO for analysis and the sodium fluorescein samples were analysed at ISOR.

The chemistry of the ground waters. Since July 2008 the chemistry of the ground water at the injection site has been studied regularly. IES with the aid of OR have taken down hole samples from the CarbFix wells every second month. Temperature, pH, alkalinity, conductivity, major and trace elements, dissolved organic carbon, nutrients, ¹⁸O, ¹³C, δD and ³⁴S isotopes have been measured and analysed by IES.

Construction of the Injection System

In January the construction was in its last phase and test runs of certain equipment were to start and engineers, technicians and scientists at OR, Mannvit and Verkis held two construction meetings. A final meeting for construction appraisal was held at the CarbFix site January 29th (Figure 3). March 2nd a coffee party was held to celebrate the end of construction and the CarbFix was ready to few weeks test run prior to being able to start injecting CO₂.
Testing of the Injection System

In January 2010 testing of equipment started and was conducted with periods during February. Early March 2010 it was discovered the gas lead into the pilot gas separation plant contained a high percentage of air. This was very serious indeed as the risk of explosion might increase as well as this might also have an impact on the gas content delivered to the CarbFix project. Necessary amendments were made but this incidence delayed the time schedule in the CarbFix project for several months.

In July the pilot plant started operation along with a planned three week testing phase prior to delivery of gas to CarbFix. After a short period of experiments the group experienced a continuous period until October with devices breaking down. Therefore time plan of delivery of CO\textsubscript{2} for CarbFix and injection of the gas needed constant revision.

In late November and start of December two scientists from Columbia University arrived for testing the CarbFix system with the Icelandic groups. The groups conducted a gas tracer injection experiment with N\textsubscript{2} gas flow (as CO\textsubscript{2} gas was not jet available). Different questions and issues were raised as was expected. This visit from Columbia University stressed the importance of being able to find solutions from different angles as a group (Figure 4).

Since the visit in November the CarbFix project has been up and running, water has been constantly injected into the injection well, however without CO\textsubscript{2} gas. Startup of CarbFix needs the CO\textsubscript{2} gas produced in the gas separation plant as mentioned above. The injection is now planned in 2011.

Risk Assessment and amendments: In 2010 several meetings were held assessing the risk of the CarbFix project and implementing necessary amendments.

Licenses and Consultation

The Environmental Agency has given a positive statement for the CO\textsubscript{2} injection and the use of the tracers, trifluoromethylsulphur pentafluoride (SF\textsubscript{3}CF\textsubscript{2}), amidorhodamine G dye and radiocarbon \textsuperscript{14}C. The Municipality of Olufus has granted an operation license for the CO\textsubscript{2} injection.
Modelling

In 2010 chemical modelling scenarios are being performed by the Institute of Earth Sciences in Iceland and the Centre National de la Recherche Scientifique, France, by lab experiments and numerical modelling. In 2010 development of a three dimensional reactive transport model that simulates hydrology and mineral alteration associated with the CO₂ injection has been ongoing at OR. TOUGH2, iTOUGH2 and TOUGHREACT are used in the model development. The mineral reactions database in TOUGHREACT has been revised and extended, providing an internally consistent database suitable for mineral reactions of interest for this study. Hydrological parameters of the model were calibrated using iTOUGH2 to simulate field observations such as well drawdown, flow rates and tracer breakthrough curves. Modeling results indicate groundwater velocity in the reservoir to be significantly lower than expected. The slow groundwater velocity will necessitate increasing groundwater flow by producing downstream wells at low rates after CO₂ injection has started. The main objective of this potential production will be to pull highly concentrated carbonated water away from the immediate surroundings of the injection well to prevent clogging. Managing plans for the potential production need, however, to be carefully designed to minimize the amount of CO₂ that will be pumped out of downstream wells. The three dimensional CarbFix numerical model has proven to be a valuable tool in simulating different injection and pumping schemes by showing what effect different pumping scenarios have in transport and distribution of injected CO₂.

Fluid-rock reactions has been coupled to the hydrology model using TOUGHREACT. Preliminary results confirm dissolution of primary basaltic minerals as well as carbonate precipitation. Secondary mineral abundance is highly dependent on temperature, pCO₂ and flow rate. Ongoing work includes validation of revised thermodynamic and kinetic databases, and simulations of the CarbFix CO₂ injection at Hellisheidi.

