Phase I Final Report

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Phase I ("Feasibility Study") Report

General comments –

This report will contain two major parts:

1. a summary of the work accomplished under each Task identified in the original SOPO (including specific discussion of the Go/No-Go criteria), and
2. a suggested modified SOPO for Phase II.

The work accomplished under each Task will be discussed by Task. For each Task, the original description will be given, followed by comments on the performance of that Task and a summary of the Task's status. In addition, whenever a Go/No-Go requirement is associated with a particular Task, that requirement's status will be discussed.

Our original Statement of Project Objectives (SOPO) contains the following Go/No-Go requirement:

> *The DOE will make a go/no-go/re-direction decision prior to the beginning of Phase II. This decision will be based on the following:*
>
> - *The development of preliminary engineering design and cost estimates - these estimates will include estimation of capital and operating costs, installed cost per MWe, levelized cost of energy (LCOE), the return on investment (ROI), and similar economic measures,*
> - *Results of the MOHC investigation,*
> - *Installation and operation of the seismic monitoring system,*
> - *Ability to obtain necessary permits, and*
> - *Total expected capital cost of Phase II.*

Because we are proposing a modification to our project involving a new technology and location to a different site, the modifications to the SOPO for Phase II will be preceded by technical and economic justification for that change, including the revised capital costs.

As discussed in the original SOPO, the objective of the project was to drill and test a single-well implementation of CO_2-based EGS. An important part of the project, though not specifically included in the SOPO Tasks as it was accomplished before project submission, was to pick a site for our proposed single-well huff and puff experiment. Based on information available to the public, we chose a site near Ridgeway Arizona Oil Company's well 9-21, on the St. Johns Dome helium production field, and 16 miles east of Springerville, Arizona. A map of the area and a geologic section diagram are attached as Appendices A and B, respectively.

The technical challenges of this project are fairly simple to explain. Though Brown in his seminal patent[1] and papers such as that presented at the 2000 Stanford Geothermal Workshop[2] and at an American Chemical Society Meeting in 2009[3] postulated that supercritical CO_2 (SCO2) would be an efficient fluid for heat recovery in an Enhanced Geothermal System (EGS) environment, that postulate has never been demonstrated in the field. Our award, from a 2010 FOA,[4] aims to provide a field demonstration of CO2-based geothermal energy production. The original SOPO was designed to test an EGS system with SCO2; our proposal for modifying Phase II assumes slightly different technology, but still centers on using SCO2 to produce power from geothermal heat.

As we proceeded with the implementation of Phase I, it became increasingly obvious that our timetable for project completion was overly optimistic, for two major reasons: 1) we severely underestimated the time required for permitting, and 2) we lost most of our cost-share funding during the recession and it proved difficult to replace. Both factors were exacerbated because our project is the first of its kind anywhere in the world. We are profoundly grateful to the Department of Energy and the Geothermal Technologies Program for their willingness to grant no-cost time extensions as needed.

The proposal that Phase II be modified arose primarily from the economic modeling we performed. Obviously, in an EGS system, moderate to high formation permeability is required in order that the heat carrier (SCO2 in our case) can traverse the formation. However, during the course of our modeling it became increasingly evident that there was a very delicate balance between sufficient permeability to generate power and loss of SCO2 into the formation.

Need for New Geothermal Energy Technology

The US geothermal power industry is currently facing severe difficulties. A number of companies within the industry are going out of business or moving operations to other countries because of a lack of good sites here. This trend has been exacerbated by a number of recent high-profile failures, including the Ormat North Brawley project and the Hudson Ranch II project from EnergySource, both in the Imperial Valley. These failures make it

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[1] Brown, Donald W., **Geothermal Energy Production with Supercritical Fluids**, US Patent 6,668,554, 30 December 2003.

[2] Brown, Donald W., **A Hot Dry Rock Geothermal Energy Concept utilizing Supercritical CO_2 instead of Water**, Donald W. Brown, Earth and Environmental Sciences Division, Los Alamos National Laboratory, Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 24-26, 2000, SGP-TR-165.

[3] Brown, Donald W., **Geothermal Power Production Utilizing Supercritical CO_2 Combined with Deep Earth Carbon Sequestration**, Preprints, Fuel Chemistry Division American Chemical Society, Washington DC Meeting, August 2009.

[4] **Geothermal Energy Production from: (A) Low-temperature Resources; (B) Coproduced Fluids; and (C) Geopressured Resources**, Funding Opportunity Announcement Number DE-FOA-0000318, 12 May 2010.

exceptionally difficult to raise investor funds for new projects. This situation is reminiscent of the oil and gas industries in the era prior to the development of technologies to extract oil and gas from shale formations. The major energy companies were unable to find good new projects in the US, so most new projects were either offshore or in other countries. More recently, the combination of horizontal wells and fracking allowed commercial extraction of oil and gas from US shale formations, fundamentally changing the oil and gas industries and making the US the largest oil producer in the world.

GreenFire Energy believes that something similar is possible with geothermal energy. Specifically, we believe that the combination of horizontal wells, stimulation technologies designed to enhance the near-well environment around those wells by orders of magnitude and the use of supercritical CO2 ("SCO2") can permit economical and low-risk development of many geothermal sites that cannot be developed using conventional technology. The goal is to combine natural and induced convection to bring heat to the horizontal wells in sufficient amount to allow the wells to operate at commercial levels of power output without thermal depletion. Stimulation of the near-well environment allows that convection to occur at a high rate. The use of CO2 as the geothermal fluid provides additional advantages, including circulation via a thermosiphon and a relatively low heat capacity that allows the SCO2 to reach operational pressures over a relatively short horizontal run. This latter fact is critical; with its high heat capacity, water would require a lengthy horizontal run in which to achieve operating temperatures. As drilling long horizontal wells is expensive, it is unlikely that water can be used successfully in such wells.

This is the first of a set of projects designed to bring this technology, Convective Cycle CO2G™, to market. It demonstrates the ability to construct a closed-loop circuit and to circulate CO2 within that circuit via the thermosiphon. At present, we do not foresee stimulating around the horizontal well to be built. However, should sufficient funds be found in the future, we would consider adding this to the task list.

An important aspect of this project is that we have gained access to two relatively new and intact vertical wells about the right distance apart at Ram Power's Orita leasehold in the Imperial Valley. This is an exceptionally unusual circumstance that will save us at least $5 million to $10 million, the cost for drilling our own vertical wells.

This project represents an opportunity to develop a whole new form of geothermal energy technology, one that has lower costs, far less risk, and minimal operational costs. It involves no contaminant releases to the air or subsurface. It breaks the link between operating a baseload power technology and the consumption of water. It addresses many of the problems that have plagued the geothermal industry. And, if successful, it should make geothermal energy an industry in which projects can easily be financed via traditional project financing or even debt.

Section I - Discussion of Tasks, Phase I

A summary of the expenditures for Phase I and the original approved expenditures for Phase II are attached as Appendix C. A more detailed account of project expenditures for Phase I and budgets for Phase II are provided below in Section 2 – Justification for Changes and Modified SOPO.

Task 1 – **Identify and assemble relevant data [i.e., to assure that the project is feasible]**

Original description - *A number of research groups, chiefly from National Laboratories, have investigated the theoretical possibility of using CO2 as a heat-transfer fluid in enhanced geothermal systems. However, there is no single site where all the data and studies are gathered together, nor has anyone published a review of the relevant literature.*

This step will require an intensive search of worldwide literature, including journals, meeting proceedings, and the patent literature to assure capture of the relevant literature. It is expected that most of the important publications will be from either the US or Australia.

Since the data come from many sources, it will be necessary to make sure that reliable data and models pertinent to the project are available. For example, cores from wells near the chosen site at the Springerville-St. Johns Dome are available from the Arizona Geological Survey and the state's Oil and Gas Conservation Commission,[5] but there are two problems with those core samples: first, they have not been characterized by even so much as permeability, porosity, or mineralogy, and second, because the operators' interest was mostly in the overlying sedimentary formations, the cores do not go very far into the crystalline basement rocks.

Once the needs of the project and the available data and models have been compared, it will be possible to decide which needs are most critical. Having defined the most critical data requirements, the cost and time required to obtain that data can be calculated and put into the engineering design for subsequent process stages.

Comments – Extensive searches of the literature were performed, including:

- A search of the scientific and geologic literature through the normal on-line sources
- A search of the patent literature via the US Patent Office files
- Research on the St. Johns Dome area with the cooperation of the Arizona Geological Survey, including access to relevant well log and core data

[5] http://www.azogcc.az.gov

- Access to the databases and cooperation of personnel of Ridgeway Arizona Oil Company, which had drilled most of the CO2 wells at the Dome.

It became obvious that very little data on the crystalline basement rocks were available; the only available data was for the top few hundred feet of that formation. Appendix D shows the wells drilled at the St. Johns Dome; note that only a few wells have been drilled into the basement rock. From the files at the Arizona Geological Survey, it was determined that none of the wells drilled more than 200 feet into the Precambrian basement rock. Clearly, no substantial data on the characteristics of the crystalline basement rock will be available until wells are drilled into that part of the formations.

It was also evident that no compilation of review of the literature discussing CO2-based EGS had ever been published, suggesting that completion of this Task should involve writing a review paper including, as far as possible, everything published worldwide on the subject. Unlike technologies of earlier conception, CO2-EGS technology has a definite starting date and place, and is barely 20 years old, so a relatively complete review was deemed possible.

Deliverables and status – ***Completed*** – A review paper[6] covering the literature from the inception of the idea of CO2-based EGS to mid-2011 was presented as a poster at the Geothermal Resources Council meeting in San Diego in October 2011. Since that date, we have been tracking additional papers published in the field, and are in position to expand that paper to include publications through May 2014. A copy of the paper is attached as Appendix E.

Task 2 – Develop preliminary engineering design and cost estimate – *Completed*

Original description – *These estimates will include estimation of capital and operating costs, installed cost per MWe, levelized cost of energy (LCOE), the return on investment (ROI), and similar economic measures.*

The exact requirements for data will depend on the results of Task 1.0, but it is relatively certain that several types of well logging will be required to fully characterize the formation. Because the formations of interest at the St. Johns Dome are crystalline basement rock, typically one or more types of granite or metamorphic rock, and because most of the existing wells do not penetrate very far into the granite, little information is currently available.

Comments – Cost estimations for this project were somewhat difficult, as the only analogous systems from which to model are existing EGS projects, whose economics

[6] Eastman, A.D., *CO_2-Based Geothermal Energy – A Review of Work to Date*, presented at Geothermal Resources Council 35th Annual Meeting, San Diego, CA, 23-26 October, 2011.

are seldom publicly available. However, we were able to construct what we believe to be a reasonable model, shown in Appendix F. Many costs were estimated by analogy with existing geothermal projects. Drilling and reservoir engineering costs are somewhat nebulous, and will remain so until actual drilling is started. It is worth noting that the capital cost per MW is in the same general area as that for most conventional and EGS geothermal projects.

Using the equations and algorithms included in the LCOE calculator developed by the National Renewable Energy Laboratory,[7] the LCOE can be calculated. Appendix G shows the assumptions made and the resulting LCOE, which turns out to be 129.8¢/kWh.

Deliverables and status – ***Completed*** – Appendices F and G show the estimates of capital and operating cost, installed cost per MWe, and LCOE. The LCOE of 129.8¢/kWh is not a very satisfying estimate, since it is well outside the range for which we hoped. However, some of the assumptions used in that calculation are not yet verified by field data, and indeed cannot be until there is field data to use. For that reason, it was foreseen in the original SOPO that sensitivity analyses should be performed to see where the assumptions might be weakest.

Go/No-Go Criterion – ***Satisfied*** – *The DOE will make a go/no-go/re-direction decision prior to the beginning of Phase II. This decision will be based on the following: the development of preliminary engineering design and cost estimates - these estimates will include estimation of capital and operating costs, installed cost per MWe, levelized cost of energy (LCOE), the return on investment (ROI), and similar economic measures.*

We consider this criterion satisfied. As described above, preliminary engineering design and cost estimates were performed, including the usual measures of economic viability. Note also that the next section, Task 3, describes sensitivity analysis of several factors included in the general cost model.

Task 3 – Perform sensitivity testing – *Completed*

Original description – *Sensitivity testing will enable us to hone in on the areas of greatest financial and technological impact, thereby showing where the most effort is necessary.*

Comments – Of all the variables in the LCOE calculation, we estimated that the capital cost and the replacement cost of CO2 (reflected in the "fixed O&M cost" category of the LCOE inputs) would probably be most important. Therefore, as noted in the discussion of Task 2, GreenFire built a spreadsheet LCOE model using the equations of the NREL LCOE calculator. The spreadsheet was a combination of Appendices F and G; the

[7] http://www.nrel.gov/analysis/tech_lcoe.html

capital cost and the contribution of changing CO2 loss rates are imported from Appendix F into the LCOE calculation inputs of Appendix G.

Why should capital cost and CO2 loss be the most important variables? With respect to capital cost, SCO2 requires pressures throughout the system in excess of 1070 psi, the critical pressure for CO2. This, of course, requires somewhat stronger and more costly metallurgy than steam plants that can operate at lower pressures. The extra costs will be most evident in the construction of the heat exchanger of a binary-cycle power plant, but will be partially offset by the reduced necessity for pumps and compressors because of the formation of a CO2 thermosiphon. Since a detailed engineering estimate is premature at this point in the project, sensitivity analysis is prudent in order to inform us as to how much latitude is available.

With respect to the effects of CO2 cost, even though the agreement with RAZO and its successor company Kinder Morgan would give us a certain amount of CO2 cost-free, even that 'free' CO2 must be transported to the project site. This is particularly important because the best CO2 wells at the Dome are about 35-40 miles from our chosen site, and the few CO2 wells drilled near the site were not especially productive.

There is another reason to be concerned about the cost of CO2, and that is the possibility of CO2 loss into the formation. Pruess' original modeling of CO2-EGS assumed a loss of about 5% per cycle, based on his experience with water; assuming roughly 100 cycles per year, this is a 500% loss of CO2 per year! This figure would certainly make the entire project cost-prohibitive. We assumed a far lower number, 50%/year, for a number of reasons:

- Pruess used the geology of the Fenton Hill EGS project for his modeling; that site is known to be extremely permeable, with numerous highly-permeable fractures in the heated zone
- We anticipated a project in a very tight granitic formation, where loss from the heated area will be minimized
- Within the project area, permeability should be extremely limited outside the stimulated area

Despite those reasons, the differences in viscosity and surface tension between water and SCO2 suggest that the loss of CO2 into a given formation will be much higher than that of water. Indeed, Boussinesq's Equation[8] states that flow into formations will be inversely proportional to the viscosity of the flowing material. Since the viscosity of water at, say 150°C and 2,000 psi is approximately five times that of SCO2, SCO2 should diffuse into formations approximately five times faster than water, all else being equal.

[8] See, for example, Vásquez, J.L., **The Porous Medium Equation**, Oxford, 2006, pp. 19 ff.

We therefore investigated the effect of CO2 loss on LCOE, feeling that this could be a very critical factor to the economic viability of the project.

Selected results of the sensitivity analyses are attached as Appendix H. As expected, the effects of financial variables such as the discount rate, loan period, etc., are minimal. The effects increasing power plant costs and even CO2 initial fill costs are not too detrimental. However, the effects of higher drilling costs are quite significant, and the effects of CO2 loss can be catastrophic. Consider, for example, the effects of assuming Pruess' 5% loss per cycle (i.e., 500% per year) – which results in an LCOE of $12.03/MWh! To reach an LCOE of 13.3¢/kWh would require reducing the CO2 loss to only 1%/year, or 0.01%/cycle, a figures that is probably well outside the range of reasonable possibility.

Of course, in the case where CO2 capture and sequestration is mandated, the outlook is quite different. Assuming no cost and pipeline delivery for CO2 (i.e., where no compression is necessary), the LCOE becomes 8.2¢/kWh, regardless of the loss rate. (Of course, this is somewhat simplistic, as the loss rate will eventually affect the LCOE.)

At the time our project was originally funded, CCS seemed well on its way to be mandated throughout the US, so it was not unreasonable to work on that assumption. Since then, however, the exigencies of politics have led to a situation where CCS is not now mandated and may not ever be required. With that in mind, the results of the LCOE calculations and sensitivity analysis led us to investigate ways to prevent CO2 loss to the system, and resulted in our development of the closed-cycle system and our request to repurpose the funding for Phase II of the project.

Deliverables and status – The greatest potential negative effect on LCOE can be traced to the cost of CO2 losses to the formation, with drilling and formation engineering (e.g., fracturing or pressure shearing) costs a distant second. We believe that the risks of potential large CO2 losses justify redirection of the process.

Task 4 – Design and install a seismic monitoring system at site – ***Completed***

Original description – *Public concern about induced seismicity caused by geothermal drilling has been exacerbated by recent incidents in Basel, Switzerland,[9] and at The Geysers[10] in California. For that reason, seismic testing is now necessary before any geothermal resources can be tapped. Even though the St. Johns Dome is in a very seismically inactive area, there are faults in the vicinity – including a major lineament crossing the margin of*

[9] See, for example, Glantz, J., *Quake Threat Leads Swiss to Close Geothermal Project*, **New York Times**, 10 Dec 2009, http://www.nytimes.com/2009/12/11/science/earth/11basel.html
[10] Gurrerio, J., *AltaRock project abandoned, geothermal potential still untapped*., 13 Dec 2009, http://www.examiner.com/x-2903-Energy-Examiner~y2009m12d13-AltaRock-project-abandoned-geothermal-potential-still-untapped?cid=exrss-Energy-Examiner

the Dome itself – and it will be necessary to establish a baseline seismic activity record before any demonstration of CO2-geothermal technology can proceed.

A number of companies have experience in design and installation of seismic networks; one such company will be employed to design and set up the monitoring network, perhaps including downhole geophones in one or more of the nearby wells not currently producing natural gas or CO2.

Comments – We contracted with Foulger Consulting to design, build, run, and interpret a five-station passive seismic network centered on our site at St. Johns Dome. A land access permit from the Arizona Land Department, giving permission to place the sensors, was obtained from the Arizona Land Department for four of the five stations; the fifth is on private land in New Mexico, so permission was obtained from the landowner to place the sensor.

The sensors were installed and operated for about 18 months. The results confirmed our suspicions that the St. Johns Dome area is one of the least seismically active areas in the Western US. This conclusion has several consequences for geothermal exploitation in the area. First, it is very unlikely that hydraulic fracturing or pressure shearing will interfere with an active fault zone, since there just are not very many of those. Second, because there is so little background seismic activity, the existing seismic network (probably augmented with some downhole sensors, etc.) can readily be used to determine the location and extent of microseismic events created by shearing.

Deliverables and status – Foulger Consulting wrote several reports documenting their work. Their latest report, summarizing the results of the passive monitoring for over 18 months, is attached as Appendix I.

Go/No-Go Criterion – ***Satisfied*** – *The DOE will make a go/no-go/re-direction decision prior to the beginning of Phase II. This decision will be based on the following: Installation and operation of the seismic monitoring system.*

This criterion has clearly been satisfied. The seismic monitoring system was successfully designed, permitted, installed, run, and the results evaluated. As we expected, the St. Johns Dome area has very little background seismic activity.

Due to the nature of the Imperial Valley and the existence of large amounts of seismic data, and the fact that the closed-loop technology does not require fracturing or pressure shearing, we do not anticipate a need for seismic monitoring at the new site. For that reason, we are hoping to sell the network to Kinder Morgan (the owner of the CO_2 resource at the St. Johns Dome) or another party.

Task 5 – Investigate and choose a suitable MOHC – ***Completed***

Original description - *Certain nanoporous structured materials (called metal organic heat carriers [MOHCs]) show great promise for transformational improvement in efficiency of low-temperature geothermal, waste heat recovery, and commercial HVAC and refrigeration systems. PNNL is presently engaged in development of MOHCs to boost the efficiency of an Organic Rankine Cycle (ORC). Technical feasibility will involve conducting proof-of-principle measurements with several candidate MOHCs to demonstrate feasibility of obtaining: 1) high selectivity for water over CO2 at supercritical CO2 (SCO2) pressures, 2) water adsorption capacity >20 wt-%, and 3) high adsorption enthalpy (>1.5X the latent heat of condensation of water). Several MOHCs previously synthesized have demonstrated the required adsorption capacity and adsorption enthalpy for water. However, no prior work has been performed examining these properties in a high-pressure SCO2 working fluid.*

For one or more MOHCs that meet the required thermophysical property targets, a cost/benefit analysis will be performed with respect to deploying the nanomaterial at St. Johns' Dome. Impacts of MOHCs on pumping power requirements and flow rates through key components such as the heat exchanger also will be evaluated. Working closely with GreenFire engineering staff, the cost and performance data will be used to develop an estimate of the impact of MOHC technology on the capital startup costs and LCOE generation at the plant.

Comments – An agreement was negotiated with B.P. "Pete" McGrail and his group at Pacific Northwest National Laboratory. His group has been working on MOHC's, and as part of our agreement synthesized and tested a number of potential MOHC's that would work in supercritical CO_2 environments by absorbing the water in the solution. This has two advantages, both of which are significant. First, the absorption is strongly exothermic, essentially raising the amount of heat captured by the SCO2. Second, by capturing and removing the water from the SCO2 stream, the MOHC's dry the formation and fluid, which minimizes the corrosive properties of the SCO2 stream. A schematic of the process is shown as Appendix J.

Deliverables and status – PNNL has demonstrated in the laboratory a number of MOHC systems that work with several different liquid streams. A recent paper[11] describes some of that work. PNNL has also communicated to GreenFire the identities of several MOHC's that are candidates for use in SCO2 streams. Their most recent report is attached as Appendix K.

[11] McGrail, B.P., Thallapally, P.K., Blanchard, Nune, S.K., Jenks, J.J., and Dang, L.X., *Metal-organic heat carrier nanofluids*, Nano Energy (2013), **2**, 845-855.

Go/No-Go Criterion – ***Satisfied*** – *The DOE will make a go/no-go/re-direction decision prior to the beginning of Phase II. This decision will be based on the following: results of the MOHC investigation.*

We believe this criterion to be satisfied: the research at PNNL demonstrated the concept of using MOHC's to increase heat in the system by capturing formation water in the circulating fluid. Though that functionality is still interesting in theory, because the closed-loop system utilizes commercial CO2, which is nearly dry (<480 mg water/m^3), that functionality is probably not necessary in the closed-loop system.

PNNL has proposed a modification of the original MOHC's to increase heat capacity by capturing CO2 rather than water. They have also proposed using MOHC's to capture valuable minerals, such as lithium, in geothermal brines. Though these are interesting ideas, we do not believe they are critical to process success, and recommend no further funding as part of Phase II.

Task 6 – Obtain permits for demonstration unit operation – Partially completed

Original description - *The Arizona Land Department is the responsible agency, since the St. Johns Dome is on state lands, not Federal or Indian. Because there are already numerous natural gas/CO2 wells on site, many of the permitting requirements have already been fulfilled. For example, we have been informed by the Land Department that the environmental and archaeological surveys submitted by the gas field operator to obtain their permits will also be accepted for our geothermal operations permit, since the same site will be used.*[12] *Estimated time to obtain a geothermal permit is in the range of 3-6 months.*

The following permits will be required:

1. *Geothermal Exploration Permit, through the Arizona Land Department*
2. *Well drilling permit, through the Arizona Oil and Gas Conservation Commission*
3. *Underground Injection Control Permit, through the US EPA*
4. *Aquifer Protection Permit, through the Arizona Department of Environmental Quality*
5. *Potential permit for MOHC utilization; because MOHC's (see Task 5.0) have never been used in a field demonstration, the permitting process for those materials is uncertain, but the permitting agencies are likely to be the US EPA and the AZ Department of Environmental Quality*

[12] Joe Dixon, Arizona Land Department, personal communication to Alan Eastman, October 2009

If the permits cannot be obtained in a timely manner, execution of Phase II will be delayed. Obtaining the permits should be easily possible, but the timing – as with all permitting – is difficult to predict exactly.

Comments – We greatly underestimated the time required for permitting, especially because the project is the first project of its kind anywhere. As explained below, the exploration, land access, and well permits are not a problem.

Six major permits (not five) were involved in Phase I, as shown in Appendix I:

1. **Geothermal exploration permit**, from AZ Land Department, *granted*.
   This permit allows exploratory activities, including seismic monitoring and site preparation for drilling. The AZ Land Department is the appropriate permitting agency because the St. Johns Dome site is on Arizona School Trust Land, so the state alone has regulatory authority.
2. **Land access permit**, from AZ Land Department, *granted*.
   This permit allows access to the site for purposes of seismic monitoring and site preparation. In addition to the land access permit, we contacted the ranchers who hold grazing rights on the site and obtained their permission to work on land over which they hold leases.
3. The **drilling permit**, from the AZ Oil and Gas Conservation Commission; *not applied for, but expected to be easy to obtain*.
   This permit is issued by an employee of the AZ Geological Survey who is also the Commissioner for the O&GCC. Because the requirements for this permit are relatively simple to meet, it takes only a couple weeks to secure the permit and it is usual to apply for the permit just before drilling is scheduled to begin. GreenFire has contacted a drilling consulting company that was responsible for about fifteen of the most recent and trouble-free wells at the St. Johns Dome; that company believes they have solved the most common problems with drilling in that area.
4. Some sort of **permit for using the MOHC's**.
   It is uncertain who might issue this permit or if a permit is even required. Our contacts with the AZ Department of Environmental Quality indicated that they are considering including MOHC usage into the Aquifer Protection Permit, since (like CO2) the MOHC's would be injected into formations where contamination of an aquifer might be possible.
5. The **AZ Aquifer Protection Permit (APP)**, from the AZ Department of Environmental Quality.
   This is one of the two major permits required, and is designed to protect aquifers from contamination by materials injected underground. We have met

with the agency and started the permitting process. Because the Arizona Legislature requires that the agency charge $118/hour for time spent by agency employees working on any application, and because CO2-EGS is a new technology, the agency has little incentive to move quickly on any application. We were given an estimated time to issuance of 12-18 month, and an approximate cost of $100,000-$125,000. Because of the invention of the closed-loop system and the different location, we have chosen to cease work on this permit.

6. The US Environmental Protection Agency **Underground Injection Permit, Class V**. EPA Region IX (San Francisco) is the relevant permitting agency.
   Because injection for CO2-EGS is somewhat similar to injection for carbon sequestration, this agency concluded that we would be eligible for a Class V permit rather than the much more restrictive Class VI permit. Much of the information required for that permit is the same as what Arizona requires for the APP, making the APP probably the rate-determining step. As with the APP, we have chosen to cease work on this permit.

Deliverables and status – See the Comments above for each permit. A summary of the permits and their status is attached as Appendix L.

We have chosen not to continue our applications for some of the permits because of our intent to pursue the closed-loop technology in the Imperial Valley of California rather than CO2-EGS at St. Johns Dome.

Go/No-Go Criterion – ***Partially Satisfied*** – *The DOE will make a go/no-go/re-direction decision prior to the beginning of Phase II. This decision will be based on the following: ability to obtain necessary permits.*

As noted above in the discussion of Task 6 and shown in Appendix L, six major permits are required for demonstration of CO2-EGS at St. Johns Dome. We have obtained two of them, one (the drilling permit) should be applied for only a few weeks before drilling, one (the MOHC permit) represents a new type of permit, and two (the APP and UIC permits) will take at least another year to obtain and cost over $100,000 each.

Given the opportunity to develop new technology that is faster, cheaper, and more efficient at the Imperial Valley in California. We have chosen to discontinue pursuit of the permits that we do not yet have. This strategy will require that permits for the new area be sought, as shown in the proposed changes to the project SOPO.

Task 17 – Build and maintain good community relations – *Completed*

Original description – This task was not in the original description, but was added because of its importance to the project.

Comments – Several visits were made to the towns of St. Johns, Springerville, and Eager, the municipalities closest to the project site.

Deliverables and status – Two public meetings were held and relationships established with both political (mayors, city counselors) and media (newspaper editor) representatives in the three towns. We have continued in contact with those people as the project's timeline has shifted.

Section II – Justification for Changes and Modified SOPO

Why change?

As noted in the discussion of Task 3, the sensitivity analysis, the CO2-EGS system is extremely sensitive to CO2 losses to the formation. As the system was originally proposed in a political environment that foresaw mandatory carbon capture and sequestration, it is not surprising that nobody worried about those losses; after all, losses simply increased the degree of sequestration! However, in our current political environment, it is essential that any geothermal project be economically viable, preferably without subsidies, so the potential economic losses from CO2 migration into the formation become extremely important.

One obvious way to eliminate a number of problems is to simply enclose the flowing SCO2 in a pipe. This completely eliminates losses to the formation, as well as a number of other problems, such as collection of minerals in the formation, which could conceivably precipitate out in unfortunate places like on turbine vanes and so forth. A closed-loop system also can still benefit from the formation of a thermosiphon, which can obviate or drastically reduce the need for pumps.

One might wonder why a closed-loop system has never been tried before. Actually, such systems have been investigated before – but only with water or other fluids, never with SCO2. One example[13] proposes the use of production fluids from oil and gas wells as the heat-transfer fluid. Others claim the use of the same types of heat carriers that are used in binary power plants, namely Freons or low-boiling organic materials like isopentane[14], or

[13] McHargue, T.R., *Loop geothermal system*, US Patent Application 2011/0048005, 3 Mar 2011.
[14] Wiggs, B.R., *Direct Exchange Geothermal Refrigerant Power Advanced Generating System*, US Patent Application 2012/0144829, 08 Dec 2010.

even heavy materials like ethylene glycol (antifreeze).[15] Still others have proposed single-well systems in which cool water[16],[17] or Freons[18] are pumped down an annular tube into the formation, then back to the surface. The water then rises into the larger wellbore annulus and is pumped to the surface, where energy is extracted using either a turbine or a binary cycle power plant to generate electricity. In these types of systems, though contact of the heat-transfer fluid with formation rock is limited, there is still enough to enable interaction between the fluid and the minerals in the formation. More importantly, because contact with the formation is deliberately quite limited, the potential amount of heat that can be picked up is also quite limited; it is likely that project economics will be compromised by this problem.

In every case, those attempts failed technically, economically, or both. The failures were the result of one or more of several factors:

- Pumping the water around the loop was too expensive
- Loss of a non-aqueous fluid (e.g., Freons, etc.) to the formation was too expensive
- Too little heat could be collected from the formation
- Thermal depletion of the formation was very rapid

We believe that by using SCO2 as the moving fluid and by using a turbine rather than a Rankine-cycle power plant to produce power, we have solved the two major problems with such systems: getting enough heat into the fluid to raise its temperature/pressure to a useful level, and getting enough heat to the pipe to sustain the process for a reasonable time. By using a turbine rather than a Rankine-cycle binary power plant, the important engineering variable becomes pressure at the turbine inlet. And since SCO2's heat capacity is much lower than that of water, it is relatively easy to raise SCO2's temperature and therefore its pressure to the desired operating range.

Using supercritical CO2 instead of water in a closed-loop system solves most of those problems. For example, if a thermosiphon can be achieved (and modeling, lab studies, and real-world experience show that it can be), the economic penalty of pumping will be minimized or eliminated.

Obviously, using a closed-loop system eliminates loss of the working fluid. This is particularly important with CO2, since CO2's viscosity is so low compared to that of water and, as SCO2 exhibits neither hydrogen bonding nor surface tension, there are few

[15] Vaughn, S.F., and Dahlheim, M.R., *Closed-loop Systems and Methods for Geothermal Electricity Generation*, US Patent Application 2012/0174581, 12 Jul 2012.

[16] Hildebrand, H., *Method and system for exchanging earth energy between earth bodies and an energy exchanger, especially to produce an electric current*, EP 1327111, US 7,059,131, 13 Jun 2006.

[17] Rogers, W.H., and Smith, M.J., *Geothermal Power System*, US Patent application 20110067399, 24 Mar 2011.

[18] Wiggs, B.R., *Single Well, Self-Flowing, Geothermal System for Energy Extraction*, US Patent Application 2013/0192816, 28 Jan 2013.

physical forces keeping SCO2 from quickly escaping into geologic formations. Of course, SCO2 exhibits the normal laws of diffusion; those effects have been well documented and are indeed used by oil companies in CO2 flooding. However, if the economics of a project depend on recovering virtually all the SCO2 injected into a formation (as CO2-EGS does), the price of SCO2 must be extremely low or the project will be economically disfavored. This is why we have proposed a change in focus from the St. Johns Dome site. If CO2 capture and sequestration were mandated, it is likely that the price of CO2 would be low enough to permit economical CO2-EGS – but that type of CO2 geothermal technology is highly unlikely to be economically viable if CO2 must be purchased at current market prices.

There is an additional problem with the economics of CO2-EGS. The cost of CO2 compression is subject to economies of scale. For volumes of 5,000 tons of CO2 or more per day, the cost should be on the order of $20 per ton. For smaller volumes, the price can be $50 or more per ton. As the cost of CO2 is the largest operational cost of CO2-EGS, this is a significant concern. In a closed-loop system, however, the cost of CO2 plays out quite differently. A supplier of industrial gases provides the CO2. The cost per ton is high – on the order of $1,000 per ton – but the amount per ton is low and the loss rate approaches zero. If we assume 50 tons per MW, then the cost is $50,000. It is on the order of 1% of capital expenditures and there should be no associated operational expense.

The substitution of CO2 for water is extremely important in collecting heat from the formation through the walls of the piping in a closed loop. First, the lower viscosity of SCO2 makes achieving turbulent flow in the pipe much easier: the Reynolds numbers under typical conditions are very high for flowing SCO2, but are much closer to the laminar/turbulent transition zone for water. Because the heat capacity of SCO2 is far less than that of water, SCO2's temperature will rise far more quickly with distance in the horizontal pipe run than water; this is clearly shown in the rather simple model we commissioned, which assumed isothermal conditions outside the pipe.

Temperature rise is important because of the connection between temperature and pressure; here again, the use of SCO2 is essential because SCO2 has a much greater pressure increase with temperature than does water. In our project, we assume use of a turbine rather than a Rankine-cycle heat exchanger, etc., so pressure to turn the turbine is of utmost importance. In fact, the entire closed-loop system is perhaps best considered an enormous Rankine-cycle power production system where SCO2 is the working fluid and the piping in the ground is the heat exchanger.

Cost estimates of a closed-loop system

The cost estimates discussed under Task 2 were derived in large part from the average costs of existing geothermal plants; because the project at the St. Johns Dome was essentially similar to such plants (with the exception of the geothermal fluid used) we believed those estimates to be reasonable. However, with a change in technology to a closed-loop system, a somewhat different analysis is required.

We have therefore done a far more detailed estimated project cost analysis to remedy that deficiency. Appendix M shows a schematic diagram of our conception of the closed-loop system, and Appendix N shows the cost analysis, broken down into expenditures for site investigation, geothermal rights, permitting, legal/insurance, drilling, surface equipment, startup, and electrical interconnect. The assumptions are clearly indicated in the Table and are, we believe, reasonable and on the conservative side.

Since the surface facilities will be much different for a CO2 working fluid than for water, we are also working on a much more detailed analysis of the configuration and cost of the surface facilities. Appendix O is a flow diagram showing how we intend to incorporate in the surface facilities for the first project the abilities to include or bypass the power production equipment, pumps/compressors, and cooling tower. As the project progresses, we will be able to be more specific about the exact costs of such equipment.

As one example of the different environment for SCO2 operation, Timothy Held and coworkers[19] describe the significant advantages of SCO2 turbines relative to steam turbines in size and efficiency. Appendix P shows the difference in size for a 10 MW turbine of each variety.

As another example, because we will be working at the surface with relatively pure CO2 rather than the very corrosive brines present in the Imperial Valley, we will be able to use much less expensive metallurgy, nor will there be deposition of brine solids on the surface process equipment.

Go/No-Go Criterion – ***Satisfied*** – *The DOE will make a go/no-go/re-direction decision prior to the beginning of Phase II. This decision will be based on the following: development of capital cost estimates for Phase II.*

We have developed what we believe to be a realistic estimate of costs for Phase II, shown in Appendix T. The costs have been developed and/or vetted by our corporate advisory board, which is composed of industry veterans who collectively have over 100 years of experience in all aspects of geothermal project development.

[19] Held, T., Persichilli, A.m Kacludis, A., and Zdankiewica, E., Supercritical CO2 Power Cycle Developments and Commercialization: Why sCO2 can Displace Steam, Power-Gen India& Central Asia 2012, 19-21 April 2012.

Heat flow around closed-loop systems

Obviously, for any geothermal process it is vital to be able to get heat from the subterranean formation into the process fluid, and to be able take heat from that formation over a long enough period of time for the project to be economically viable. There are therefore two essential questions to be answered:

1. Can enough heat be added to the process fluid to produce the required power at the surface?
2. Can the heat from the formation last long enough for a reasonable process lifetime, either by using pre-existing heat or by replenishing the heat of the formation on an ongoing basis? In other words, will the system thermally deplete?

We have engaged outside experts to help us determine the answers to those questions by mathematical modeling. When looking at the results of modeling at this stage of the process, it is important to realize that the models furnish guidance, not exact results.

It is obvious from the comments of the reviewers that they are quite familiar with modeling of geothermal processes – and that they would prefer to see an extensive series of models that practically guarantee success before any fieldwork is undertaken. We have, of course, done some modeling as part of our work, but believe that extensive modeling on this project may not be as productive as for other types of geothermal projects.

One reviewer quite accurately commented that the initial conditions assumed in the beginning could have a large effect on the results of the modeling process. We believe that some of the reviewers' comments are misleading because they are based on the water-based systems with which the reviewers are most familiar, and not on the quite different properties of SCO2. The question of water- vs. air-cooling is one pertinent example.

Because the results of the modeling depend strongly on the assumptions made – and the assumptions may or may not hold in the 'real' world – the results of the models should be used as guides to further work and directions to be taken, not as confirmation or rejection of pre-set conclusions. Indeed, part of the reason to even attempt a project like ours is to get better data for future modeling, since modeling is cheaper than drilling by quite a bit!

For that reason, we have not been very excited about turning our project into yet another modeling effort, but would much prefer to work out in the field. DOE has for years funded many modeling studies that have filled the professional journals with excellently executed work, while supplying numerous graduate students with the training to produce yet more models. However, the application of those beautiful models to the less-than-perfect physical world has not gone smoothly, as anyone who has followed the somewhat difficult progress of EGS can testify. In general, no matter how detailed and thorough the modeling, there will be surprises – some of them unpleasant – in the field. This is particularly the

case for new technologies (such as our closed-loop process) where relevant field data to use as initial conditions for the models is sketchy or altogether lacking.

Modeling the temperature of SCO2 in the horizontal pipe run

To determine if SCO2 in a pipe at process conditions could absorb sufficient heat, a first-pass model from engineering principles was made by Professor Kent Udell of the Mechanical Engineering Department of the University of Utah of heat in the horizontal pipe run. The model assumes a linear pipe of given diameter inside a drill hole of a larger diameter, with the pipe bathed in water at a given temperature. SCO2 is injected into the pipe at a given temperature, pressure, and flowrate, and the temperature of the CO2 in the pipe was calculated as a function of distance along the pipe, together with the total amount of heat absorbed. The latter figure determines how much energy will be available at the surface for power generation. For ease of modeling, the pressure differential caused by increased pressure with temperature was not considered. (That effect cannot be modeled directly, but requires recursive techniques and so was left for another time – and funding.) However, it is clear that this model will be somewhat optimistic in its predictions.

Appendix R shows the spreadsheet from the model, and Appendix S a typical result, with parameters believed to be typical of a closed-loop CO2G system, i.e., a 200°C reservoir with 100°C CO2 at the inlet, 7" pipe 1 km long in an 8" drill hole, and mass flow of 120 kg/sec. Note that the temperature quickly rises over the first few hundred meters and approaches formation temperature even with a fairly fast mass flow rate. Note also that 11.5 MW of energy can be extracted under those conditions. These numbers argue that the basic premise of closed-loop extraction is sound. Similar results were obtained for a variety of different conditions.

Modeling heat delivery to the horizontal run

The next crucial question to answer is whether enough heat can be supplied from the formation for a long enough period to make a closed-loop project economically viable. We commissioned Curt Oldenburg of Lawrence Berkeley National Laboratory to do a simple, preliminary first-pass model of how much heat can be supplied by induced convection to the horizontal loop of a convective-cycle system as a function of several variables. Oldenburg used the "scale analysis" method that he developed[20] for such first-pass modeling of convective zones.

According to the resulting model, the most important factors in delivering hot water to the pipe by induced convection are the permeability of the formation surrounding the pipe,

[20] For example: Oldenburg, C., *Comparison of scale analysis and numerical simulation for saturated zone convective mixing processes,* Lawrence Berkeley National Laboratory Report LBNL-40365, 1998.

the temperature of the resource and the surface area of the pipe. In addition to the simple model, Oldenburg ran a "quick and dirty" model with TOUGH2, a very sophisticated modeling system[21] well known in geothermal circles – and whose development was, incidentally, funded by DOE. The results of the TOUGH2 model are in the same ballpark as the Oldenburg model, though they suggest that Oldenburg's treatment is extremely conservative, as Oldenburg himself confirms. Even slight changes to the boundary conditions will make a big difference in the results of the modeling. For example, Oldenburg mentioned that he deliberately used a very low value for the thermal conductivity of the saturated formation.

It is important to note that Oldenburg's model does not include any convective driving force in the formation other than that due to buoyancy generated by heat loss to the pipe. Because natural convection driven by large-scale temperature and salinity gradients is an important part of the geological conditions in much of the Imperial Valley, its impact could be substantial, and will increase the amount of heat delivered to the horizontal pipe run.

Oldenburg has asked us not to reproduce the details of the modeling at this time, but we can cite his conclusions:

- Steady-state solutions of an aquifer heated from below and delivering heat by convection and conduction to a constant-temperature pipe have been calculated.
- The higher the permeability, the more vigorous the convection and the more heat transfer there is to the pipe.
- The higher the permeability, the closer the temperature near the pipe is to 250° C, resulting in greater heat conduction into the pipe.
- Assuming sufficiently high permeability, the system can generate commercial quantities of power.

The question of thermal depletion

Thermal depletion, the cooling of a formation as heat is withdrawn from it over time, is always a concern in geothermal systems. The models cited above show that it should be possible to produce commercially useful amounts of power from a closed-loop system drawing heat from the water (and rock) in a convective/advective geothermal reservoir. Those models also give a rough idea how much heat can be withdrawn per unit time. The unknown factor right now is the size of the system from which the water is being withdrawn. Until that is known, it is impossible to precisely calculate the effective life of the reservoir.

[21] Karsten Pruess of LBNL was presented a Lifetime Achievement Award for designing the original TOUGH program; see http://esd.lbl.gov/research/projects/tough/, accessed 12 June 2014.

That said, it is useful to compare the volume transferring heat to the surface of the horizontal pipe in a closed-loop system with the volume heating the water of a typical EGS system. In an EGS reservoir, a typical fracture system may be 50 by 1300 feet, with a 0.0066 foot (2 mm) opening; giving a total volume of only 429 cubic feet. In a closed-loop system such as that at the Orita site, assuming a 10' radius for the high-permeability zone next to the horizontal pipe and a pipe length of 3200', the volume is approximately one million cubic feet. Assuming that only 3% of the water is in permeable systems, there is about 30,000 cubic feet of water available to heat the horizontal pipe. Clearly, the closed-loop system has a very solid chance of showing very slow thermal depletion.

Proposed site for continuing work

We propose moving the project to the Ram Power's Orita Project in the East Brawley Known Geothermal Resource Area in the Imperial Valley of Southern California. The Imperial Valley already features sixteen operating geothermal power plants, but is believed to have unrealized potential for another 2,000 MW of power.[22] According to the president of Ormat, the area is "the Saudi Arabia of geothermal."[23]

The geology of the Imperial Valley is fairly well known. Appendix Q[24] shows a generalized cross section.

The East Brawley KGRA[25] is shown as "EB" in the figure in Appendix R.[26] Appendix S shows the location in more detail.

When the area was designated a KGRA, Unocal, Occidental, and Phillips Petroleum drilled eight test wells in the area. More recently, Ram drilled three wells in the area (Orita #2, #3, and #4), but though the temperatures were easily high enough for geothermal power production, well productivity was too low, suggesting that permeability was insufficient for their requirements. As a result, Ram terminated its PPA[27] and ceased work on the project.

We have successfully concluded negotiations with Ram Energy for the use of two of their wells, Orita #3 and Orita #4, drilled in 2010-2011. Ram will donate that use as part of the cost share for our project. Because the wells are relatively recent, they are in good shape.

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[22] Crawford, I., *From the Salton Sea to Sacramento – On the Trail of a Geothermal Gold Rush in California,* Geothermal Resources Council **Bulletin**, May/June 2014, pp 16-19.
[23] Ibid., p.17.
[24] Hulen, J., Kaspereit, D., Norton, D., Osborn, W., and Pulka, F.S., Refined Conceptual Modeling and a New Resource Estimate for the Salton Sea Geothermal Field, Imperial Valley, CA., Geothermal Resources Council **Transactions**, **26**, 29-36 (2002.)
[25] http://ram-power.com/current-projects/orita-california; accessed 21 June 2014.
[26] Hulen, et al, ibid.
[27] Richter, L.X., *Ram Energy terminates PPA for Orita project in the Imperial Valley*, Think Geoenergy, 1 Sep 2011, accessed as http://thinkgeoenergy.com/archives/8501, 21 June 2014.