Monitoring

In 2010 a monitoring and accounting plan has been developed, which integrates surface, subsurface and atmospheric monitoring.

Surface Monitoring involves CO₂ flux measurements, closed chamber method, (Figure 5), sampling of injected gases from the power plant and pressure and temperature logging at the well heads. In March and April CO₂ flux measurements were carried out by ISOR at 165 fixed sites on the platform for the injection well HN-2 and the observation wells HN-4 and HK-34, in the Holocene lava and along the old Hellisheidi road and the Threngsli road. All background CO₂ flux measurements are finalised. All year pressure and temperature logging has been ongoing in the monitoring wells. Sampling and analysis of tracers has been ongoing in those wells to further characterize the groundwater reservoir.

Subsurface Monitoring and Sampling Infrastructure involves monitoring the transport and reactivity of the dissolved CO₂ and how much CO₂ is stored in its various forms. In spring 2010 sampling infrastructure were already installed in the monitoring wells (fixed submersible pumps that allow sampling of groundwater at reservoir conditions) and non-reactive and reactive tracers had been shipped to Iceland. Construction of a piston-bailer that will be used to retrieve samples from the injection well HN-2 was developed as well as the design of a sampling line. In late November and start of December two scientists from Columbia University arrived for testing the CarbFix system with the Icelandic group as mentioned above. The group managed to take the last background water samples from the CarbFix wells before CO₂ injection, verifying the sampling equipments and sample collection procedures and go through the 14C tracer filling procedure and other issues.

Atmospheric Monitoring. Since August 2009 OR has operated a weather station at the injection site for continuous monitoring of atmospheric CO₂ data. The station further keeps track of all key injection parameters regarding the “bookkeeping” of the injection and provides information online, available to all collaborators in the project. The results show that only diurnal CO₂ changes have been detected and
dispersed CO₂ from the Hellisheidi power plant has not been observed. It is therefore anticipated that concentrations exceeding ~40 ppmv above mean CO₂ values will be indicative of CO₂ leak from the injection zone. These possible abnormal CO₂ concentration values may be inspected in conjunction with wind speed and wind direction to estimate the probability of leaks from the subsurface.

Plug Flow Reactor
IES in collaboration with OR and CNRS finished designing and constructing a 2.5 m long laboratory plug flow reactor that will be filled with basaltic material. In 2010, IES worked on testing the plug to assure proper working of all items. The start of the experiment is now scheduled in 2011. Reactive transport models will be implemented to model the replacement reactions within the plug.

Patent
In December OR started preparing a patent application on CarbFix for EPO and an US-provisional application.

Webpage
From the beginning, the CarbFix group has stressed the importance of sharing the generated knowledge with the scientific/engineering community as well as with the public. Annual reports, which include a description of project progress, new developments, and budget information, are available on the project website (www.carbfix.com).

Meetings
The Scientific Steering Committee and the Management Team held the following joint meetings in 2010:

- Conference Call: January 25th, February 1st, 15th and 23rd, March 9th and 26th, April 12th and 19th, May 3rd and 17th, June 2nd and 28th, July 13th, August 18th, September 28th, October 15th and 28th, November 12th and 18th, December 16th.
- Physical Meetings: November 29th and December 2nd.

Engineers, technicians and scientists at OR, Mannvit and Verkis held Construction Meetings on the following dates in 2010:

- Construction Meetings: January 12th and 25th.
- Construction appraisal at the CarbFix site: January 29th.

Scientists, engineers and technicians at OR held test meetings on the following dates in 2010:

- Test & Test Run Meetings on CarbFix: February, 2nd, 9th, 16th and 23rd, March 2nd and 26th, April 27th, May 4th, 11th, 18th and 25th, June 1st, 8th, 15th, 22nd and 29th, August 11th, 18th, 25th and 31st, September 7th, 15th, 21st and 28th, October 5th, 13th, 29th and 27th.
- Joint Meetings on Test Running and Safety Issues on CarbFix, SulFix and Gas Separation Plant: November 3rd, 10th and 17th, December 8th, 15th and 22nd.
- Joint Meetings on Risk Assessment on CarbFix, SulFix and Gas Separation Plant: March 5th, April 20th, May 6th and 25th, June 26th, July 1st, August 5th and 16th.

Scientists at OR and ISOR held a meeting on tracers, sampling, analysing and cost in 2010: March 3rd.