Using them will greatly decrease the cost of the project, since those two existing wells will be connected using horizontal drilling.

Interestingly, there is a CO2 deposit, the Imperial CO2 Field, about 18 miles north of Brawley.[28] The field lies in the Salton basin and is part of the Salton Sea geothermal system. From 1934 to 1954, 650 million cubic feet (MMcf) of CO2 was produced commercially for dry ice production. About 54 wells produced CO2 from shallow (about 600 feet) sandstone reservoirs. Though access to the field is partially limited because of the Imperial National Wildlife Refuge, it is possible that in time, CO2 for our projects could be produced locally.

Modifications to Phase II budget and availability of cost share

As of the writing of this report, as shown in Appendix T, our estimated total budget for Phase II is $4.6 MM, using the closed-loop technology in the Imperial Valley, rather than CO2-EGS technology at the St. Johns Dome. Though the estimated number is somewhat more than the original budget, this estimate is far more thoroughly researched and undoubtedly more realistic. The table below compares the original and revised Phase II and II budgets.

Comparison of Original and Revised Phase II Budgets

Budget	Government contribution	Cost share	Total
Original Phase II	$1,565,410	$2,401,354	$4,057,764
Revised Phase II	$1,565,410	$5,434,590	$7,000,000

In contrast to our situation at the beginning of Phase I, we have a fair amount of confidence in this spending plan for several reasons. Most importantly, the site already has significant geothermal development, so permitting agencies and drilling contractors are very familiar with the area. We have engaged several geothermal industry veterans for our corporate advisory board; their experience in geothermal development has greatly helped us to get good cost estimates. Finally, GreenFire personnel now have far greater experience and familiarity with the entire industry, allowing us to have a better feel for what is reasonable and to be expected.

We are also in a much better position with respect to cost-share funding than we were in Phase I. We have already attracted several hundred thousand dollars in investment capital and expect to secure another $4 MM or more in the next 90 days.

[28] Eppink, R.G., Heidrick, T.L., Alvarado, R., Marquis, M., DiPietro, P. and Wallace, R., **Subsurface Sources of CO2 in the Contiguous United States, Vol., 1: Discovered Reservoirs**, DOE/NETL-2014/1637, 5 March 2014, p. 31..

That alone gives us more than the required cost share for Phase II; the remaining funding will handle cash needs and movement towards other projects not funded by DOE. We expect that successful conclusion of Phase II will encourage further and larger investment as we proceed toward full-scale commercial application of this technology. With respect to Phase III, we have an estimate from a turbine manufacturer that design of a suitable turbine will take about a year and cost about $1 MM.

Technical readiness for Phase II

Because of what we learned in Phase I, GreenFire is ready to enter into Phase II. We have, for example, acquired an advisory board whose advice and expertise has greatly improved our ability to make realistic cost projections for the most important phases of the project. More informed and realistic understanding of drilling expenses and procedures are a notable example here, thanks to the experience of Lou Capuano of our advisory board. Similarly, Halley Dickey's experience in expertise in CO2 turbine design has given us a good set of process parameters we must meet in order to get efficient power production as we proceed into commercial operation.

We propose using a different drilling subcontractor in Phase II than was originally proposed, for two major regions. First, our Arizona subcontractor, though eminently qualified for drilling at the St. Johns Dome, but is not familiar with the problems and infrastructure of the Imperial Valley, so it is prudent to use a different subcontractor; that firm has not yet been specified, though we are talking with several possibilities. Second, we need a drilling firm that is experienced with and capable in horizontal drilling. Again, we are looking at several firms for this job.

Given the depth and breadth of existing data in the Imperial Valley, and the relative simplicity of the subsurface arrangements with closed-loop technology, we do not plan to do further seismic work, obviating the need for the seismic subcontractor.

We had a third major subcontractor in Phase I, the Pacific Northwest National Laboratory, where Pete McGrail's group worked on possible MOHC's for increasing the heat capacity of supercritical CO2. Though some of that work depended on capturing formation water and will not be appropriate in the closed-loop technology, Dr. McGrail has mentioned to us that some other MOHC's they have investigated reversibly bind CO2 and may be useful in the closed-loop context. Nevertheless, the reviewers' comments were highly negative with respect to continuing this effort; we believe that it is not critical to the closed-loop process and have not included MOHC's in the revised SOPO.

Finally, the restructuring of GreenFire from an LLC to a C-corporation and bringing to the company a CEO with experience in starting, funding, and growing startup companies, and the new closed-loop technology (which is far easier than CO2-EGS for investors to

understand) have made GreenFire a much more desirable entity to potential investors. This will make both cost share and commercialization much easier to attain.

Modified SOPO for Phase II

General Comments: The modifications we propose in the Phase II SOPO reflect what we learned in working on Phase I. In particular, we have developed a new CO_2-based geothermal technology (Convective Cycle CO2G™) that replaces the percolation of CO2 through the formation rock with a simple pipe run, making the entire system a closed loop. To assure good long-term performance, the geologic formation through which the CO2 pipe is passed must contain hot water, which can move through the rock convectively. A schematic diagram of the system is attached as Appendix M.

Overall, such a system has a number of signal advantages:

- Existing, proven technology from the oil and gas industry is used to do both vertical (for the injection and production wells) and horizontal (for the horizontal run through the formation) pipe runs.
- No fracturing or pressure shearing is necessary, eliminating the risk of induced seismicity.
- Because no fracturing or pressure shearing is necessary, this will decrease net project cost.
- No water is consumed in any part of the operation, assuming air cooling in the power plant.
- The CO_2 no longer has any contact with formation rock, eliminating formation changes with time and eliminating deposition of dissolved material on process equipment.
- Due to a lowered injection pressure, the system will generate more power.
- Because of the decreased pressure drop through the horizontal part of the cycle, the SCO2 thermosiphon will be easier to start and maintain.
- The risks of CO_2 loss from the system are nearly eliminated; this has several favorable consequences, including easier and faster permitting, and greatly improved economics.
- Because the system is nearly independent of formation geology, it will be easy to replicate successful performance in many locations; all that is required is a formation containing convectively-heated hot water.

The modified SOPO incorporates the steps necessary to demonstrate this new closed-loop technology at a site in the Imperial Valley of Southern California. At this site, we plan to connect two existing wells at a distance of approximately 3,600 feet with a horizontal pipe run. The loop will be completed with a surface pipe between the two wells. For testing purposes, the surface power system will be simulated by an orifice plate to give a pressure

drop identical to the CO_2 turbine that will eventually be installed. Using the orifice plate is a very inexpensive and elegant way to test every part of the system except the power plant. Since CO_2 turbines are only beginning to come into commercial use, this is a prudent and logical step.

Phase II – New SOPO

Because Phase II of the project has been extensively changed, the SOPO for Phase II has been completely rewritten, to reflect the differences in site and technology. However, the goal of the project as a whole remains the same: to demonstrate the validity of using supercritical CO2 as a heat-transfer medium in geothermal power production.

In a perfect world, the preferred site for testing closed-loop SCO2 geothermal would feature a shallow, high temperature, highly permeable, water-saturated zone – exactly what all geothermal projects would prefer, actually. The perfect site would also have a number of recently drilled wells into the formation's hottest zone, and the company that drilled those wells would allow us to use them at low or no cost for our project. Also, the permitting process should be easy; in fact, it would be best if the wells themselves were already permitted for geothermal power production and the (usually difficult) environmental requirements had already been satisfied for the site.

In the real world, the Orita site satisfies many of these requirements: we have negotiated with Ram Energy to use, at no cost to us, two of the wells they drilled in 2010-2011 for our project. Those wells are about 3,600' apart, exactly what we had hoped. More importantly, the drilling records and well logs are available (we attached copies with our latest batch of documents.) Having access to these wells saves $5 million to $10 million; we would be foolish not to take advantage of this boon.

The original Ram Energy Orita project was permitted with a Conditional Use Permit (CUP); our preliminary talks with Imperial County, the permitting agency, suggest that we will also get a CUP and that the timeline will be short because of the existing permit.

We will use directional drilling starting from each of the two existing wells and meeting in the center to establish the loop. The temperatures are certainly high enough (> 200°C) and the formation is water saturated.

The biggest deviation from our idea of perfection is that the permeability is lower than we would prefer. Stimulation may provide the range of permeability we would like, but would raise the project cost substantially beyond what we can afford at this time.

Even without higher permeability, we believe that we will be able to test the thermosiphon and demonstrate the general idea of closed-loop geothermal at Orita. Using an orifice plate rather than a turbine will save at least $1 million and perhaps a year in lead time. Admittedly,

the loss in temperature through an orifice plate will not be as high as it would through a turbine, but it should be enough to allow the thermosiphon to develop and to demonstrate the concept. We have designed in a connection for additional cooling at the exit of the orifice plate, if necessary. An air cooler would be sufficient (rather than a water cooling tower) because of CO2's far lower heat capacity compared to water, and because we will not allow the SCO2 to leave the supercritical state, unlike water, where much of the heat removed is due to the necessity for the vapor-liquid phase change.

Overall, the existence of the two completed wells at Orita coupled with a generally favorable geologic situation makes Orita a reasonable site for proving the concept of closed-loop geothermal energy using CO2 as the working fluid.

Note that Old Task 12, "Inject and test the effect of MOHC's," is not included in this revised SOPO. In the original Task 12, it was assumed that MOHC's would function basically by removing water from the system, gaining heat through the heat of reaction as MOHC molecules absorbed the formation water. In the power production unit, the water would be desorbed, giving up that energy. Since the new closed-loop system does not allow contact of the circulating CO_2 with formation water, that part of the action of the MOHC's is irrelevant. In agreement with the comments of the DOE technical reviewers, this Task will not be carried through into Phase II.

New Task 7.0 – Obtain appropriate permits

Task definition: GreenFire will obtain all required permits, including:

- *Conditional Use Permits* for both above- and below-ground activities
- A *CEQA Negative Declaration* (in lieu of an Environmental Impact Report)
- Authority to Construct for the project as a whole

and will file a *Notice of Intent to Drill Geothermal Well*

All of these permits will be obtained through the appropriate permitting agencies, in this case, Imperial County and the Imperial County Air Pollution Control District

Comments: Table I below shows the permits that are required for this project and the permitting agencies involved.

Table I
Permits Required

Permit required	Permitting agency[3]
Conditional Use Permit (for well drilling)	Imperial County[1]
Conditional Use Permit (non-well activities)	Imperial County
CA Environmental Quality Act Initial Study/ Negative Declaration	Imperial County[2]
Authority to Construct	Imperial County Air Pollution Control District Imperial (APCD)
Notice of Intent to Drill Geothermal Well[3]	CA Div. of Oil, Gas, and Geothermal Resources (DOGGR)[2]

1 – In Imperial County, due to the county's experience with geothermal, the CA Division of Oil, Gas, and Geothermal Resources (DOGGR) delegates CA Environmental Quality Act (CEQA) matters to the county.
2 – For geothermal projects, California EPA delegates CEQA authority to DOGGR, hence to Imperial County.
3 – Two separate permits will be required for this project, since we will be commencing directional drilling from two different wells.

It is noteworthy that the Ram Energy project whose wells and wellpads we will be using was given Conditional Use Permits and a Negative Declaration under CEQA: in essence, this project has already been given the appropriate permits. Because of their familiarity with the area, the existing permits, and the straightforward nature of our project, our discussions with Imperial County suggest that the entire permitting process for our project should take as little as four months and about $50,000 to $100,000.

New Task 8.0 – Horizontal drilling from existing wells to form loop

Task definition: GreenFire will use directional drilling techniques from the oil and gas industry to complete a horizontal well connecting Orita Well #3 and Orita Well #4.

Comments: The purpose of this task is to put in place the underground portion of the loop through which the supercritical CO2 will flow. The overall goal is to build a continuous closed loop of pipe from the top of the injection well (Orita #3) to the top of the production well (Orita #4.) Intermediate objectives involve discreet steps in the plan to accomplish the goal.

Though it is little used in geothermal fields,[29] horizontal drilling is well known as the basis for the recent oil and gas boom in shale formations. The process of connecting wells via horizontal drilling, while much less common, is well-known in the oil and gas industry.

[29] Though DOE has funded research in directional drilling for geothermal applications, like DE-EE0002782, to Baker Hughes Oilfield Applications.

The first example of such work seems to have been in 2005,[30] though the technology has been rapidly evolving and improving.

The bulk of the work of this task will be accomplished by a yet-to-be determined drilling subcontractor superintended by Capuano Engineering, with special assistance in horizontal drilling from Scientific Drilling International, which has developed its own method of connecting wells via directional drilling. Letters of support from the latter two firms are attached as Appendices C and D, respectively.

Briefly, the major conceptual steps[31] involved are:

- Prepare both locations for drilling
- Enter the Orita #3 well and seal off the bottom part (e.g., below about 9,000')
- Start the directional drilling in the direction of the Orita #4 well, then drill to horizontal and continue drilling about halfway to the Orita #4 well.
- Insert a sounding device into the Orita #3 well at total depth.
- Enter the Orita #4 well, seal off at 9000', as with the Orita #3 well.
- Start the directional drilling toward the Orita #3 well, then drill to horizontal and drill toward the #3 well until the wellbore is directly above the sounding device.
- Remove the sounding device and drill to connect the two wellbores.
- Run a 7" casing through the bores from each well, after putting a slightly larger sleeve on one of the casings. When the two meet, make sure both casings go into the sleeve. Put several thousand pounds of weight on the junction to seal it.

Important outputs from this task include drilling reports and well logs for each well, test reports from the blowout preventer stacks on each of the wells. The drilling reports and well logs will be shared with the National Geothermal Data Service.

Note also that we intend to lay down along the horizontal run a fiber optic sensor to deliver temperature and pressure data than can be used as the starting information for various modeling studies on heat flow, etc.

New Task 9.0 – Design and construct surface equipment

Task Definition: GreenFire will design and construct surface equipment to inject, control, and monitor SCO2 behavior in the system.

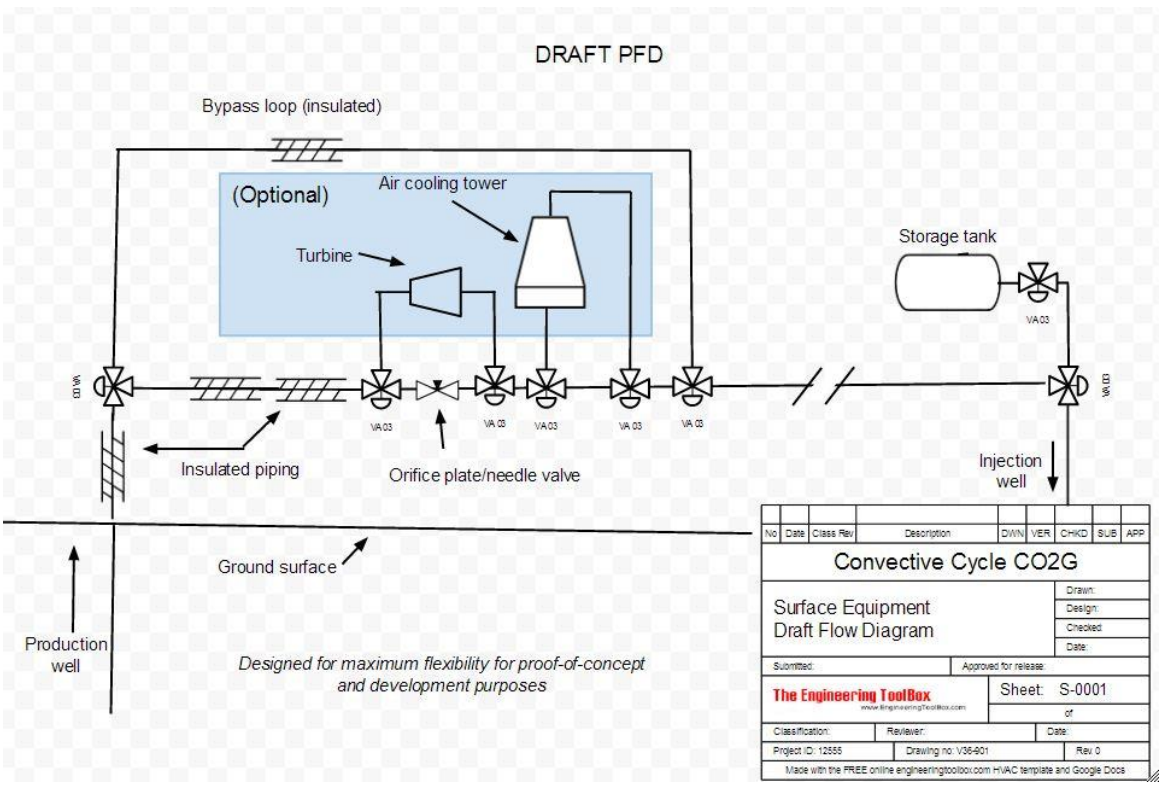
Comments: In addition to the underground part of the loop system, there must be surface equipment to put the SCO2 into the loop and measure the temperatures, pressures, and flow rate of the SCO2 as it passes through the loop and as energy is taken from the heated SCO2 to produce power or simulate power production in the orifice plate. The purpose of

[30] Lee, D., Hay, R., and Brandao, F.,**First U-Tube Well Connects Horizontal Wells**, Drilling Contractor, Sept/Oct 2005, 71-77.
[31] The detailed procedure involves 44 steps; for the sake of clarity, we have summarized them here.

this task is to design and build such a system. The goal is to build a surface facility that provides for introduction of SCO2 into the system at desired pressures, gives useful information on the fluid dynamics and thermodynamics of the flowing SCO2, and is flexible enough to allow modification as required. For example, it may be necessary to include a cooling tower, or to insert a turbine in place of the orifice plate, so such capabilities must be designed into the facility. A conceptual flow diagram of such a system is shown below as Figure 6.

Figure 6

Conceptual Flow Diagram for Surface Facility



Because of its importance to the project, designing the orifice plate has been given a separate task. However, the design of the surface facility must consider the size and flanging requirements for both a power turbine and an orifice plate and either make accomodations for replacing the orifice plate with a turbine at a later time, or include valving to do so, as shown in Figure 6.

Intermediate objectives in the present task involve the steps in designing and constructing the facility, including:

- Obtain rights to build at either Orita #3 or Orita #4, preferably #4, since that will be the production well through which the hottest, highest-pressure SCO2 will be available. A product here will be a signed lease or other permission to use the property.
- Using the preliminary flow diagram of Figure 6 and using calculations of the temperature, flowrate, and pressure of the produced SCO2, design a piping and valve scheme to allow for movement of the SCO2 through the system and monitoring the temperature, pressure, and flowrate at important locations.

Products for this part of the task include:

- A list of supplies and equipment needed, with cost estimates
- A final flow diagram, including estimated temperatures, pressures, and flow rates at important locations
- A complete piping and instrumentation diagram (P&ID), showing the interconnection of process equipment and the instrumentation used to control the process. The symbols used in the drawings should be based on International Society of Automation (ISA) Standard S5. 1.
- A floor plan of the facility and the ground on which it will be installed
- A plan and cost estimate for the building
- A list of the utilities required at the building
- A hazard and operability (HAZOP) study.
- A draft operating manual

It is planned that this design work will be done through our subcontractor, Capuano Engineering. The actual construction will be contracted to local contractors to be chosen later and timed so that construction will be done as close as possible to the end of the drilling process.

New Task 10.0 – Design and install orifice plate

Task definition: GreenFire will design and install an orifice plate to accurately simulate the pressure drop expected from a turbine. It is understood that the temperature loss will not be an accurate simulation of a turbine.

Comments: The purpose of this task is to specify, order, and install an orifice plate in the surface equipment. Using an orifice plate rather than a turbine will save about a million dollars and perhaps a year in lead time. The orifice plate will be made to fit between flanges engineered into the surface facilities described in Task 9. Note: a question has been raised as to whether the flow of CO2 through an orifice plate will provide the cooling required for circulation of the CO2. Admittedly, the loss in temperature through an orifice plate will not be as high as it would through a turbine, but it should be enough to allow the thermosiphon to develop and to demonstrate the concept. We have designed in a

connection for additional cooling at the exit of the orifice plate, if necessary. An air cooler would be sufficient (rather than a water cooling tower) because of CO2's far lower heat capacity compared to water, and because we will not allow the SCO2 to leave the supercritical state, unlike water, where much of the heat removal requirement can be ascribed to the required vapor-liquid phase change.

This task will produce a specification diagram/document for an appropriate orifice plate, and the orifice plate itself. Obviously, the specification document will be used to order the plate from a suitable manufacturer to be chosen locally; a local shop can probably be used because the manufacturing process is likely to be relatively simple. The plate itself will be installed in the surface equipment.

We recommend that a Go/No-Go Meeting be held at the end of this step to ascertain readiness to proceed to Task 11.

New Task 11.0 – Load system, test the thermosiphon and orifice plate

Task definition: GreenFire will load CO2 into the system, bring it to the supercritical state, test the starting and running properties of the thermosiphon, and observe the behavior of the system through the orifice plate. As part of the process, we will also pressure-test the system for leaks, measuring any leakage. From the pressures and temperatures on either side of the orifice plate, we will assess the power generation capability of the system. From measurements of pressure, temperatures, and flowrates over multiple weeks of operation, we will assess the amount of heat loss in the formation, permitting an estimate of thermal depletion time.

Comments: The purpose of this task is to ascertain the performance of the loop system in several key areas:

- Test of piping integrity by pressurizing with air and repair of any leaks found
- Ability to load CO2 into the system
- Establishment and operation of the thermosiphon
- Correct operation of the monitoring systems
- Ability to heat CO2 as it passes through the system
- Simulation of power generation by the orifice plate

The project goal is that all of these areas operate successfully. The objective of the task is virtually the same as the entire task objective: to successfully simulated power producting using the loop system in a convective environment.

Achievement of the goal and objective will require that testing proceed for a reasonable time period, preferably 3-6 months. During that time, the system will be run at various flow rates, etc., to establish the optimum results as measured by calculated energy production at the orifice plate. The temperature of the SCO2 at 1) the beginning and 2) the

end of the injection well, and 3) the top and 4) the bottom of the production well will be plotted to determine how much thermal depletion, if any, is occuring in the reservoir.

There will be a number of products from this task:

- A report of system behavior under static pressure, assuring system integrity or measuing the leakage rate through any leaks.
- A report showing the amount of SCO2 added to the system, and monitoring the startup of the thermosiphon
- Reports showing flow rates of the SCO2 in the system, plus the temperatures and pressures at various points.
- A report showing the calculation of approximate power potential in the loop, given the temperature, pressure, and flow rates on either side of the orifice plate.
- A report showing temperature vs time plots for the four locations noted above.

New Task 12.0 – Project management and reporting

Task definition: GreenFire will manage the project in accordance with DOE regulations and practices, making sure that project goals are met. GreenFire will also submit all required reports, including those at the normal quarterly intervals. GreenFire will also share appropriate data with the NGDS national data system.

Comments: The purpose of this task is simple: to assure that all aspects of the project are carried out in compliance with DOE procedures, and to make sure that the project goals are met. This purpose leads to the following objectives and goals:

- Make sure that all procedures (including financial and technical record keeping) are followed
- Produce periodic progress reports, plus reports at critical project landmarks, including at the end of the project

New Task 13.0 – Build and maintain good community relations

Task definition: GreenFire will build and maintain good relations with the Imperial Valley community, its citizens, institutions, and stakeholders.

Comments: The purpose of this task is to inform local citizens, citizens' groups, and governmental jurisdictions of the aims and progress of the project. GreenFire personnel will make themselves available to local media, and will establish good relationship with reporters. GreenFire will also develop informational materials on subjects such as safety practices at the project site, the technology employed, the benefits of the technology to the Imperial Valley and the country as a whole. GreenFire will also prepare a plan of action to meet potential safety problems and limit the effects of such potential problems on the project and the community.

Several products will emerge from this effort:

- Informational packets on subjects such as project safety, technology, the benefits of the technology, and progress at the site
- Power Point presentations on the project that can be delivered to local civic groups
- Press releases on project progress, as warranted

Request and Recommendation – Proceed with Phase II

We have the opportunity to develop a new technology that has substantial advantages over CO2-EGS:

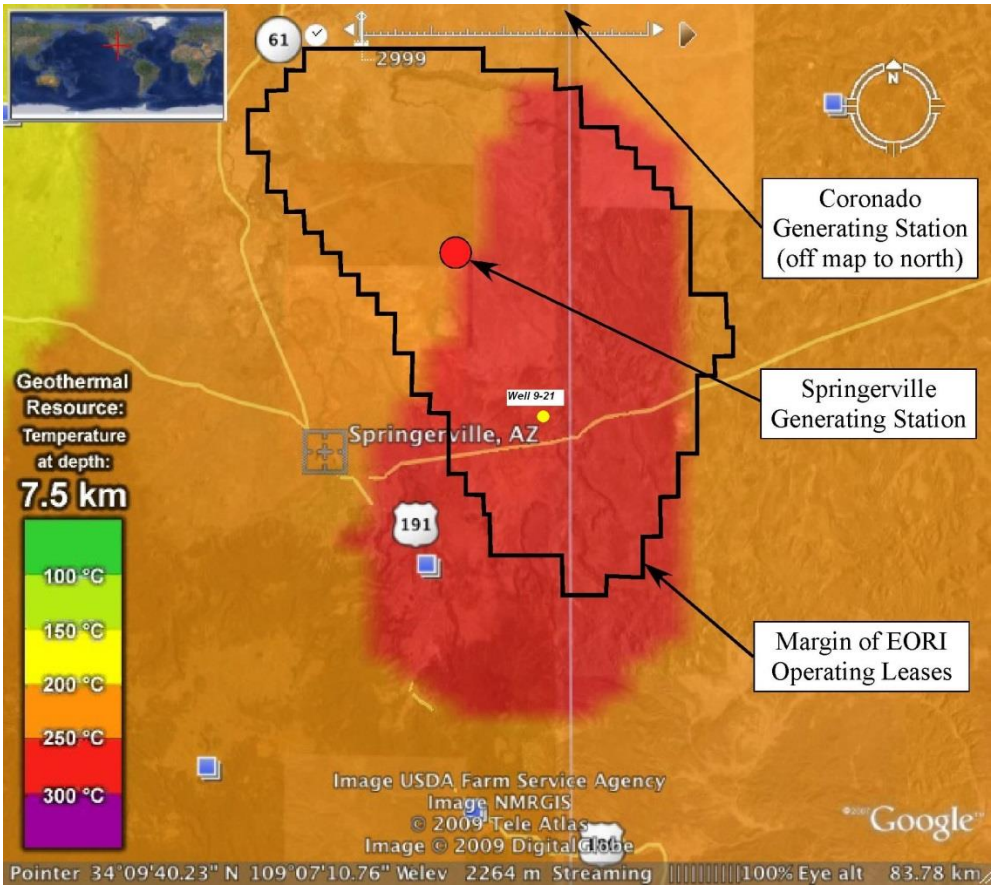
- No contact between CO2 and formation minerals
- No contamination of aquifers with CO2 (or vice-versa)
- Rather than a single-well huff-and-puff well, it will be possible to develop an entire circulating system for the same expenditure
- Permitting will be much easier and faster in the Imperial Valley, since they already are comfortable with geothermal projects and all permits go through one office
- No fracturing or pressure shearing is necessary
- No water is consumed, except in drilling and (if necessary) stimulation

Given these advantages and the substantial completion of our Phase I tasks, we respectfully request that we be allowed to transfer our Phase II DOE funding under Grant DE-EE-0004432 to our project in the Imperial Valley of California.

Section III - Appendices

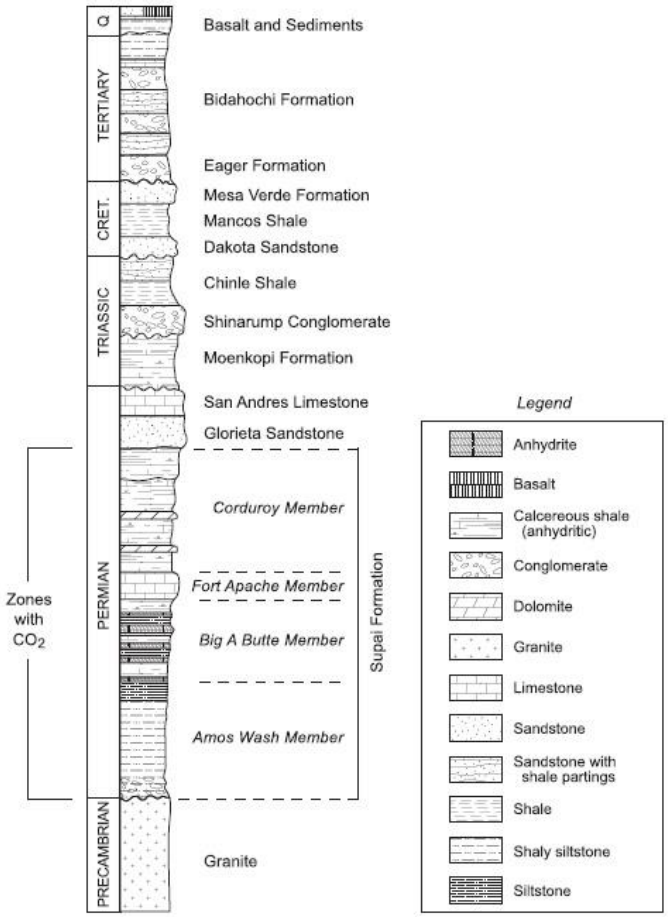
Appendix A

Map of Well 9-21



Appendix B

Geologic Section of St. Johns Dome



Appendix C

Expenditures by Phase

Period	DOE Amount	Cost Share	TOTAL
Phase I actual	$343,590	$128,732	$473,322
Phase II est.	$1,565,410	$5,434,590	$7,000,000

Appendix D

Wells Drilled at the St. Johns Dome

From Arizona Well Location Map and Report, AZ OGCC, OG-12, 2009

Sorted by Date and Operator

Permit	N Twp	E Rge	Sec	Loc	Operator	Lease & No.	Date	Status[1]	Spls[2]	Elev.	at[3]	T.D.	Formation at Total Depth
1-03	13	27	28	NW NE	Rincon Syndicate	1 State	1939/08	D	N/A	5970	GL	498	Permian Kaibab
66	9	31	20	SE NW	Belcher, Mae	1 State	1959/06	D	1664	7274	DF	2921	Precambrian Granite
76	12	23	25	SW NE	Pan American Petr.	1NMAL-B	1959/06	D	375	6253	KB	4497	Precambrian metamorphic
98	13	25	12	SE SE	Pan American Petr.	1 NMAL-A	1959/09	D	372	5888	KB	3680	Precambrian metamorphic
100	12	31	9	NE NW	Townsend Oil	1 Vaughn-Fed.	1959/12	D	N/A	6258	GL	585	Permian Coconino
199-1	8	28	6	NW NE	Cities Service	04 State	1962/06	S	N/A	7674	GL	976	Cretaceous
187	10	30	27	SW NE	Eastern Petroleum	1 Coyote Creek	1962/06	JA	N/A	6975	GL	476	Permian Coconino
199-2	8	28	15	SW NW	Cities Service	202 Hall	1962/07	S	N/A	7324	GL	1186	Cretaceous Dakota
197	9	27	22	SW SW	Cities Service	201 J. Coulter	1962/07	S	N/A	712	GL	1353	Cretaceous
200-1	10	25	2	SW SE	Cities Service	204 State	1962/07	S	N/A	6689	GL	287	Tertiary Eagar?
200-2	10	25	2	SW NE	Cities Service	240A State	1962/07	S	N/A	6744	GL	637	Permian Glorieta?
1-01	9	27	26	SE SE	Cities Service	203 State	1962/08	S	N/A	7681	GL	1193	Cretaceous
198-2	9	27	34	NW NW	Cities Service	13 State	1962/08	S	N/A	7671	GL	1230	Cretaceous Dakota
201-2	9	27	35	SW SW	Cities Service	10 State	1962/08	S	N/A	7800	GL	428	Cretaceous basalt
207	10	30	27	SW NE	Eastern Petroleum	1A Coyote Creek	1962/09	D	N/A	6975	GL	2351	Precambrian Granite
159	11	31	29	SE SE	Ram Oil	1 State	1963/02	D	N/A	7090	GL	830	Permain Coconino?
370	10	24	4	SW NE	Tenneco Oil	1 Federal-B	1967/01	D	N/A	6865	KB	4657	Precambrian Schist
371	10	30	26	SW SW	Tenneco Oil	1 Merrill	1967/02	D	N/A	7033	KB	1577	Permian Supai
375	11	28	22	SE NW	Tenneco Oil	1 Federal-C	1967/02	D	1383	6064	KB	1687	Permian Supai
827	5	30	22	SE SE	Phillips Petroleum	A-10 Federal	1982/11	TP	N/A	8730	GL	505	Tertiary Datil?
826	5	31	5	NW SE	Phillips Petroleum	A-09 Federal	1982/11	TP	N/A	8310	GL	345	Tertiary basalt
828	5	31	34	SW SW	Phillips Petroleum	A-11 Federal	1982/11	TP	N/A	7715	GL	480	Tertiary basalt
825	6	29	36	SE NE	Phillips Petroleum	A-08 Federal	1982/11	TP	N/A	8890	GL	425	Tertiary basalt
824	6	31	4	NE NE	Phillips Petroleum	A-07 Federal	1982/11	TP	N/A	8855	GL	340	Tertiary basalt
823	7	27	15	SE NE	Phillips Petroleum	A-06 Federal	1982/11	TP	N/A	9082	GL	325	Tertiary basalt
828	8	27	15	SE SW	Phillips Petroleum	A-01 Federal	1982/11	TP	N/A	8393	GL	335	Tertiary basalt
819	8	28	27	SE NW	Phillips Petroleum	A-02 Federal	1982/11	TP	N/A	8370	GL	90	Tertiary basalt
820	8	29	21	NE NE	Phillips Petroleum	A-03 Federal	1982/11	TP	N/A	7422	GL	480	Tertiary Datil?
821	8	30	35	SW NW	Phillips Petroleum	A-04 Federal	1982/11	TP	N/A	7833	GL	505	Tertiary Datil?
822	8	31	15	NE SW	Phillips Petroleum	A-05 Federal	1982/11	TP	N/A	7394	GL	501	Tertiary Datil?
835	11	22	29	SW SW	Ridgeway AZ	1 Federal	1983/03	D	1853	6300	GL	4155	Precambrian Granite
836	12	26	17	NW NW	Sumatra Energy	1-17 Santa Fe	1983/03	D	1850	6410	GL	4143	Precambrian
855	12	28	28	NE NW	Combined Drilling	1-A State	1986/04	JA	N/A	6090	GL	160	Permian Kaibab
861	10	28	36	SE SE	Salt Grass	A-1 State	1986/10	D	1861	6706	GL	1072	Permain Supai
862	12	28	28	NE NW	Combined Drilling	1-B State	1987/02	D	1864	6096	KB	3296	Precambrian?
878	6	30	23	NW SW	Tonto Drilling Serv	1 Alpine-Fed	1993/08	TD	1875	8556	GL	4505	Permian Supai
880	12	29	15	NE SW	Ridgeway AZ	1 Plateau Catl	1994/08	D	1877	6372	GL	2431	Precambrian Granite
883	12	29	15	NE SW	Ridgeway AZ	1A Plateau Catl	1994/11	D	N/A	6372	GL	220	Permian San Andres
885	12	29	22	NW NW	Ridgeway AZ	22-01 State	1995/08	JA	1881	6338	GL	218	Permian San Andres
884	11	29	3	NE SE	Ridgeway AZ	03-01 State	1995/09	D	1880	6726	GL	1813	Permian Supai
888	12	29	22	SE NW	Ridgeway AZ	22-01x State	1997/02	TA	1893	6393	GL	2149	Precambrian Granite
897	9	31	21	NW NE	Ridgeway AZ	09-21 State	1997/03	TA	1884	7198	GL	2686	Precambrian Schist
896	10	30	22	SW SW	Ridgeway AZ	10-22 State	1997/03	GS	1886	6978	GL	2265	Precambrian Granite
895	11	30	21	NE SW	Ridgeway AZ	11-21 State	1997/03	TA	1894	6918	GL	2410	Precambrian Granite
898	9	29	22	SW SE	Ridgeway AZ	09-22-29 State	1997/04	D	1885	7178	GL	6180	Precambrian Granite
903	10	29	26	NW SW	Ridgeway AZ	10-26-29 State	1997/05	D	1887	6932	GL	3200	Precambrian Granite
899	10	31	16	NE SW	Ridgeway AZ	10-16-31 State	1997/05	D	1888	7246	GL	2728	Precambrian Granite
902	12	28	16	NW NE	Ridgeway AZ	12-16-28 State	1997/05	D	1891	5988	GL	2280	Permian Supai
900	12	30	15	NE SW	Ridgeway AZ	12-15-30 State	1997/05	TA	1889	6712	GL	2603	Precambrian Granite
901	13	29	36	SW NE	Ridgeway AZ	13-36-29 State	1997/05	D	1890	6167	GL	2454	Precambrian Granite
904	15	29	28	NE NW	Ridgeway AZ	15-28-29 State	1997-06	D	1892	5695	GL	2264	Precambrian Granite
916	11	30	18	C SW	Ridgeway AZ	11-18 State	2004/05	TA	N/A	6842	GL	2535	Precambrian Granite
934	12	26	17	NE EN	High Plains Petr.	17-1 Santa Fe	2006/10	-	N/A	6359	GL	4032	Precambrian Granite
945	11	29	24	SW NE	Ridgeway AZ	11-24-29 State	2007/02	TA	1913	6778	GL	1906	Permian Supai
938	11	30	29	SE NW	Ridgeway AZ	11-29-30 State	2007/02	TA	1911	6920	GL	1906	Permian Supai
937	11	30	16	NW SE	Ridgeway AZ	11-16-30 State	2007/03	TA	1912	6889	GL	2377	Precambrian Granite
946	11	30	32	C SE	Ridgeway AZ	11-32-30 State	2007/03	TA	1914	6945	GL	1690	Permian Supai
939	11	31	6	NW SE	Ridgeway AZ	11-06-31 State	2007/04	TA	1918	6912	GL	2711	Precambrian Granite
940	11	31	7	NW SE	Ridgeway AZ	11-07-31 State	2007/04	TA	915	6948	GL	1885	Permian Supai
941	11	31	18	NW SE	Ridgeway AZ	11-18-31 State	2007/04	TA	1917	6947	GL	2035	Permian Supai
943	11	31	29	SE NW	Ridgeway AZ	11-29-31 State	2007/05	TA	N/A	7034	GL	2850	Precambrian Granite
944	11	31	32	NE SW	Ridgeway AZ	11-32-31 State	2007/05	TA	1919	7144	GL	2900	Precambrian Granite
947	12	31	32	NE SW	Ridgeway AZ	12-32-31 State	2007/05	TA	N/A	6906	GL	85	Permian Supai

950	10	30	2	SW NE	Ridgeway AZ	10-02-30 State	2008/02	TA	N/A	7069	GL	2650	Permain Supai
953	10	30	2	SW NE	Ridgeway AZ	10-02-30x State	2008/02	TA	N/A	7069	GL	1899	Permian Supai
964	10	30	5	NW NW	Ridgeway AZ	10-05-30 State	2008/02	TA	N/A	6981	GL	2600	Permian Supai
942	11	31	20	SE NW	Ridgeway AZ	11-20-31 State	2008/02	JA	1916	6993	GL	1934	Permian Supai
948	12	29	34	NW NE	Ridgeway AZ	12-34-29 State	2008/02	JA	1920	6555	GL	1140	Permian Supai
954	12	29	34	NW NE	Ridgeway AZ	12-34-29x State	2008/02	TA	N/A	6555	GL	3048	Precambrian Granite
959	10	31	29	SW NE	Ridgeway AZ	10-29-31 State	2008/03	TA	1923	7310	GL	4202	Precambrian Granite
955	11	31	29	SE NW	Ridgeway AZ	11-29-31x State	2008/03	TA	N/A	7033	GL	1909	Permian Supai
956	12	30	31	SE NW	Ridgeway AZ	12-31-30 State	2008/03	TA	1921	6667	GL	2814	Permian Supai
957	12	30	31	SE NW	Ridgeway AZ	12-31-30x State	2008/03	TA	1922	6675	GL	2622	Permian Supai
962	9	31	5	NW SE	Ridgeway AZ	09-05-31 State	2008/04	TA	N/A	7382	GL	122	Tertiary
970	11	29	24	SW NE	Ridgeway AZ	11-24-19x State	2008/04	TA	N/A	6778	GL	2137	Permian Supai
966	11	30	23	NW NE	Ridgeway AZ	11-23-30 State	2008/04	TA	N/A	6979	GL	2550	Precambrian Granite
963	9	31	5	NW SE	Ridgeway AZ	09-05-3x State	2008/05	TA	N/A	7382	GL	2969	Precambrian Granite
979	11	29	3	NE SE	Ridgeway AZ	11-03-29x State	2009/03	TA	N/A	6726	GL	80	?

Notes:			
1	**Status:**	D	Dry hole
		GS	Gas well, shut in
		JA	Test hole, junked and abandoned
		S	Stratigraphic test
		TA	Test well, temporarily abandoned
2	**Spls:**		Indicates the number of the box where samples are stored in the OGCC storage
3	**at:**	DF	The drilling floor
		GL	Ground level
		KB	The Kelly bushing

Appendix E

Review Paper

CO2-Based Geothermal Energy

- a Review of Work to Date

Alan D. Eastman, GreenFire Energy

For presentation at the Geothermal Resources Council 35th Annual Meeting, 23-26 October 2011

Abstract

Geothermal energy for electricity production has a long and complicated history, but until recently water was the only fluid seriously considered as a heat carrier. In the last few years, however, a number of researchers around the world have begun to investigate the possibility of using supercritical CO_2 instead of water, especially in Enhanced Geothermal System (EGS) applications. No commercial power plants currently use CO_2; that may be changing, however, as one startup company (GreenFire Energy) has received DOE funding to test just that possibility. This paper is an attempt to bring what is known (and some of what has been speculated) about CO_2-based geothermal energy production together in a single place, drawing upon the usual literature sources, including also the worldwide patent literature.

Introduction- the Geothermal World: Water vs. CO_2

This paper will deal only with the use of geothermal heat to produce electrical or mechanical energy; the literature survey of this paper is current to mid-July 2011. However, in addition to its use as a heat carrier for geothermal energy, there is an extensive literature concerning sequestration of CO_2 in geologic formations; bibliography that constitutes a useful introduction to that area can be found in Reference 1.

Conventional geothermal energy requires four components:

1. hot rock,
2. water in contact with that rock,
3. permeability in the rock so that the water can be moved to the surface,
4. some type of equipment to convert the heat in the water to electricity.

Water is the conventional geothermal heat-carrying fluid for several reasons:

1. Water is ubiquitous underground; most rock formations contain at least some water, and even more contain water in hydrated minerals.
2. Water has a high heat capacity, allowing a relatively small volume of water to carry a large amount of heat.
3. Because water is already used as steam in many conventional schemes for electrical energy production, the equipment necessary is already available at commercial scale.
4. The long history of steam-based power production means that the equipment has been optimized; virtually all economies of scale have already been realized.

On the other hand, water also has some conspicuous disadvantages.

1. Water is quite reactive under formation temperatures and pressures; it readily dissolves many minerals (especially in the presence of such acid gases as CO_2 and H_2S), and can be incorporated into the crystal structures of many minerals. For example, granite can be and often is transformed to clay under geothermal conditions. Recent problems at The Geysers field in California are due to exactly this tendency.
2. Water is fairly dense, so it can take a lot of energy to pump it around. This is a particularly important factor as the depth of the geothermal deposit increases.
3. Water's surface tension is fairly high, and increases the energy required for pumping.
4. Water's high heat capacity also means that it take significant energy to turn water to steam; at conditions of moderate heat, a substantial proportion of the energy carried by the water will be used for this phase transition and is therefore not available for energy production.
5. Most formation water is saline, and must be treated before it can be used for geothermal energy.

Water is not the only possible heat-carrying fluid that could be used for geothermal energy. Carbon dioxide, in particular, has several advantages.

1. Like water, CO_2 is found underground both as a constituent part of minerals (notably carbonates), and as a pure substance.
2. CO_2's low viscosity and density render it easy to move from one place to another, both above and below ground level.
3. Much of the hot rock in the US is in the West, as shown in Figure 1; unfortunately, the West is the driest area of the country. Many large natural CO_2 deposits and a number of large fossil-fuel fired power plants are located in the West, as shown in Figure 2, and could conceivably furnish CO_2 for CO_2-based geothermal projects.
4. CO_2 is not generally as reactive to minerals as water, and the products of carbonylation tend to be less troublesome geologically than the products of hydration. Compare, for example, the effects of porosity and permeability of carbonates and clays.

Carbon dioxide also has some significant disadvantages:

1. CO_2's heat capacity is only about a fifth that of water; see Table I for basic properties of CO_2.
2. Because CO_2's density is also much lower than water, it is necessary to use CO_2 in the supercritical or at least in the liquid state. Fortunately, CO_2's critical point is quite accessible, as shown in Figure 3.
3. Virtually all current geothermal heat-recovery equipment is designed for water, and will have to be re-engineered to work efficiently with CO_2.
4. Because of the effects of CO_2 release on climate change, it is undesirable to release CO_2 to the atmosphere during the heat-recovery process, so any CO_2-based geothermal projects must be cyclic in nature.