Funds
Since 2006 the CarbFix project has been financed only by its partners through various funding agencies. In 2010 the project has been seeking additional funding from different sources. In March a grant was received from GEORG (Geothermal Research Group – see details at www.georg.hi.is) amounting USD 70.000 per year for two years and USD 30.000 for one year. In April an application was submitted to the U.S. Department of Energy (DOE) and grant was received from DOE amounting USD 1.015.180 for three years. In January an application was submitted to the Global CCS Institute in Australia but did not receive funding. An application submitted in December 2009 to the EU-7th framework programme on research and development: Marie Curie Initial Training Networks (ITN) Call: FP7-PEOPLE-2010-ITN did not receive funding. In November an application was submitted to the European Union 7th framework programme on energy, Call FP7-ENERGY-2011-1, Stage 1 requesting funding of EUR 1.400.000 to the CarbFix project. Results regarding outcome of this applications are expected by spring 2011.
Financial Status and Outcome 2010

The four participants in the CarbFix project have been performing preliminary studies in the field since 2006. Orkuveita Reykjavíkur finalised constructing the injection facilities and started testing them in 2010.

When the CarbFix project was formally launched in September 2007, the initial total budget for the project was estimated to be EUR 7.333.262 over a period of three years (Table 1). The real total expenses for all participants according to exchange rate 2007 are EUR 6.622.059. For further detail on estimated and real segmentation between participants see Table 1. The referent exchange rate 2007 was 90,0 ISK/EUR and 0,7 USD/EUR. Since September 2007 the exchange rate of the Icelandic króna (ISK) has significantly weakened compared to the euro. For further detail of exchange rates see Note 1 and 2 on page 15.

The CO2 injection was planned in the fall 2008 but has been delayed until 2011 due to more time consuming design of the injection facilities than initially expected and delay in delivery of CO2 from the pilot gas separation plant at Hellisheidi. The following abbreviations are used in Table 1 and Index I:

- OR: Orkuveita Reykjavíkur
- IES: The University of Iceland – Institute of Earth Sciences
- LDEO: Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory
- CNRS: The Centre National de la Recherche Scientifique, France
- CBI: Central Bank of Iceland

Table 1. Initial estimated CarbFix budget in 2007 and expenses according to exchange rate 2007*

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<td>806.308</td>
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<tr>
<td>CNRS</td>
<td>301.800</td>
<td>192.462</td>
<td>197.264</td>
<td>691.526</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>3.154.905</strong></td>
<td><strong>2.088.427</strong></td>
<td><strong>2.094.930</strong></td>
<td><strong>7.338.262</strong></td>
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<table>
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<tr>
<th>Expenses according to exchange rate 2007:</th>
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<th>2008</th>
<th>2009</th>
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<td>559.106</td>
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<td>58.064</td>
<td>136.643</td>
<td>297.499</td>
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<td><strong>Total</strong></td>
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<td><strong>671.275</strong></td>
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<td><strong>2.536.930</strong></td>
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* The referent exchange rate 2007 was 90,0 ISK/EUR and 0,7 USD/EUR.

In Index I (see next page) the financial outcome of year 2010 (in addition to 2006, 2007, 2008 and 2009) is presented as well as the estimated forecast for 2011. Note that the figures are presented according to exchange rate each year, not according to exchange rate 2007. This explains the difference between figures in Table 1 and Index I. As shown in Index I it was decided to present profit or loss for each year. Instead of moving it to a specific Balance sheet for each year the profit/loss is moved to a so-called “Balance” that shows how the profit or loss moves between years. As mentioned above the CO2 injection has been delayed until 2011. Therefore the estimated cost of design and construction is credited in 2009 and execution of the injection and monitoring will be credited in 2011.

Orkuveita Reykjavíkur does not credit the CarbFix project accessibility of land and wells at the Hellisheidi field site. The estimated cost of drilling all nine CarbFix wells is EUR 6.000.000. In 2009 OR sponsored the International Conference on Carbon Capture and Storage held at the Hellisheidi Geothermal Power Plant. OR has constructed a pilot gas separation plant that separates H2S and CO2 from other geothermal gases. This pilot plant is a separate project from CarbFix, but means the CO2 will be available for the CarbFix project. For information the estimated cost of the pilot gas separation plant is EUR 2.500.000.