EGS – Enhanced Geothermal Systems (EGS)/Hot Dry Rocks

Conventional geothermal energy not only utilizes water, but the water must be at relatively shallow depths, usually less than 1000 feet below the surface. In order to access geothermal heat at greater depth - but where there is usually less water - there has been significant interest in the last twenty years in so-called "Enhanced Geothermal Systems," or EGS, also called "Hot Dry Rocks." In this concept, water is injected into a hot permeable rock formation, and the resulting hot water or steam used for energy production. A diagram of a typical EGS system is shown as Figure 4, and good summaries of recent progress are available.[2, 3, 10, and 11] A landmark study of the potential of EGS in the United States was performed at MIT in 2006.[5]

Problems with water-based EGS; solutions with CO_2

Unfortunately, as pointed out earlier, the locations of hot dry rock and availability of large quantities of water do not often coincide, especially in the US West. Also, most hot dry rock is fairly deep - Figure 1 shows temperatures at 6 km, for example – and water's density makes it very difficult to pump from any considerable depth.

On the other hand, the natural pressures of deep formations make it easy to keep CO_2 in the supercritical state. In addition, the density of supercritical CO_2 ($ScCO_2$) can change substantially with temperature, as shown in Table III, making it relatively simple to circulate, even at great depths. It is even theoretically possible to envisage a situation where the difference in density between hotter and cooler $ScCO_2$ is sufficient to set up a siphon, where pumping is not necessary to circulation. Numerous publications to be cited later discuss this phenomenon and its effects, notably a thermosiphon's profound effect on project economics.

Publications in the Field

With this background in mind, it is now feasible to investigate the literature in the field of CO_2-based geothermal energy, which we will take to be essentially synonymous with CO_2-based EGS. One firm in the area, GreenFire Energy, calls this CO_2G™; for simplicity, we shall use this abbreviation from now on.

Taking an overall look at the field, it is convenient to divide contributors into several main groups. The Visionary is Donald W. Brown, formerly of Los Alamos National Laboratory, who initially proposed CO_2G. Following the initial proposal, there has been a substantial amount of mathematical modeling by several different research groups, the Modelers. Some of the modeling contributors to the field do not fit well into any of the research groups, so they are considered separately. Finally, one startup company is attempting to take CO_2G from the lab and the computer out into the field, the Implementers. In general, as with any new technology, the process over time has been from the more abstract to the more concrete and from the laboratory to the field.

The Visionary

Donald W. Brown (Los Alamos National Laboratory)

Don Brown, now retired but formerly of Las Alamos National Laboratory, was among the first to suggest that CO_2 would be a good substitute for water in geothermal energy, and was certainly the first person to seriously consider using supercritical CO_2 in EGS systems. Brown was the principal investigator in the Fenton Hill (NV) EGS project, one of the most carefully undertaken of all EGS

projects in the world. His publications on that field[e.g., 7, 10, 11] constitute careful documentation of the results and suggestions for further research in the area.

As early as 2000, he suggested in a meeting that supercritical CO_2 would make a good substitute for water in EGS systems.[9] However, Brown filed for a patent entitled "Geothermal Energy Production with Supercritical Fluids" in 1999. The patent was awarded to him in 2003 and assigned to the Regents of the University of California, operators of the Los Alamos facility.

The Brown patent describes every significant aspect of CO_2-based geothermal energy, including use of CO_2 as a heat carrier and a fracturing fluid, plus the possibility of a CO_2 thermosiphon to reduce pumping costs. It is likely that any company wishing to operate in the United States will either have to obtain a license to use that patent's teachings or find some way around its provisions. There seem to be no foreign equivalents at this point, but consultation with a patent attorney would be prudent by anyone seeking to use this patent's technology anywhere in the world.

The Modelers

The setting for Brown's disclosure of his ideas was the 25th Workshop on Geothermal Reservoir Engineering, held at Stanford University in January 2000. That series of workshops, organized by Professor Roland Horne, currently the Thomas Davies Barrow Professor of Earth Sciences at Stanford, has been the primary site for disclosure and discussion of CO_2-based geothermal energy ever since. The workshops are held early each year and attract 150-200 of the key people in geothermal energy research worldwide. Virtually all of the work in CO_2G presented at the Stanford workshops has been computerized modeling, and most of the papers have come from relatively few research groups.

The Horne group (Stanford University)

Though he organizes the workshops where much CO_2G work has been presented, Horne's primary research interests are various aspects of reservoir engineering, notably modeling multiphase fluid flow in porous formations and inferential determination of various reservoir properties. However, some of his students have performed work germane to CO_2G. Wang and McClure performed interesting modeling studies[13, 14] of single-well EGS, and Pistone et al presented an interesting paper on CO_2 solubility in geothermal reservoirs.[12]

The Pruess/Xu group (Lawrence Berkeley National Laboratory)

If any one research group could claim predominance in modeling EGS systems in general and CO_2G in particular, it would be that of Karsten Pruess of Lawrence Berkeley National Laboratory's Earth Sciences Division, Hydrogeology Department. Pruess was recently elected to the US National Academy of Engineering; Tianfu Xu has been his chief collaborator for a number of years. Many research groups worldwide have adopted their modeling software programs. TOUGH and its later incarnation TOUGH2[37] are used to model multiphase fluid and heat flow through porous media. An expansion of the program, called TOUGHREACT, was developed by Pruess, Xu, and collaborators in 2006[35] to include fluid-rock interaction and is probably the most-used modeling program in the geothermal field.

The group has done a large amount of work[22, 30, 32, 36] modeling CO_2 injection into saline reservoirs, simulating CO_2 sequestration, including building a new module of the TOUGH2 program specifically to

study CO_2 storage in saline aquifers.[31] In 2006, Pruess published a very interesting paper[28] on what might happen in terms of fluid flow and heat transfer in the event of CO_2 leakage from a storage reservoir. Several of the papers have application to CO_2G, including a two-paper set that discusses solids precipitation and mitigation during injection[20] and develops a model for salt precipitation.[19]

As early as 2006, Pruess and group turned their attention to CO_2-based geothermal energy, starting with papers speculating that geothermal energy in general could be produced with simultaneous sequestration of the CO_2.[33, 34] Several more recent papers have discussed the possibility of combining EGS-based CO_2 geothermal energy with carbon sequestration.[17, 27]

A series of papers discussing fluid transport in geologic formations[23-26, 28] led to papers specifically on the behavior of CO_2 as a geothermal fluid. One of them[29] discusses in depth the way CO_2 might be produced from a geothermal well, while the other[29] proposes a model of how CO_2/brine mixtures might partition by phase in CO_2G systems.

Still more recently, the group has been adding geochemical reactions to the scope of their modeling studies, resulting in a very interesting series of papers[15-18] on fluid-rock interactions in EGS/CO_2 systems.

The Gurgenci group (University of Queensland)

Another very important group of modelers is headed by Professor Hal Gurgenci at the Queensland Geothermal Energy Centre, associated with the University of Queensland in Brisbane, Australia. Gurgenci has particularly been involved in modeling the potential technical and economic benefits of the thermosiphon possible with CO_2.[40-41, 43-45] A recent paper[38] summarizes their work in the area, looking at optimization of a CO_2-based EGS power plant. Papers from his group have also dealt with heat and fluid transport in geothermal reservoirs,[42] and, like the Pruess group,[20] with the very important topic of how long it would take to remove the water from a given reservoir by injecting CO_2.[39] Most of the papers dealing with CO_2G have been co-authored by graduate student Aleks Atrens.

The Saar group (University of Minnesota)

The group headed by Professor Martin Saar, Associate Professor and Gibson Chair of Hydrogeology and Geofluids in the Department of Earth Sciences at the University of Minnesota, has done a large amount of modeling. Their work is primarily on fluid flow through heterogeneous formations, and coupling of heat and mass transfer in geologic systems. In the context of this paper, their emphasis is combining CO_2 sequestration with the production of geothermal energy. All the published papers in this area have had graduate student J.B. Randolph as co-author.

Saar and Randolph's publications can be divided into four main groups. The first group (papers 47, 57-61) treats the coupling of carbon dioxide sequestration and geothermal energy capture. They range from papers detailing modeling efforts[59-60] to more general treatments. The second group concentrates on the impact of reservoir permeability on the energy transfer issues; papers include two comparing water/EGS with CO_2/EGS,[46,50] and one that is more general in nature.[53] There are two papers[52, 54] on how enhanced oil recovery using CO_2 can be coupled to geothermal energy. The last group[49, 51, 55] describes how a moving subterranean CO_2 plume can be used to produce energy in the absence of fracturing.

Finally, Saar and Randolph have filed a World Patent[56] entitled "Carbon Dioxide-based Geothermal Energy Generation Systems and Methods Related Thereto." It claims primarily the CO_2 plume described in the last group of papers as a source of geothermal energy without the necessity for fracturing.

Other modelers

The earliest papers (around 1980) in this group discussed using CO_2 to increase the buoyancy of geothermal water[72] and the effects of CO_2 and carbonate chemistry on geothermal engineering.[71] After a 20-year hiatus, a series of papers in 2003[69-71] from Mitsubishi and the Japanese Central Research Institute of the Electric Power Industry discussed the possibility of CO_2 sequestration in geothermal fields and the associated CO_2/water/rock interactions.

A 2004 paper[68] from the French Office of Geologic and Mining Research (Bureau de recherches géologique et minières) suggested that CO_2 sequestration be combined with EGS to generate enough power to offset much of the cost of the sequestration process.

In 2008, a group from Croatia published in Energija I Okoliš (Energy and the Environment) a paper[66] suggesting the use of CO_2 as a heat-transmission fluid in EGS systems.

A PhD thesis[65] in 2010 from the University of Utrecht discussed the feasibility of combining geothermal energy production and CO_2 storage, using CO_2 as the working fluid. Also from the Netherlands but from Delft University came a paper[63] presented at the 2011 Stanford Workshop modeling flow simulations during mixed CO_2/H_2O injection into the formation.

Brian Anderson's group at the University of West Virginia has started modeling CO_2G in conditions perhaps obtainable in that state. A 2010 paper[64] develops an integrated model to compare net electricity generation for water- and CO_2-based geothermal systems. This paper attempts to include many of the infrastructure components that are often omitted from other models and thus furnishes an extremely important starting place for "real-world" financial modeling.

Christopher White's group at Louisiana State University is modeling the use of CO_2 to stimulate geopressured geothermal reservoirs; one of his students gave a paper[62] on the subject at the 2011 Stanford Conference.

Finally, an anonymous poster has put a posting on the Internet entitled, "How Supercritical Binary Geothermal Power Plants Work." That page[65] basically cites the Brown patent.[8]

The Implementers

GreenFire Energy

GreenFire Energy is a startup company with the avowed goal of moving beyond modeling and actually attempting to implement CO_2G in the field. They have made presentations[75, 77] describing their vision of how CO_2G might work in the field, and how CO_2G could be combined with CO_2 sequestration.[76] They have also filed a US Patent application claiming processes to obtain both thermal and kinetic energy from a geothermal source using supercritical CO_2.[74]

At this point in time, GreenFire has yet to demonstrate successful power generation from geothermal heat using CO_2 as the working fluid. However, they received a grant[78] from the US Department of

Energy in late 2010 to test the concept, so it is reasonable to expect substantial progress in the next few years.

Others working toward commercialization

None so far.

Tables and Figures

Table I

Basic Physical Properties of Carbon Dioxide[4]

Property	Value	Units
CAS Number	124-38-9	-
Molecular weight	44.0095	-
$\Delta H_f°_{gas}$	-393.52	kJ/mol
$S°_{gas, 1 bar}$	213.79	kJ/mol
Critical point	309.25	K
	7.38	Mpa
Triple point	216.55	K
	517	kPa
$Sublimes_{1 atm}$	195	K
Solubility, $H_2O_{298 K, 100 kPa}$	1.45	g/L
$Density_{sol, 1 atm, -78.5°C}$	1.562	g/mL
$Density_{liq, 56 atm, 20°C}$	0.770	g/mL
$Density_{gas, 1 atm, 0°C}$	1.977	g/L

Table II

Density of Carbon Dioxide with Pressure and Temperature[4]

Pressure, psia	Temperature, °C					
	100	**150**	**200**	**250**	**300**	**350**
1000	7.3427	5.9763	5.1248	4.5204	4.0604	3.6945
1200	8.2518	6.6438	5.6703	4.9887	4.4740	4.0667
1400	10.1940	8.0189	6.7778	5.9325	5.3041	4.8118
1600	12.3150	9.4461	7.9062	6.8851	6.1374	5.5571
1800	14.6230	10.9230	9.0533	7.8450	6.9729	6.3022
2000	17.1080	12.4450	10.2170	8.8108	7.8097	7.0462
2200	19.7330	14.0060	11.3930	9.7807	8.6468	7.7887
2400	22.4270	15.5950	12.5790	10.7530	9.4831	8.5290
2600	26.3840	18.0080	14.3670	12.2120	10.7340	9.6338
2800	28.8390	19.6160	15.5590	13.1810	11.5630	10.3660
3000	31.0850	21.2070	16.7450	14.1470	12.3890	11.0930
3200	33.1090	22.7670	17.9220	15.1050	13.2080	11.8150
3400	34.9190	24.2850	19.0850	16.0550	14.0210	12.5320
3600	36.5390	25.7520	20.2300	16.9950	14.8260	13.2420
3800	37.9910	27.1610	21.3540	17.9230	15.6230	13.9450
4000	39.3020	28.5070	22.4530	18.8370	16.4110	14.6420
4200	40.4900	29.7890	23.5260	19.7370	17.1880	15.3300
4400	41.5750	31.0050	24.5700	20.6210	17.9540	16.0100

Figure 1

US Geothermal Heat at 6 km[5]

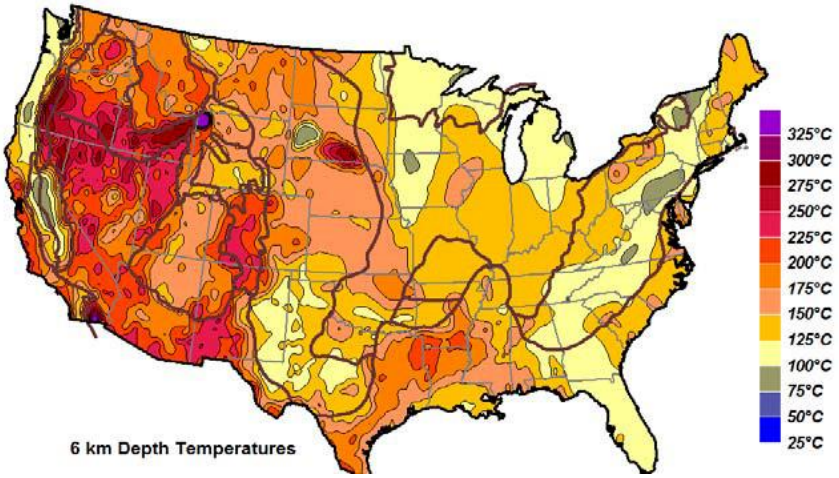


Figure 2

Coal-Fired Power Plants in the US West

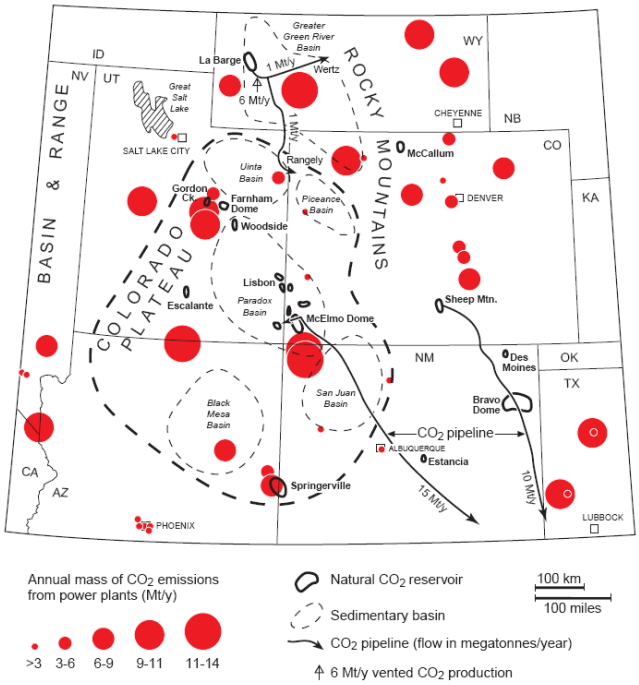


Figure 3

CO2 Phase Diagram

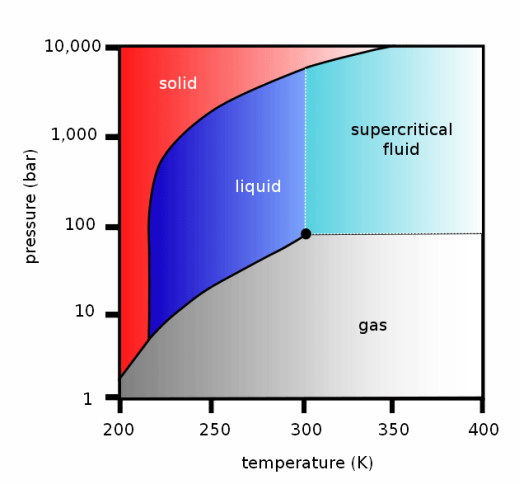
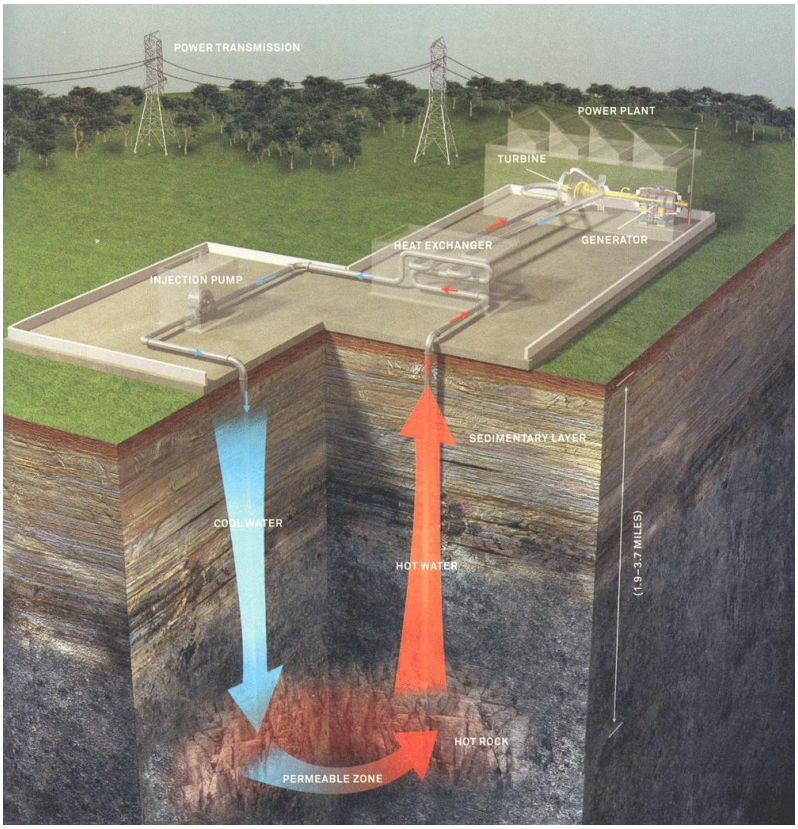


Figure 4

Enhanced Geothermal System/Hot Dry Rocks



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Appendix F

St. John's Dome Capital Cost Estimate

Assumptions		
15 MW CO2-EGS Plant		
5000 tons/MW circulating CO2		
Task	**$,000**	**Notes**
CO2 sourcing/compression	$ 10	CO_2 from Kinder Morgan on site
Permits	$ 100	
Geothermal leases	$ 40	
Geophysical monitoring	$ 3,000	
Injection/production wells	$ 15,000	
Reservoir stimulation	$ 15,000	
Power plant	$ 16,750	
Project management	$ 1,740	
Subtotal	*$ 51,640*	
Contingency (20%)	$ 10,328	
Total	**$61,968**	
CO2 calculations		
Annual loss rate	5%	%/year
Makeup CO2 cost	$ 200	$/ton
Makeup CO2 compression	$ 100	$/ton
Annual CO2 cost	$ 1,125	$,000

Appendix G

LCOE and Other Economic Calculations – St. Johns Plant

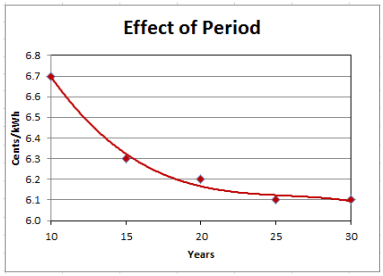
LCOE Calculation Inputs				
Class	**Factor**	**Value**	**Units**	**Notes**
Financial				
	Periods	40	Years	
	Discount rate	12%	%	Reasonable for a new technology
	Capital recovery factor	0.1213		
System cost and performance				
	Capital cost	$4,132	$/kW	From Appendix F
	Capacity factor	96%	%	0.92 is typical for water geothermal
	Fixed O&M cost, excluding CO2 replacement	$400	$/kW-yr	Includes monitoring, management, leases, permits, licenses, etc.
	CO2 replacement cost[1]	$150,000	$/kW-yr	Loss rate of 50%/yr
	Variable O&M cost	0.002	$/kWh	
	Heat rate	0	Btu/kWh	Not included; we do not buy heat
	Fuel cost	0	$/MM Btu	Not included; we do not buy heat
	Calculated LCOE	**129.8**	**¢/kWh**	

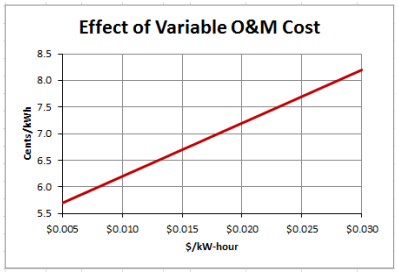
1 – Assumes CO2 @ $150/ton + $50/ton compression cost

Appendix H

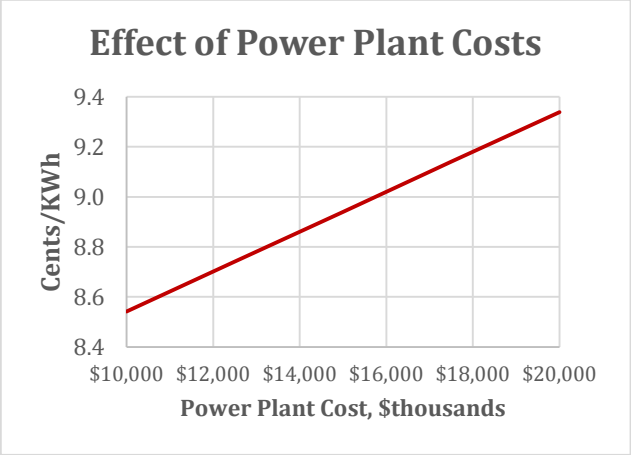
Sensitivity Testing Results, LCOE (¢/KWh)

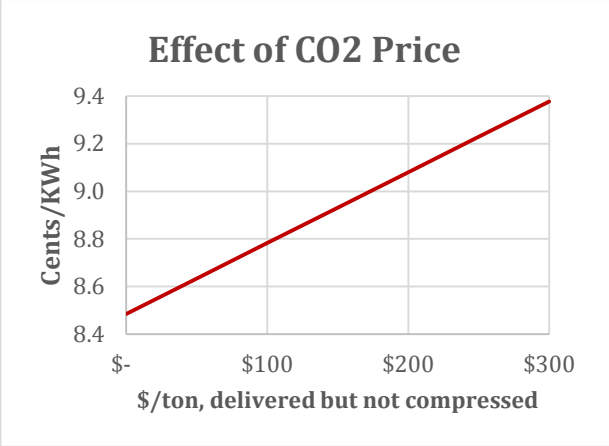
Note: the first three graphs used slightly different assumptions than the later graphs, but the inferences are not thereby changed

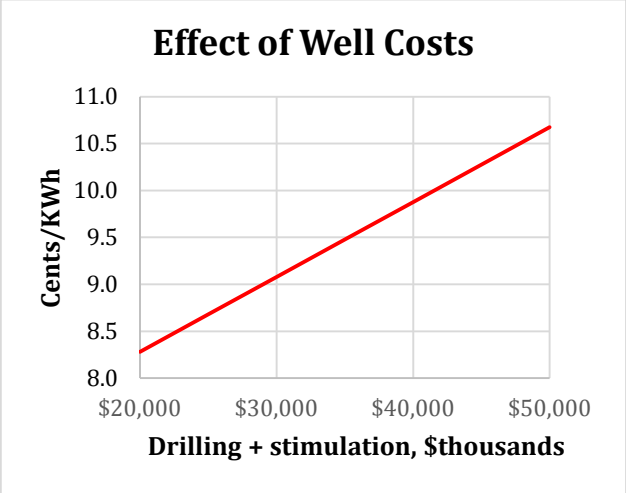


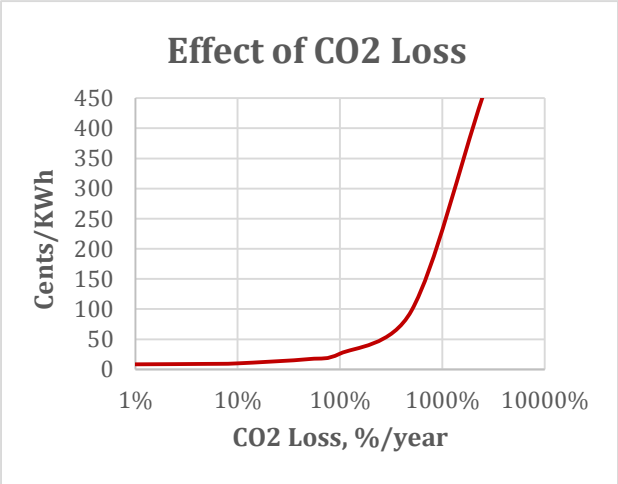


Note: in the graphs below, the constant values are those given in Appendices F and G









Appendix I

Summary Report from Foulger Consultants

Foulger Consulting

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January 27, 2013

Report to Greenfire Energy

Maintenance of the St. John's Dome Seismic Network
& Processing of Data Recorded
for the period
2 December, 2011 - 18 October, 2012

Gillian R. Foulger

Executive summary

All stations of the network are currently working well. The only malfunction we have experienced during the ~ 14-month period of network operation is the breakage of the vertical component of station SJ1. This has been dealt with by swapping out the spare sensor.

During the period 2 December, 2011 - 18 October, 2012, we examined by hand 2,733 windows of interest, and identified and located 31 earthquakes. Of these, 18 plot within ~ 25 km (15 miles) of the St. John's Dome network. They lie in 4 areas:

1. *Scattered around a cone-shaped topographic feature called Coyote Hills, ~ 5 km (3 miles) NE of Springerville, and west of the network. This topographic feature resembles in shape a volcanic construct and if it is a recent feature of this kind the earthquakes there might indicate relatively*

shallow geothermal activity. Alternatively, they might be caused by shallow fluid migration (water or CO_2);

2. *A location ~ 3.5 km (2.2 mile) northeast of station SJ3, likely on Mr. Geisler's land;*
3. *A region ~ 22 km (~ 13 miles) southeast of the network. This area generated earthquake activity during an earlier reporting period; and*
4. *A zone north of the latter area, along the Red Hills fault.*

In total, since the beginning of recording 12 August, 2011, we have located 49 earthquakes, 36 of which lie within ~ 25 km (15 miles) of the network.

The next network service visit is recommended for February/March 2012.

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5 Results 62

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5.3 Magnitudes 69

6 Summary and concluding remarks 69

The 9 - 11 May, 2012 service run

A site visit was made to the St. John's Dome seismic network 9 - 11 May, 2012. All the stations were visited, standard maintenance work done, and the data were downloaded. The work was performed by Ramsey Haught.

The property owners, Elaine Rogers (SJ5) and George Geisler (SJ3) were both contacted prior to entering their land. Both were happy to be called and interested to know the status of the experiment. Neither had any concerns regarding continued presence of the equipment on their property.

All five stations were visited 10 May, and the memory cards replaced with new ones. At each site the solar panel was cleaned, and the battery voltage measured and compared with that logged by the RefTek 130 recorder (displayed on the "status screen" on the Palm hand-held device). The GPS state and error were checked, and the seismometer tested by a foot stomp.

All the sites appeared to be in good order. There was no evidence of anyone coming to the sites, and there were no fresh footprints either human or cow. The memory cards were backed up to an external USB disk, and returned, with the spares and field equipment, to our Palo Alto office.

The 16 - 18 October, 2012 service run

Sites SJ1, SJ2 and SJ4 were visited 16 October, and sites SJ1, SJ3 and SJ4 17 October. Both land owners were contacted before entering their property and after finishing the site service to notify them of completion of the work. Ramsey spoke with Elaine Rogers and left a message for George Geisler. Both property owners expressed no concerns with the continued presence of the equipment on their property.

On visiting site SJ1, Ramsey noticed that the fence around the State Well 9-21 had been painted (Figure 1). All memory cards were replaced with new ones. At each site the solar panel was cleaned, the battery voltage measured and compared to what the RefTek 130 displayed. At no station was there evidence of anyone coming to the sites, and there were no fresh foot prints from people or cattle. The memory cards were backed up to an external USB disk as usual. The GPS state and error were checked and seismometers tested by a foot stomp.

All the sites appeared to be in good order except SJ1, where the vertical component of the seismometer appeared to have failed (Figure 2). This problem had not been immediately obvious earlier because of cross talk between the components (ghost recordings of the functioning components are often seen on the defunct one). This problem also obscured the malfunction in the foot stomp test. However, it became apparent after reviewing the recorded data that there was a large difference in amplitude for recorded events on the three channels.

It can be difficult to diagnose what has broken in a situation like this. Ramsey initially suspected the RefTek 130 and swapped it out for the spare. After several hours of recording, the problem was still present. Ramsey then checked the seismometer resistance and found that channel 1 was open. The original Reftek was re-installed and the broken seismometer replaced with the spare. Data were recorded overnight, checked in the morning. That time, all three components appeared to be working correctly.

Figure 1: Photograph of State Well 9-21, taken 16 October, 2012.

Repair status of broken seismometer S/N 905

Ramsey examined the seismometer to check if the problem was something simple that we could repair in house. There was no corrosion inside the case, but the resistance across the vertical coil indicated an open circuit. The sensor was later checked by *Foulger Consulting* seismograph engineer, Russ Sell, and he concurred.

We have set the process in motion to have the seismometer repaired. It will be shipped back to the manufacturer and we will seek an estimate for the repair before committing to any expense. The sensor had a 1-year warranty when it was purchased, but this is now expired.

Preparation of the data for processing

The data were downloaded at our Palo Alto office, archived and processed in the way described in detail in our report of 9 January, 2011. Following this, all the windows of data corresponding to events of interest (potential earthquakes) were scanned by Bruce Julian, Senior Geophysicist, and Gini Gandhok, Seismic Analyst. All the results were finally cross-checked and quality controlled.

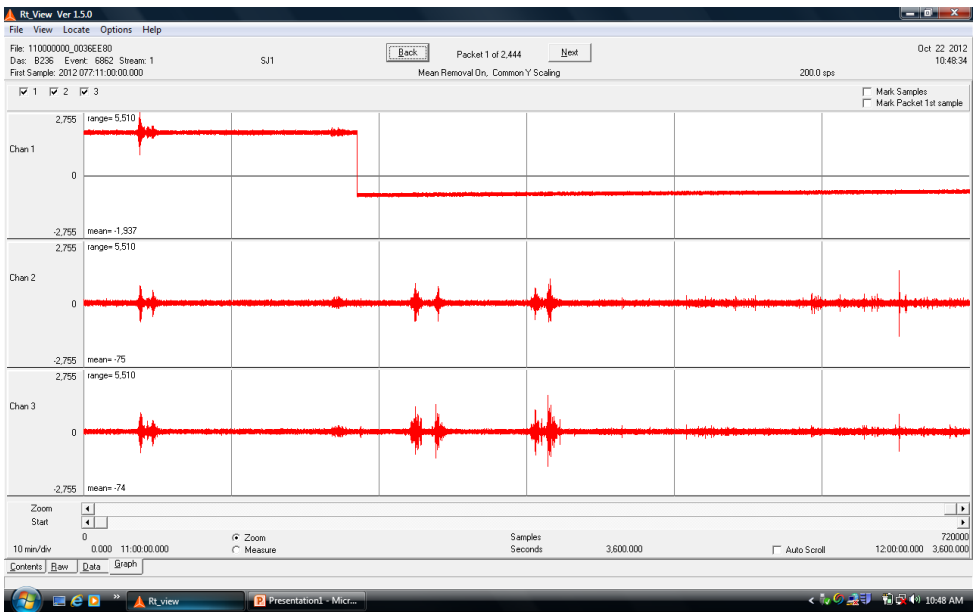

Figure 2: Failure of the vertical component of the seismometer at station SJ1 (top trace). The two horizontal components (bottom two traces) continued to work normally after the failure.

Results

Triggers, 'zoo events,' and regional earthquakes

The network continues to run well, as reported earlier, with large numbers of triggers at the five stations. Many of these are synchronized in time sufficiently closely for our processing software to extract them as events of interest. In total, we scanned 2,733 such events.

As before, various kinds of events were observed, many of them likely road traffic, aircraft and meteorological phenomena such as thunder. Others are likely noise bursts resulting from such things as wind and animals, coincidentally occurring at similar times on four or five stations. These "zoo events" (*i.e.*, events that are not earthquakes) are not easily recognized by a computer, but they are identifiable by a human analyst at the operator-scanning stage.

From the 2,733 windows of interest scanned, as for earlier work, we identified many earthquakes that had *S*-minus-*P* times greater than ~ 3 s, indicating epicentral distances from the seismic network greater than ~ 25 km (Figure 3). It is assumed that these earthquakes are not of central interest to the project and therefore no attempt was made to locate them. Any such locations would, in any case, be inaccurate as the earthquakes are so far outside of the network.

Close earthquakes

We identified 31 relatively close locatable earthquakes. An example is shown in Figure 4. The entire catalog of earthquakes we have located for the period 12 August, 2011 - 18 October, 2012 is given in Appendix 1. The chronology of close earthquake occurrence is shown in graphical form in Figure 5. During the current reporting period, earthquakes were relatively evenly spread in time. There was no re-occurrence of the vigorous swarm activity recorded in October 2011, when 17 earthquakes were located in a 10-day period (Appendix 1).

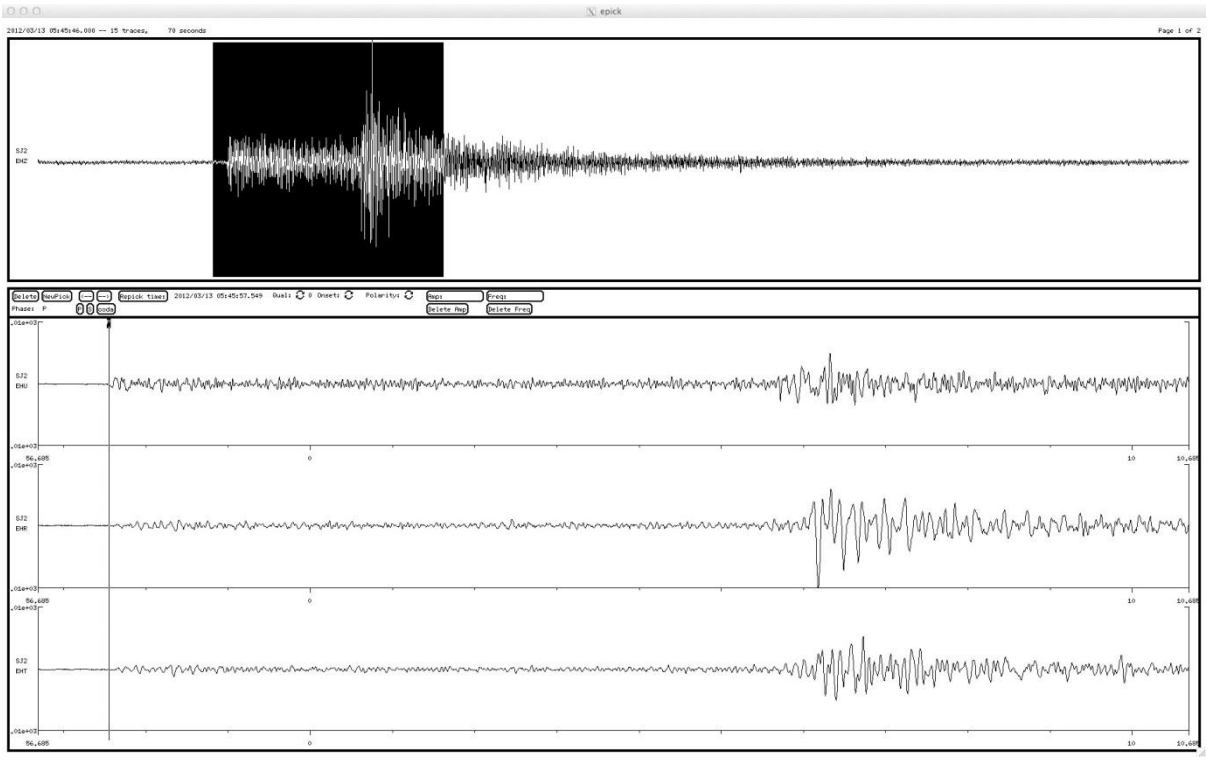

Figure 3: Example of an earthquake with an *S*-minus-*P* time of ~ 8 s, which indicates an epicentral distance of ~ 64 km (~ 40 miles).

Figure 6 shows the locations of the 18 close earthquakes that lie within the boundaries of the map illustrated. They lie in four areas:

1. Scattered around a cone-shaped topographic feature called Coyote Hills, ~ 5 km (3 miles) NE of Springerville, and west of the network. This topographic feature resembles in shape a volcanic construct and if it is a recent feature of this kind the earthquakes there might indicate relatively shallow geothermal activity. Alternatively, they might be caused by shallow fluid migration (water or CO_2);
2. A location ~ 3.5 km (2.2 mile) northeast of station SJ3, likely on Mr. Geisler's land;
3. A region ~ 22 km (~ 13 miles) southeast of the network. This area generated earthquake activity during an earlier reporting period; and
4. A zone north of the latter area, along the Red Hills fault.

A map showing locations of the entire located dataset since the beginning of recording 12 August, 2012, is shown in Figure 7. A total of 36 epicenters are plotted on this Figure. From this it can be seen that regions 3. and 4. above were also seismically active prior to the present reporting period.

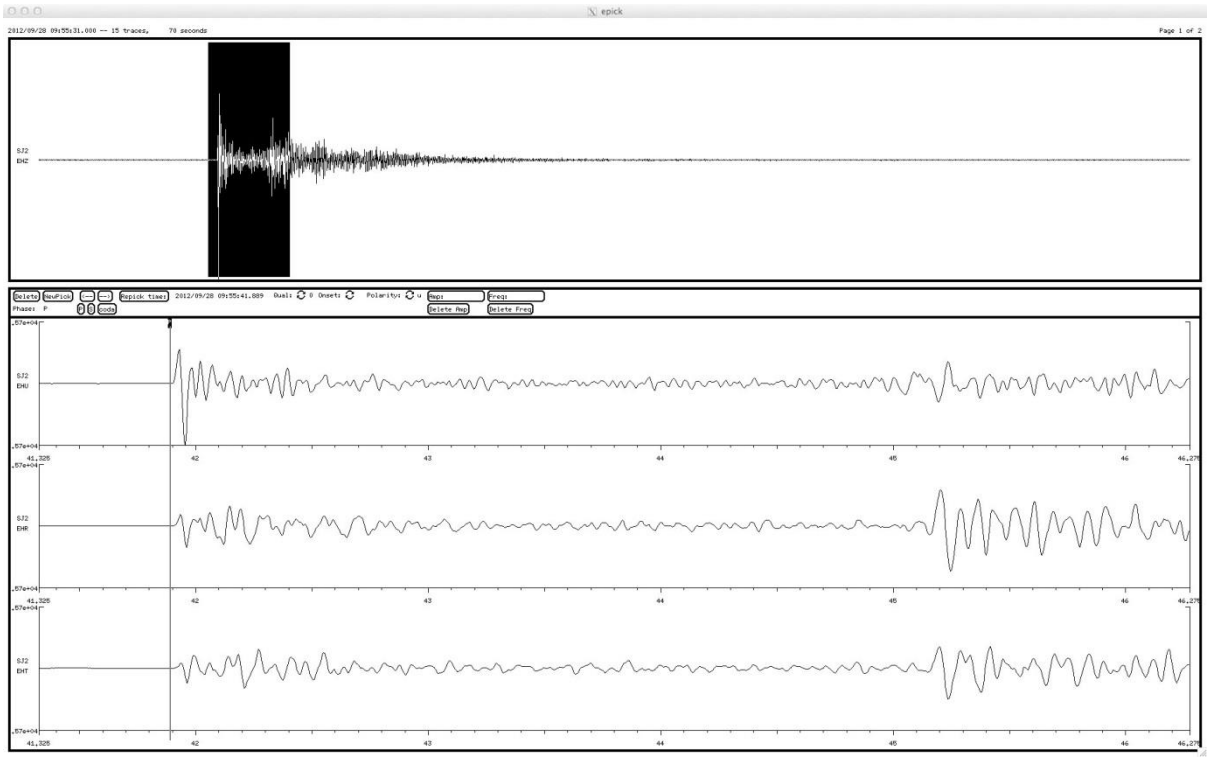

Figure 4: Example of a close earthquake, recorded at station SJ2, 26 September, 2012 at 09:55 GMT. The *S*-minus-*P* time is ~ 3.2 s, corresponding to an epicentral distance of ~ 25 km (15 miles).

A larger-scale map of the local area, showing an expanded view of the two earthquakes very close to station SJ3, is given in Figure 8.

As reported before, the absolute accuracy of the calculated hypocenters reduces with distance from the network because of geometrical considerations and also because we currently have only an approximate crustal *P*- and *S*-wave-speed model. Future improvements in the crustal model will alter our current best-estimate hypocenters.

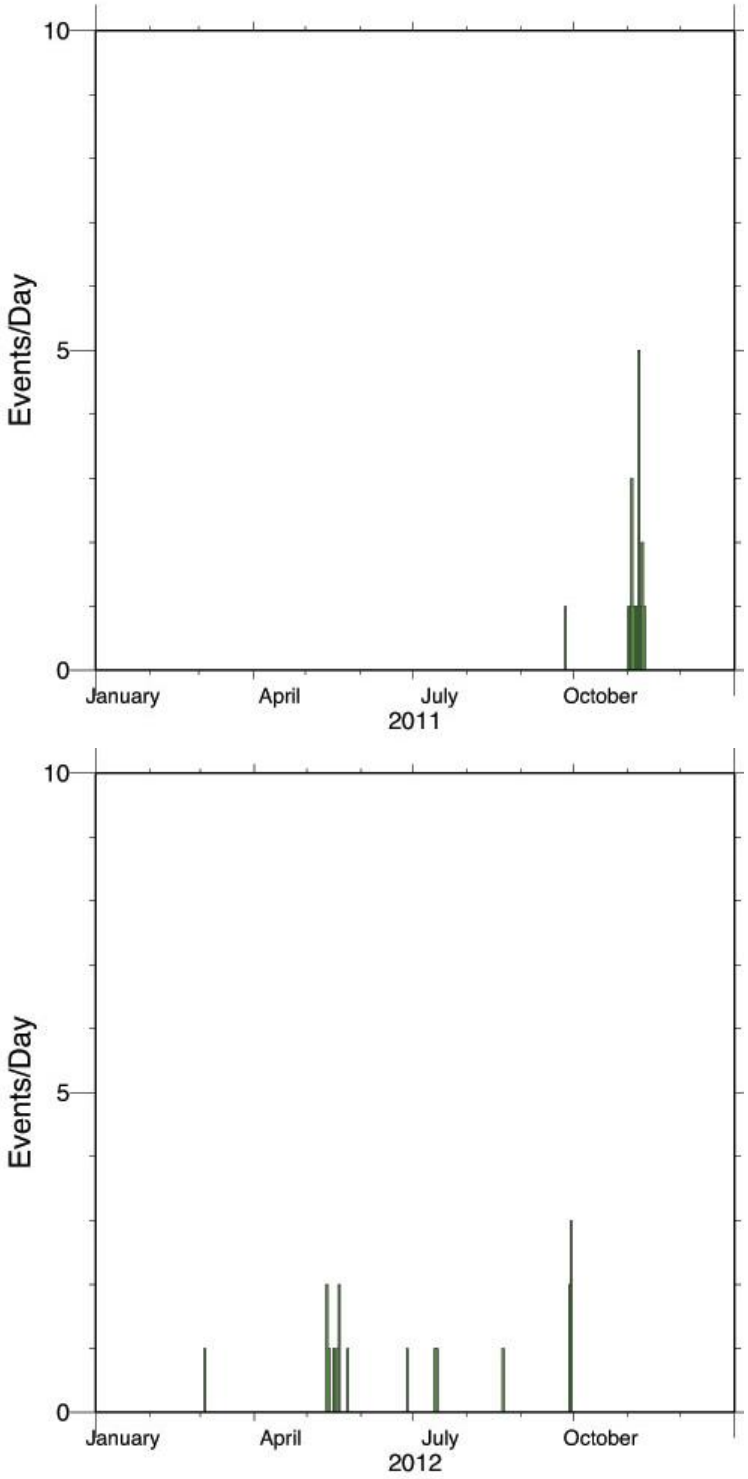

Figure 5: Numbers of events located with the St. John's Dome network as a function of time throughout the recording period. Top: 2011; Bottom: 2012.