Despite the difficult financial situation in Iceland since fall 2008 the Board of Directors at OR has supported the CarbFix project. It is a joint benefit for both OR and the CarbFix-project to grant the project this interest.
## Index I – Financial Information

### CarbFix - Budget according to actual exchange rate each year (EUR)

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<td>Real Contribution from CNRS</td>
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<td>297.499</td>
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<td>227.682</td>
<td>253.571</td>
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<td>136.643</td>
<td>297.499</td>
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<tr>
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OR = Orkveita Reykjavíkur (Reykjavík Energy)
IES = University of Iceland - Institute of Earth Sciences
LDEO = Columbia University - Lamont Doherty Earth Observatory
CNRS = Centre National de la Recherche Scientifique
<table>
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<th>Note</th>
<th>Description</th>
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| 1    | Average Exchange Rate 2006 87,72 ISK/EUR Average Exchange Rate Jan-June 2008 110,12 ISK/EUR CBI*  
Average exchange rate 2007 87,60 ISK/EUR Average Exchange Rate July-Sept 2008 125,59 ISK/EUR CBI  
Average Exchange Rate Apr-June 2009 172,37 ISK/EUR Average Exchange Rate Jan-Mar 2010 176,17 ISK/EUR CBI  
Average Exchange Rate July-Sept 2009 180,73 ISK/EUR Average Exchange Rate July-Sept 2010 154,79 ISK/EUR CBI  
Average Exchange Rate Oct-Dec 2009 183,75 ISK/EUR Average Exchange Rate Oct-Dec 2010 154,03 ISK/EUR CBI  
Average Exchange Rate Jan-Mar 2011 158,86 ISK/EUR CBI  
Average Exchange Rate 2006 0,7970 USD/EUR  
Average Exchange Rate 2007 0,7308 USD/EUR  
Average Exchange Rate 2008 0,6834 USD/EUR  
Average Exchange Rate 2009 0,7192 USD/EUR  
Average Exchange Rate 2010 0,7546 USD/EUR  
Average Exchange Rate Jan-Mar 2011 0,7439 USD/EUR |
| 4    | In year 2007, 2008 and 2009 Orkuveita Reykjavikur granted IES a substantial support through the Environment and Energy Research Fund and the Division of Innovation and Development. The proportion of this funding in IES’s contribution to the CarbFix project was 57-67%. In 2007 and 2008 IES was granted a support from Hitaveita Suðurnesja and Norðurál The proportion of EU funds in the contribution from IES was 7% in 2006, 5% in 2007, 13% in 2008 and 2009 and 60% in 2010. |
| 5    | In year 2010 OR and IES recieve a grant from GEORG (The Geothermal Research Group - www.georg.hi.is)) |
| 6    | Salaries: Project Manager, Research Scientists, Engineers, Technicians and Lawyer |
| 7    | Includes salary and wages for personnel and fringe benefits. 30.8% in 2006-2009 and 28.5% in 2010-2011 |
| 8    | Includes filed supply: Setup in boreholes, downhole pumps, containers, dieselmotors, connection to electricity grid, oil and electricity on site, equipment for sampling, heavy machinery, ISOR fieldwork and analysis and OR’s cost of designing, constructing and maintaining the injection setup |
| 9    | Laboratory and filed supply and analyses |
| 10   | Cost of the CarbFix website and management meetings. Cost of the International Conference on Carbon Capture and Storage held at the Hellisheidi Geothermal Power Plant in September 2009 |
| 11   | 2010 and 2011 OR counts in overhead cost (15%) |
| 12   | IES verhead cost (22,5%) |
| 13   | 2010 and 2011 the ICR is significantly increased because of a federal (U.S. Department of Energy) grant for the CarbFix project. Columbia/EI charges 61% overhead for a federal grant and Lamont charges 54%. |
| 14   | CNRS overhead cost (22,5%) |
| 15   | The CO2 injection was planned in the fall 2008 but was delayed until 2011. Therefore the estimated cost of design and construction is credited in 2009 and 2010 and execution of the injection and monitoring is credited in 2010 and 2011 |
| 16   | OR contributed less to CarbFix in 2010 than estimated due to delay of injection and monitoring, see note no 17 |
| 17   | IES and LDEO contributed more to CarbFix in 2010 than estimated |
| 18   | IES cost of International Conference on Carbon Capture and Storage held at Hellisheidi September 2009 |
| 19   | When examining this surplus it should be kept in mind that OR does not credit the CarbFix project accessibility of land and wells at the CarbFix injection site. OR did not credit the CarbFix project the cost of drilling a new monitoring well, HK-34, at the CO2 injection site in 2008. (Cost of drilling a well like the injection well is ~ EUR 2 million and drilling a monitoring well is ~ EUR 0.3 million. The estimated cost of drilling all wells in the CarbFix project is ~EUR 6 million). OR sponsored the International Conference on Carbon Capture and Storage held at the Geothermal Hellisheidi Power Plant in 2009 |