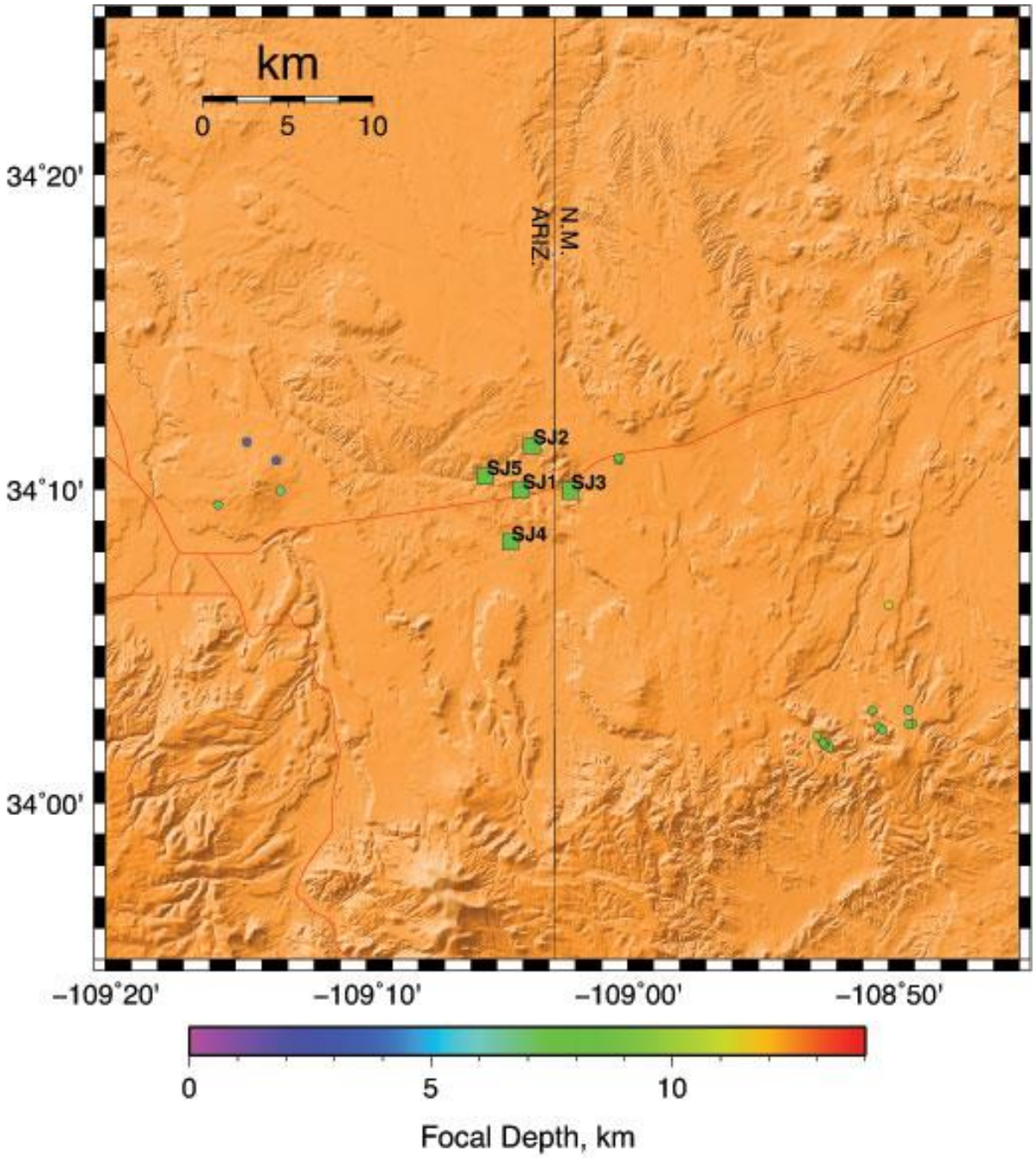

Figure 6: The region within ~ 25 km (15 miles) of the St. John's Dome network, showing the locations of the 18 local earthquakes recorded 2 December, 2011 - 18 October, 2012. Red lines: roads.

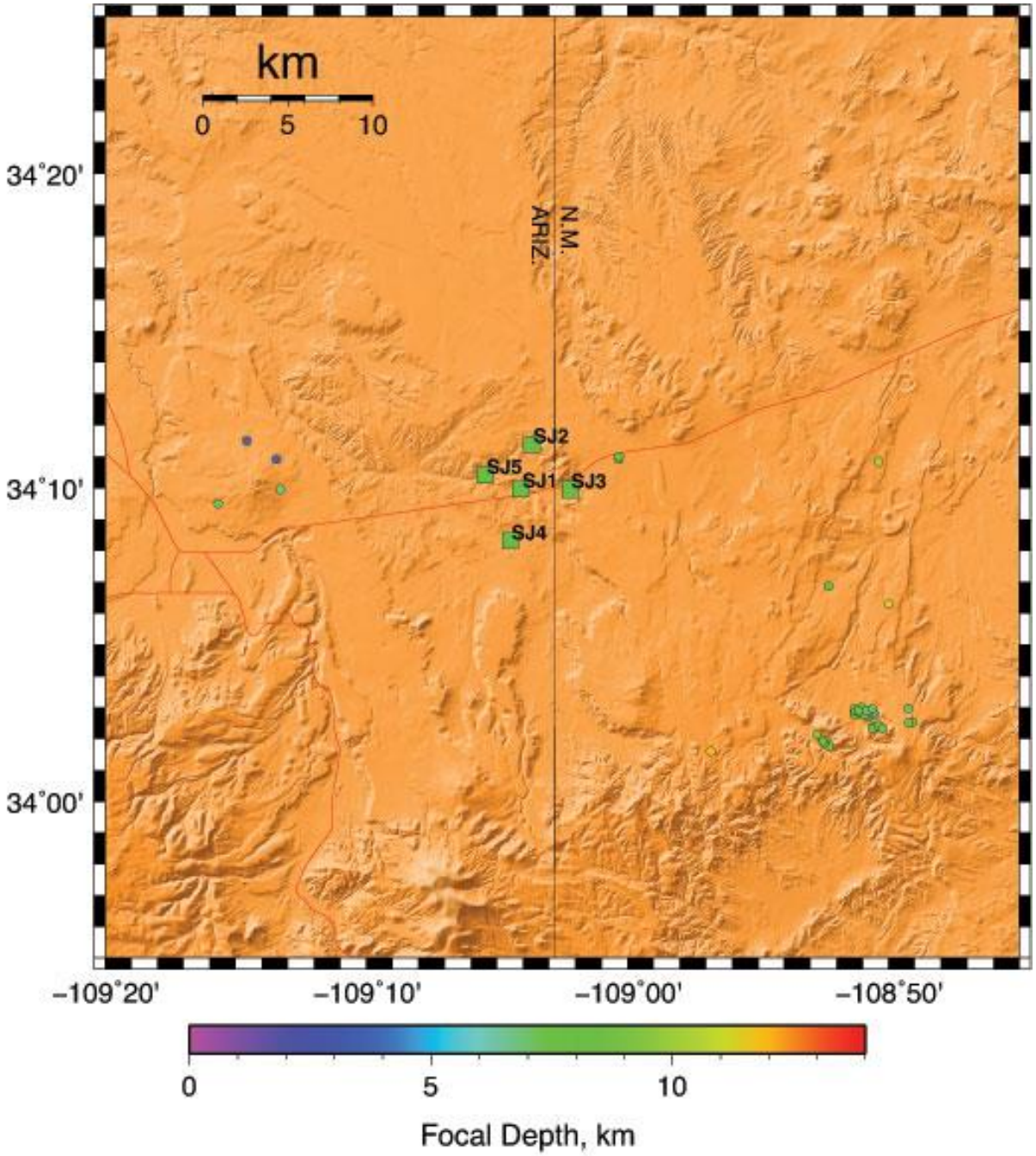

Figure 7: Same as Figure 6 except for the entire catalog, and including earthquakes located from 12 August, 2011 to 18 October, 2012. A total of 36 earthquakes are plotted.

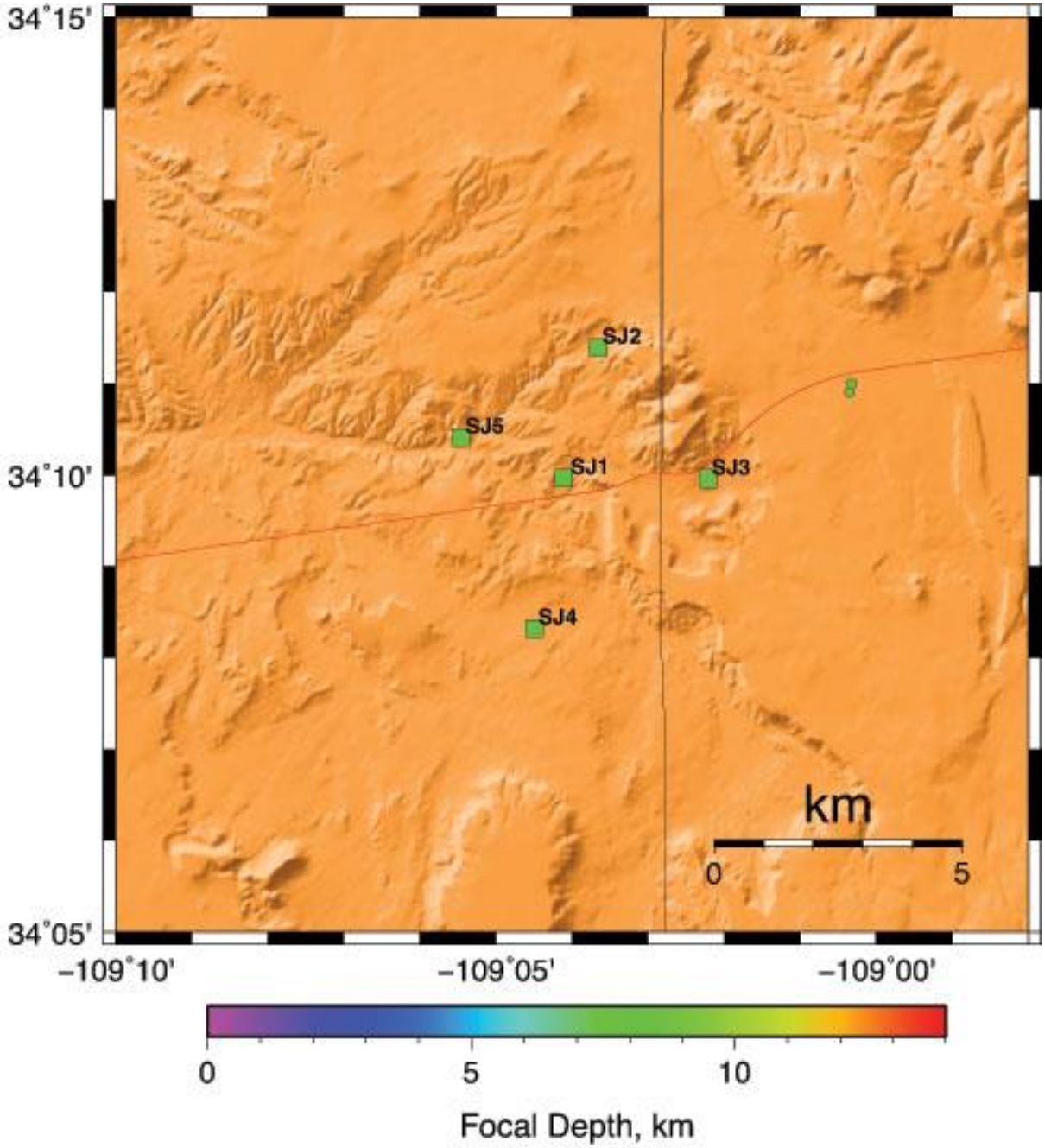

Figure 8: Map showing an expanded view of the area immediately around the St. John's Dome network, showing locations of the 2 local earthquakes recorded 3.5 km (2.2 miles) northeast of station SJ3. Red lines: roads.

Magnitudes

Since two earthquakes were very close to the network, we were able to determine their *seismic moments*. Seismic moment is a measure of earthquake size that is related to the fundamental physics of the source, and from it so-called "moment magnitudes" can be calculated. We calculated moment magnitudes M_W of 2.4 for each of these two earthquakes (Appendix 1).

Calculation of moment magnitudes depends on equipment calibration values, and also on crustal structure, and if these data are upgraded, *e.g.*, by improvement of the crustal structure using well data or calibration shots, estimates of these moment magnitudes will improve and change.

Other magnitudes reported in our catalog in Appendix 1 are coda-length magnitudes (M_d), which were measured by calibrating our recordings empirically to the magnitude M_d 1.5 of the event of 11:05 UTC, 3 November, 2011, reported by the New Mexico Tech Seismological Observatory[32].

Summary and concluding remarks

All stations of the network are currently working well. The only malfunction we have experienced during the ~ 14-month period of network operation is the breakage of the vertical component of station SJ1. This has been dealt with by swapping out the spare sensor.

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4. A zone north of the latter area, along the Red Hills fault.

In total, since the beginning of recording 12 August, 2011, we have located 49 earthquakes, 36 of which lie within ~ 25 km (15 miles) of the network.

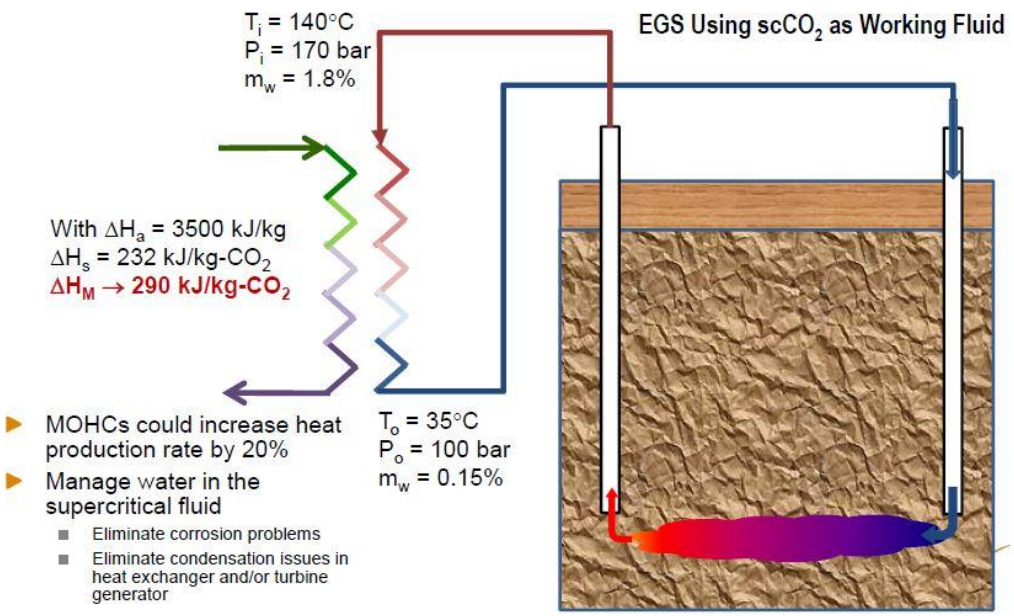
[32] http://www.ees.nmt.edu/outside/Geop/NMTSO/quakelist.html

Appendix 1: Numerical data for earthquakes located in the vicinity of the St. John's Dome network since the onset of recording 12 August, 2011. M_d is duration magnitude (calibrated to an event reported on the regional network catalog) and M_W is moment magnitude (calculated using calibration data from the St. John's Dome network).

Date	Time	Lat	Long	Depth b.s.l.	Mag	Mag type	#st	GAP	Delta km	RMS	#P	#S
2011/09/26	18:01:40.76	34.1805	-108.8400	10.50	0.03	Md	5	345	18.2	0.06	5	5
2011/11/01	16:03:55.70	34.1145	-108.8718	8.28	0.48	Md	5	342	16.2	0.05	5	5
2011/11/02	02:48:49.86	34.0500	-108.8505	8.27	1.06	Md	5	346	21.5	0.03	5	4
2011/11/03	11:05:01.32	34.0463	-108.8426	6.12	1.50	Md	5	348	22.3	0.06	5	5
2011/11/03	21:32:58.43	34.0495	-108.8555	10.48	1.04	Md	5	347	21.1	0.05	5	4
2011/11/03	22:12:51.63	34.0467	-108.8533	7.21	1.08	Md	5	347	21.5	0.01	5	4
2011/11/04	01:30:29.70	34.0465	-108.8554	7.69	0.09	Md	5	347	21.4	0.01	5	3
2011/11/05	23:12:14.90	34.0480	-108.8544	7.51	0.24	Md	5	346	21.3	0.02	5	4
2011/11/06	09:39:01.65	34.0473	-108.8433	6.90	0.44	Md	5	347	22.2	0.03	5	3
2011/11/07	04:57:28.80	34.0452	-108.8462	7.16	-0.05	Md	5	347	22.1	0.02	5	3
2011/11/07	07:26:06.01	34.0267	-108.9470	11.85	-0.23	Md	5	345	17.1	0.03	5	5
2011/11/07	09:19:33.16	34.0474	-108.8521	8.15	1.13	Md	5	347	21.5	0.03	5	6
2011/11/07	11:05:37.52	34.0399	-108.8419	7.57	0.33	Md	5	347	22.8	0.02	5	3
2011/11/07	14:10:53.22	34.0449	-108.8473	7.53	0.15	Md	5	347	22.0	0.05	5	4
2011/11/08	01:27:39.42	34.0459	-108.8487	7.38	0.23	Md	5	347	21.9	0.05	5	5
2011/11/09	05:51:15.96	34.0388	-108.8438	7.68	0.58	Md	5	348	22.7	0.02	5	3
2011/11/09	09:13:19.33	34.0484	-108.8472	7.17	0.04	Md	5	347	21.8	0.04	5	3
2011/11/10	07:32:10.25	34.0483	-108.8525	8.17	0.03	Md	5	347	21.4	0.06	5	4
2012/01/17	08:48:50.23	34.1598	-108.7278	9.57	_	_	4	353	28.5	0.03	4	4
2012/02/14	14:14:14.51	33.8574	-108.8952	15.94	_	_	5	353	35.3	0.04	5	5
2012/02/14	20:26:22.47	33.8584	-108.8829	16.13	_	_	4	354	35.8	0.05	3	4
2012/02/16	05:17:10.02	34.1485	-108.3401	18.76	_	_	5	355	64.3	0.05	5	5
2012/02/29	14:25:17.58	33.8550	-108.8959	15.50	_	_	5	353	35.5	0.03	5	4
2012/03/03	19:20:08.11	34.1818	-109.2242	3.81	_	_	4	350	12.3	0.04	3	4
2012/03/08	03:31:00.77	34.0235	-108.6772	13.17	_	_	5	351	36.8	0.04	5	5
2012/03/13	05:45:44.94	34.7590	-109.4228	18.84	_	_	5	357	71.3	0.03	4	5
2012/03/20	20:35:25.39	34.0406	-109.6376	13.16	_	_	4	355	52.5	0.03	4	4
2012/03/29	14:52:49.40	34.0168	-109.6257	13.83	_	_	4	355	52.3	0.03	3	4
2012/05/08	10:22:02.15	34.0299	-109.6408	11.72	_	_	4	354	53.2	0.03	4	4
2012/05/09	08:27:08.09	34.0041	-109.6393	6.04	_	_	4	355	54.0	0.03	4	4
2012/05/10	08:23:10.58	34.0376	-109.6251	12.48	_	_	4	355	51.5	0.02	2	4
2012/05/12	03:10:37.30	34.0421	-108.8183	8.06	_	_	4	348	24.4	0.08	4	2
2012/05/12	04:39:45.75	34.0492	-108.8438	7.40	_	_	5	347	22.0	0.05	4	4
2012/05/13	00:22:03.75	34.0495	-108.8210	7.14	_	_	4	348	23.7	0.09	4	3
2012/05/16	09:55:35.42	34.1049	-108.8336	11.40	_	_	4	346	19.9	0.01	4	2
2012/05/18	14:38:19.86	34.0419	-108.8207	8.53	_	_	4	348	24.2	0.08	4	2
2012/05/19	05:04:46.47	34.0403	-108.8398	8.49	_	_	4	348	22.9	0.01	4	3
2012/05/19	05:32:36.71	34.0388	-108.8371	7.40	_	_	4	348	23.2	0.01	4	3
2012/05/24	08:10:42.88	34.1817	-109.0058	8.24	2.41	Mw	5	313	3.3	0.01	4	4
2012/06/27	03:39:25.49	34.1833	-109.0053	8.12	2.48	Mw	5	314	3.5	0.01	5	4
2012/07/13	09:49:12.38	34.1916	-109.2429	3.88	_	_	5	340	14.1	0.03	4	4
2012/07/14	02:02:44.63	34.1582	-109.2612	6.93	_	_	5	342	15.8	0.03	5	4
2012/07/14	05:48:30.59	34.0685	-108.6791	17.18	_	_	5	351	34.7	0.03	4	4
2012/08/21	22:43:51.54	34.1658	-109.2216	6.58	_	_	5	338	12.1	0.05	4	5
2012/09/28	09:55:37.05	34.0357	-108.8792	9.35	_	_	5	346	20.5	0.03	5	8
2012/09/28	22:47:32.59	34.0325	-108.8733	7.72	_	_	5	347	21.1	0.02	5	4
2012/09/29	03:09:18.72	34.0295	-108.8713	9.00	_	_	5	347	21.5	0.04	5	4
2012/09/29	08:45:32.05	34.0311	-108.8747	8.17	_	_	5	347	21.2	0.03	5	7
2012/09/29	12:13:34.76	34.0319	-108.8756	8.32	_	_	5	347	21.0	0.02	5	6

Appendix J

Schematic Drawing of MOHC/SCO2 Geothermal Process



Appendix K

Recent PNNL Report

Project No. 59958

Metal-Organic Heat Carriers for CO_2 Enhanced Geothermal Systems

Project Management

On March 26, B.P. McGrail attended a workshop in Alberta, BC on utilization of CO_2 as a working fluid in geothermal systems that was organized by Alberta Innovates. All travel costs were paid by Alberta Innovates. Dr. McGrail gave the presentation "Novel Applications and Issues Regarding Use of CO_2 for Energy Storage and Recovery."