* CBI= Central Bank of Iceland
Summary

In early spring 2010 the construction of the CarbFix mechanism was finalised and in March CarbFix was ready to a few weeks test-run prior to being able to start injecting CO₂. However, due to air in the gas from the Hellisheiði power plant to the pilot gas separation plant and due to the power plant stop in late June the pilot plant didn’t started operation until July. After a short period of experiments a device that condenses H₂S broke down. In August, September and October there were delays of shipping of device for the pilot plant, more components and small equipments broke down almost every day. Therefore time plan of delivery of CO₂ for CarbFix and injection of the gas needed constant revision. In late November and start of December scientists from Columbia University arrived for testing the CarbFix system with the Icelandic groups. This visit stressed the importance of finding solutions from different angles as a group. Since late November 2010 the CarbFix project has been up and running, water has been constantly injected into the injection well, however without CO₂ gas. Start-up of CarbFix is planned in 2011.

All year 2010 the CarbFix project continued addressing background fluid chemistries at the injection site and characterizing the target reservoir for the planned CO₂ injection. Numerous groundwater samples have been collected by the Institute of Earth Sciences, Orkuveita Reykjavíkur and French collaborators at the injection site. The samples have been analysed at the Iceland Geosurvey, Institute of Earth Sciences in Iceland, Columbia University in New York and in various laboratories in France.

A monitoring and accounting plan has been developed by the CarbFix group, which integrates surface, subsurface and atmospheric monitoring. All year 2010 Orkuveita Reykjavíkur has been operating a weather station at the injection site for continuous monitoring of atmospheric CO₂ and to track all key parameters for the injection. The station provides information online, available to all collaborators in the project. Different monitoring methods in the project have proven their value and will be continued after CO₂ injection.

Environmental authorities and the Municipality Ölfus have granted licenses for the CO₂ injection and the tracers, based on a detailed monitoring plan of the injection facilities in the pilot project.

Chemical modelling scenarios are being performed by the Institute of Earth Sciences in Iceland and the Centre National de la Recherche Scientifique in France, by lab experiments and numerical modelling. At Orkuveita Reykjavíkur development of a three dimensional reactive transport model that simulates hydrology and mineral alteration associated with the CO₂ injection has been ongoing. Reactive chemistry has been coupled to the model and TOUGHREACT is used for reactive transport simulations. Ongoing work includes validation of revised thermodynamic and kinetic databases, and simulations of the CarbFix CO₂ injection at Hellisheiði.

In 2010 Institute of Earth Sciences in collaboration with the Centre National de la Recherche Scientifique, started testing a 2,5 m long laboratory plug flow reactor that is filled with basaltic material. The experiments with the plug are scheduled in 2011. Institute of Earth Sciences finished constructing a bailer that will be used to retrieve samples at reservoir conditions, several laboratory experiments were successful and the results submitted to international journals.

Eight PhD students were working on science projects, closely linked to the CarbFix project. One MSc student defended the thesis in late January 2010.

From the start, the CarbFix group has stressed the importance of sharing the generated knowledge with the scientific/engineering community as well as with the public. Annual reports are available on the project website www.carbfix.com. As CarbFix develops new technologies for enhanced in situ mineral carbonation, some specific parts of these technologies may be an intellectual property of the stakeholders of the project.

In December 2010 Orkuveita Reykjavíkur started preparing a patent application on CarbFix for EPO and an US-provisional application.

In 2010 the project received grants from GEORG (Geothermal Research Group – see details at www.georg.hi.is) and the U.S. Department of Energy (DOE).
Appendix I – List of Selected Publications and Presentations 2010

Columbia University USA – Earth Institute - Lamont-Doherty Earth Observatory (LDEO)

2010

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* See J.M. Matter and D. Fernandez de la Reguera

Papers in International Journals:


Conference Abstracts:


Invited Talks at international workshops and Conferences (all this presentations included the CarbFix Project):


Poster Presentation:


Radio/TV interviews:


1 Counted by the First Author
The Centre National de la Recherche Scientifique, France (CNRS)

2010

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Chapters in books:


Orkuveita Reykjavíkur (OR)

2010

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Conference Abstracts:


Invited Talks at international workshops and Conferences:

Bergur Sigfússon, 2010. “Some problems and solutions associated with high temperature geothermal utilization”. Workshop on Carbonate Reactivities /Industrial and Academic Applications in Copenhagen, Denmark in May 9-12.


List of selected talks on the CarbFix project 2010:

Einar Gunnlaugsson. The President of the Maldives, 12 March.
E. Gunnlaugsson. Visit from the Roskilde High school in Denmark, 23 March.
Bergur Sigfússon. CarbFix Seminar, 24 February.
Holmfridur Sigurdardottir. Framadagar 10 February.
H. Sigurdardottir. CarbFix Seminar, 24 February.
H. Sigurdardottir. DGA Dalkia France. 4 March.
H. Sigurdardottir. EU Sustainable Energy Week, Iceland, 25 March.
H. Sigurdardottir. Visit from the Environmental Protection College Slovenia, 1 July.
H. Sigurdardottir. The Minister of Energy in India, 27 September.
H. Sigurdardottir. The Municipality Ölfus, 19 October.
H. Sigurdardottir. Commercial counsellour of the Embassy of Hungary in Oslo, 1 December.
H. Sigurdardottir. Open House at Reykjavik Energy, 4 December.

Poster Presentation:


1 Counted by the First Author
**Papers in International Journals:**


Alex P. Gysi and Stefansson A, 2010. CO$_2$-water-basalt interaction I. Low temperature experiments and implications for CO$_2$ sequestration into basalts. Article submitted to Geochimica et Cosmochimica Acta. (CFA$^1$).


**Conference Abstracts:**


Iwona Galeczka, Wolff-Boenisch D. & Gislason S. 2010. Modeling CO$_2$ sequestration in basaltic rocks with a plug flow reactor” Symposium on Current Research in Engineering and Natural Sciences at University of Iceland. (CFA$^1$).


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1 Counted by the First Author
S. Gudbrandsson, Wolff-Boenisch, Gislason, S.R. and Oelkers, E.H., Dissolution rates of crystalline basalt at pH 2 - 11 and 5-75 °C. Delta-Min meeting, Santorini, Greece, 3-8th October 2010. (CFA¹).


Invited Talks at international workshops and Conferences:


Edda Sif Pind Aradottir 2010. Coupling reactive transport to reservoir modeling. GEORG workshop on Geothermal Reservoir Research in 4 March.

Iwona Galeczka, Wolff-Boenisch D, Gislason S., Sigfusson B. and Stefanson A. 2010. Experimental studies on CO₂ sequestration in basaltic rocks with the plug flow reactor” Delta-Min meeting, Seefeld. (CFA¹).


S. Gudbrandsson, Wolff-Boenisch, Gislason, S.R. and Oelkers, E.H., Dissolution rates of crystalline basalt at pH 2-11 and 5-75 °C. The European Geothermal PhD Day, Potsdam, Germany, 12 February. (CFA¹).

S. Gudbrandsson, Wolff-Boenisch, Gislason, S.R. and Oelkers, E.H., Dissolution rates of crystalline basalt at pH 2 - 11 and 5 °C to 75 °C. Delta-Min meeting, Santorini, Greece, 3-8th October 2010. (CFA¹).

Gabrielle J. Stockmann, 2010. The CarbFix project in Iceland. The 2nd year geology students at the University of Gothenburg, Sweden.


Poster Presentation:


¹ Counted by the First Author


Edda S.P. Aradóttir. Reactive transport models for mineral CO₂ storage in basaltic rocks. Poster at at R-VoN 2010 – A Symposium on Current Research in Engineering and Natural Sciences at the University of Iceland. 8-9 October 2010.


S. Gudbrandsson, Wolff-Boenisch, Gislason, S.R. and Oelkers, E.H., Dissolution rates of crystalline basalt at pH 2-11 and 5-75 °C. The European Geothermal PhD Day, Potsdam, Germany, 12 February. (CFA¹).


Reports:


Reykjavik Energy Graduate School of Sustainable Systems (REYST)

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¹ Counted by the First Author