Molecular Modeling Studies

In continuation from last quarter, molecular dynamics simulation studies were performed on sorption in modified MOHC candidates. Many attempts were made to use water as a guest molecule in the simulations, but the current force field and sorption module of the Accelrys Material studio software was designed for non-condensable gas molecules rather than vapors. When MOHC pores are exposed to water molecules, the MOHC structure will be saturated with liquid water or water in a special state of density close to 1. Such super-hydrophilic behavior was found, after numerous discussions with Accelrys, to be beyond the simulation capabilities of their software. Still for this initial work, the key functionality we want impart in the MOHC material is CO_2–phobicity when compared to the bare MOHC. Other dedicated molecular dynamics software is available at PNNL to explore hydrophilic properties.

For initial studies, a MOHC based on a dihydroxyterephthalic acid (DHTA) linker was considered because our previous work with the force-field based grand-canonical Monte Carlo (GCMC) simulations of CO_2 sorption studies at RT (298K) on this MOHC system closely reproduces experimental results. Two approaches were considered to modify the MOHC pore structure, one with substituting the hydrophilic functional groups on open metal centers and second, doping hygroscopic metal salts into the pore system.

Structural models of DHTA-based MOHC material DHTA-Ni was taken from the single-crystal XRD data and the solvent molecules were removed. In the first approach, the bare open metal center Ni atom was substituted individually with (a) ethylene glycol-EG; b) ethanolamine-EA and c) ethylene diamine-ED, respectively. The MOHC model decorated with these hydrophilic moieties was geometrically minimized by taking Lennard-Jones (LJ) parameters from a universal force field (UFF) with QEq partial charges. The optimized structures are shown in Figure 1. Cell optimization was done by using the same force field and the MOHC framework was assumed to be rigid.

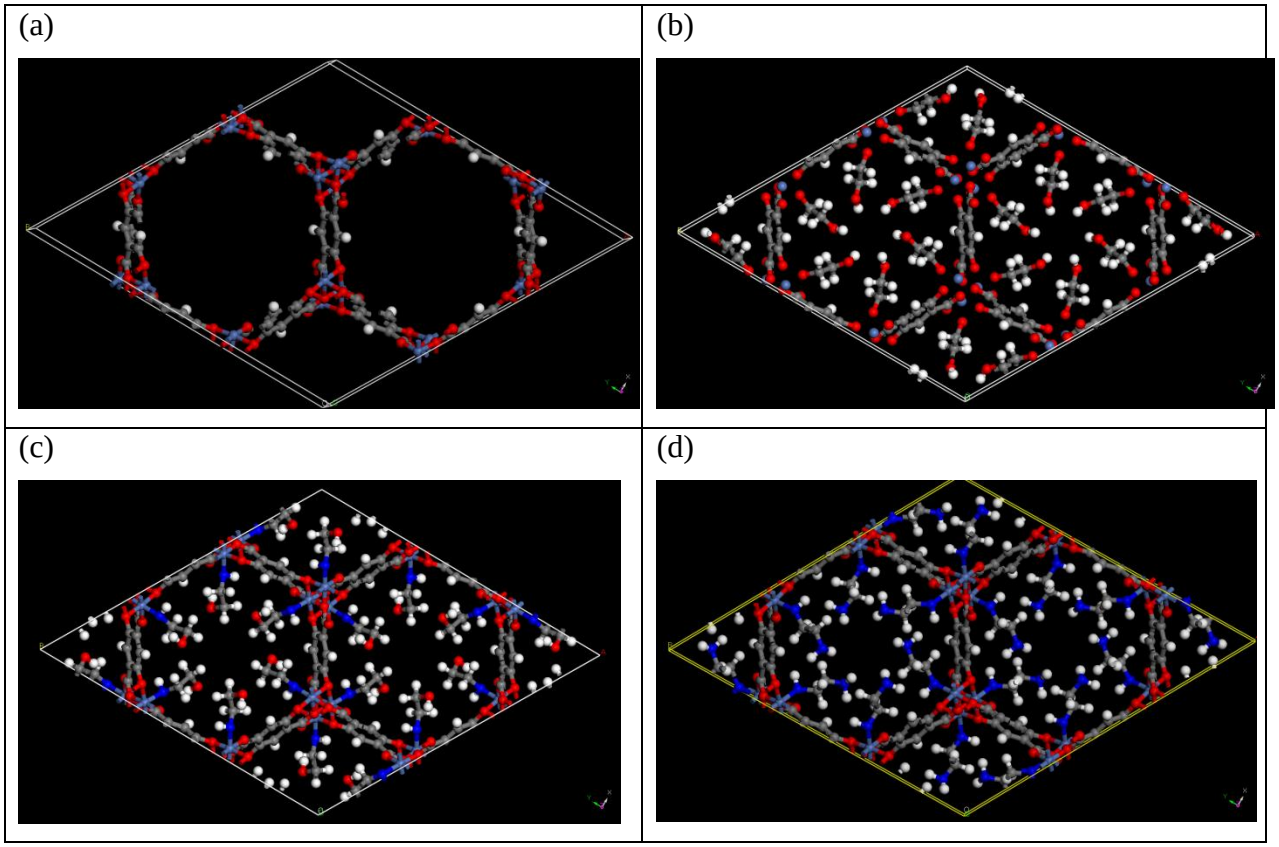


Figure 1. Geometrically optimized and decorated MOHC structures. DHTANi decorated with (b) EG, (c) EA (d) ED.

Sorption calculations were performed similar to that of bare MOHC material described last quarter, where one unit cell was adopted in the simulations with a cutoff radius of 15.5 Å for application of the LJ interactions. Periodic boundary conditions were applied in all three dimensions. A systematic simulation study was performed on the adsorption of CO_2 on all three MOHC candidates using the COMPASS force field, by defining host framework and guest molecule, temperature, pressure, coulomb & Van der Walls interactions. The sorption calculations were performed by considering one million equilibration steps followed by one million production steps. As shown in Figure 2, the predicted CO_2 sorption was drastically decreased from 30wt% to 8.2wt% (EG), 4.7 wt%(EA) and 4.5wt% (ED), respectively. Decorating the open metal centers with hydrophilic functional groups appears to be effective in imparting some CO_2-phobicity. However, some of these ligands can form covalent bonds with CO_2, which may interfere with their affinity for water sorption.

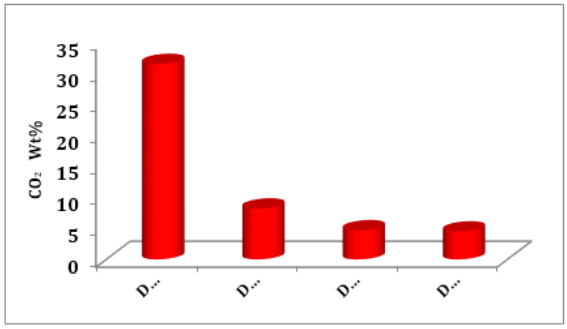
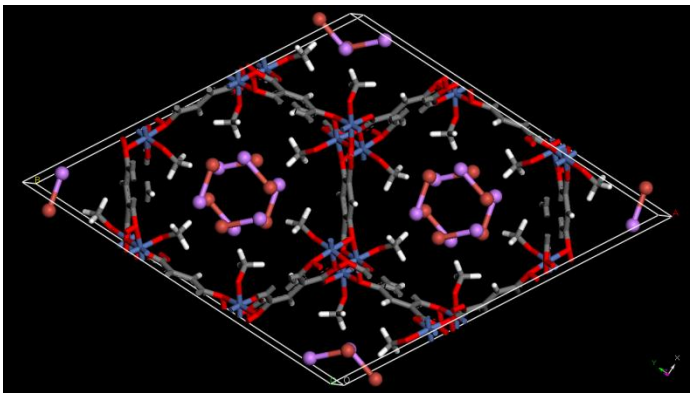


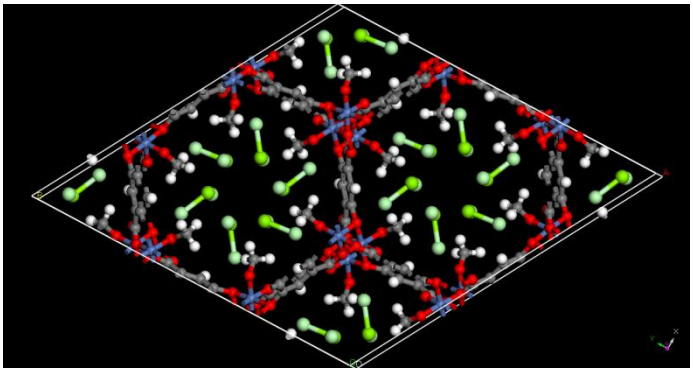
Figure 2. Comparison of CO_2 adsorption in DHTANi and decorated DHTANi at 298K.

The second approach represents a completely new concept in MOHC technology. In this approach, the open metal centers are capped with OCH_3 ligands, which should render the framework CO_2-phobic. The capped MOHC is then impregnated with hygroscopic metal salts. The nano-encapsulated salts are immobilized in the structure so that if the MOHCs contact liquid water at some location in the system (surface equipment or subsurface), the salts are retained in the MOHC pores. For simulation studies, we considered again the DHTA-based system and hygroscopic salts LiBr, $MgCl_2$, $ZnCl_2$, and $CaCl_2$. First, the Ni atoms (open metal centers) were decorated with OCH_3 ligands and the structure was geometrically minimized. Further, the hygroscopic salts were doped into the pores and the structure was geometrically and energetically minimized. The optimized structures of the new nano-encapsulant MOHCs are shown in Figure 3. From these preliminary studies, it was observed that the pores are partially/completely filled with hygroscopic salts due to the microporous nature of the host system. This may be beneficial in further blocking CO_2 access to the pores. Sorption calculations with these novel MOHC materials are in progress and will be reported next quarter.

(a)



(b)



(c)

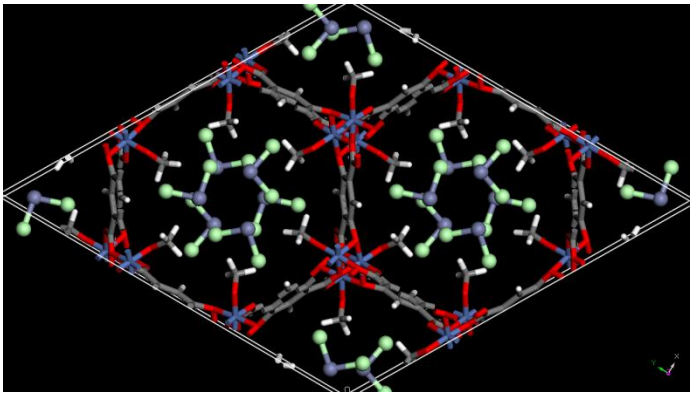


Figure 3. Geometrically optimized structures of DHTANi-OCH_3 doped with (a) LiBr, (b) $MgCl_2$, (c) $ZnCl_2$

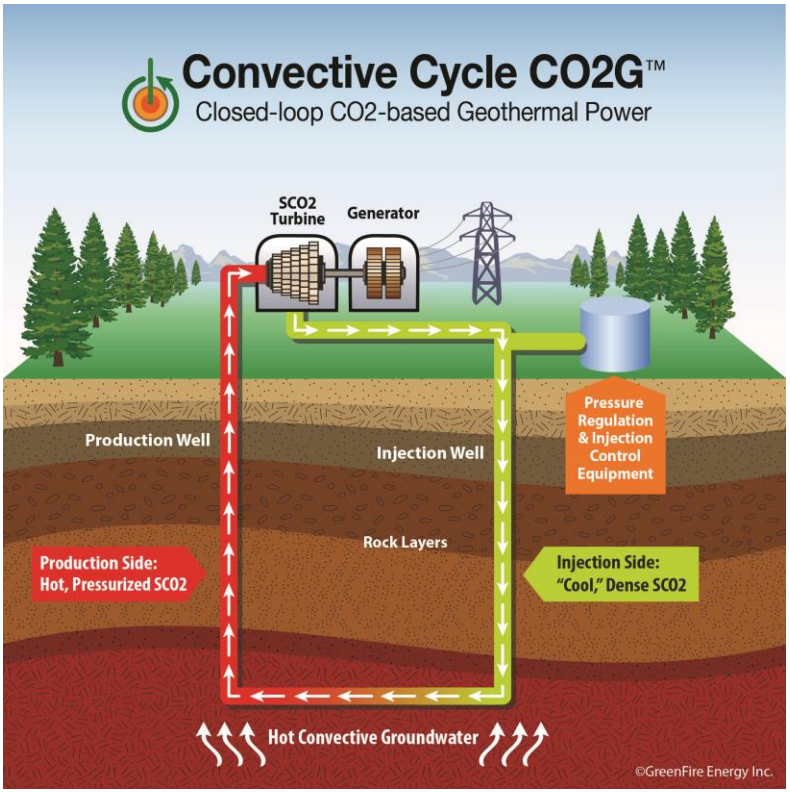
Appendix L

Summary of Permitting at St. Johns Dome

Permit title	Exploration Permit	Access Permit	Drilling Permit	Aquifer Protection Permit	Underground Injection Control Permit, Class V
Granting agency	AZ Land Department	AZ Land Department	AZ Oil & Gas Conserv. Comm.	AZ Dept. of Envir. Quality	US EPA Region IX
Purpose	Allow geothermal exploration	Allow access to property	Allow drilling	Permit subterranean injection	Permit subterranean injection
Status	Granted	Granted	Not yet applied	Met w/agency; work started	Met w/agency; work started
Contact	Joe Dixon	Joe Dixon	Steve Rauzi	Mason Bolitho	Nancy Rumrill
Subcontractor	n.a.	n.a.	Protocom Consulting	Montgomery & Assoc.	Montgomery & Assoc.
Sub. contact	n.a.	n.a.	Tim Phillips	Michele Robertson	Michele Robertson

Appendix M

Schematic Diagram of Convective Cycle CO2G™ Process



Appendix N

Estimated Cost of a 10 MW Closed-loop System

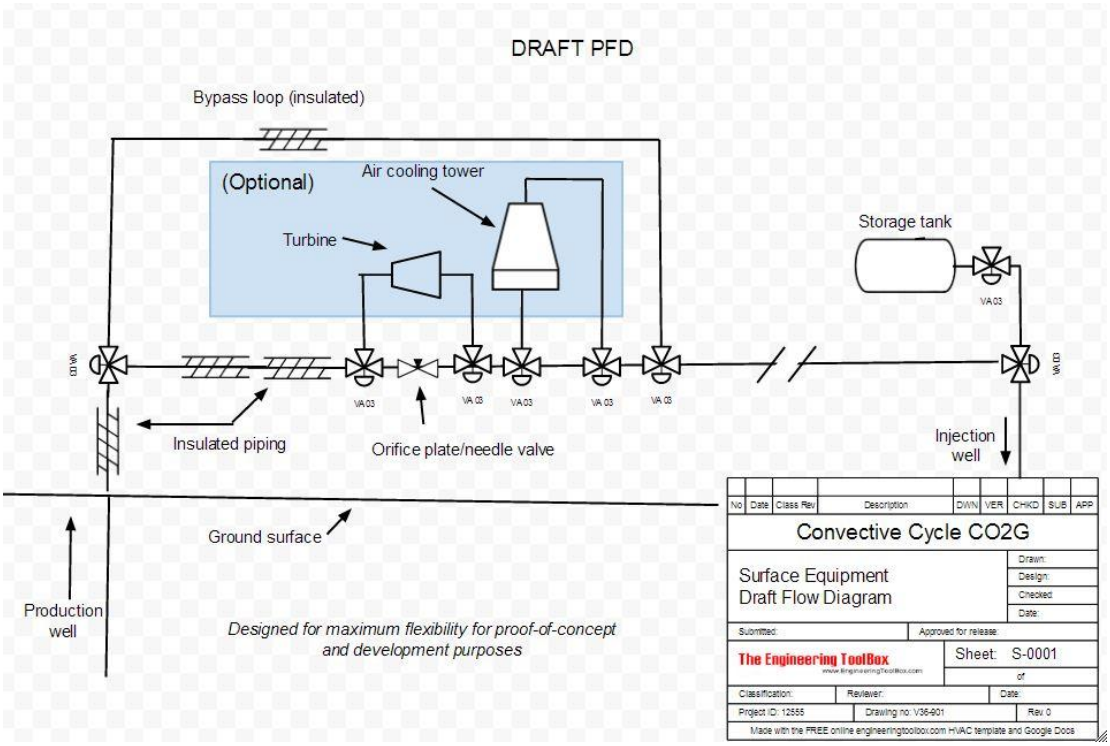
Standard 10 MW Convective Cycle Project		
Imperial Valley, CA		
Assumptions		
0.1MW/acre leased, 200°+ formation temperature		
Good permeability/convection for equilibrium		
30 tons of CO2 per MW, $300/ton of SCO2 delivered		
Expenditure Description	**Cost, $000**	**Subtotals**
Investigation[1]		**$ 3,655**
Landman	$ 25	
Environmental site analysis	$ 5	
Shallow temperature survey[2]	$ 500	
Passive seismic network	$ 650	
Active seismic investigation	$ -	
Other geophysics (MT, gravity)	$ 75	
Exploratory wells (2)[3]	$ 2,000	
Downhole geophysics	$ 200	
Analysis of integrated data	$ 200	
Geothermal Rights		**$ 12**
Legal and filing	$ 10	
Lease cost per year	$ 2	
Permits		**$ 250**
Cost of applications	$ 50	
Consultants	$ 200	
Legal and Insurance		**$ 675**
Legal	$ 200	
Bonds	$ 75	
Insurance	$ 400	
Drilling two wells		**$ 10,550**
Drilling plan	$ 250	
Drilling rig (80 days @40K)	$ 3,200	
Tubing/casing cost[4]	$ 3,500	
Tubing installation	$ 3,500	
Testing	$ 100	
Surface Equipment		**$ 6,675**
Engineering	$ 250	
Site preparation	$ 150	
Site construction	$ 1,000	
Two 5 MW power plants (turbine + gen)	$ 5,000	
Pressure tanks	$ 200	
Monitoring equipment	$ 75	
Startup		**$ 140**
SCO2-delivered cost[5]	$ 90	
Consultants	$ 50	
Power interconnect		**$ 4,750**
Electrical substation	$ 500	
10 mile power line @ $400K per mile[6]	$ 4,000	
Remote control station	$ 250	
GreenFire Project Management Fee		**$ 3,500**
Subtotal		**$ 30,707**
Contingency @ 20%	$ 6,141	
Total Estimated Cost		**$ 36,848**
Capital Cost per MW	***$ 3,685***	

Notes:

1 - Prorated across a 50 MW project
2 - Wells deep enough to be below shallow advective flow
3 - Slimholes
4 - Can vary significantly, depending on metallurgy
5 - Assumes 2000 psi; will need to be heated to critical point
6 - Site dependent; this is a recent average

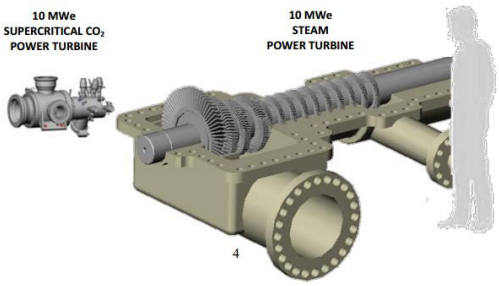
Appendix O

Flow Diagram for Surface Equipment



Appendix P

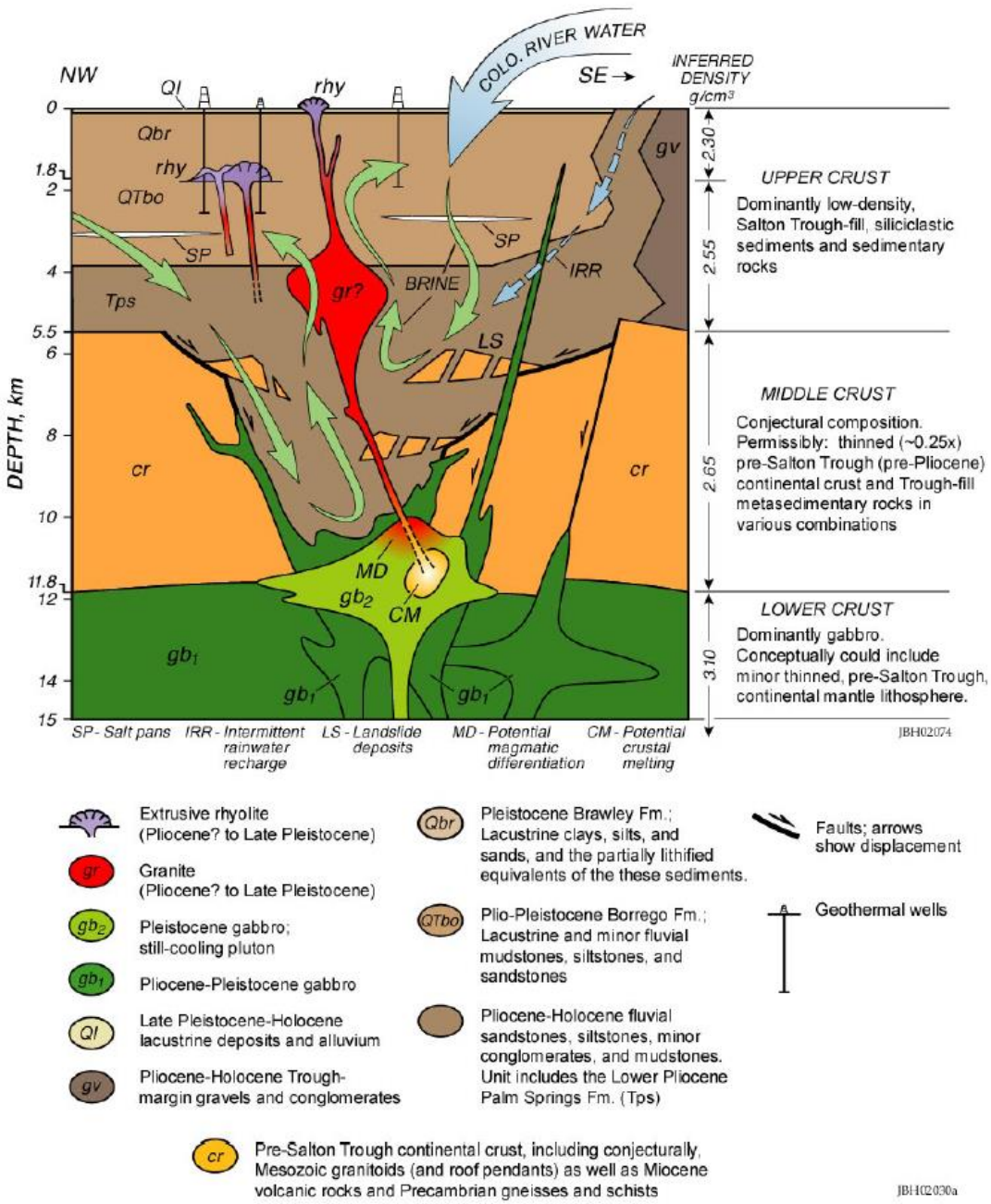
Size of 10 MW Turbines



4

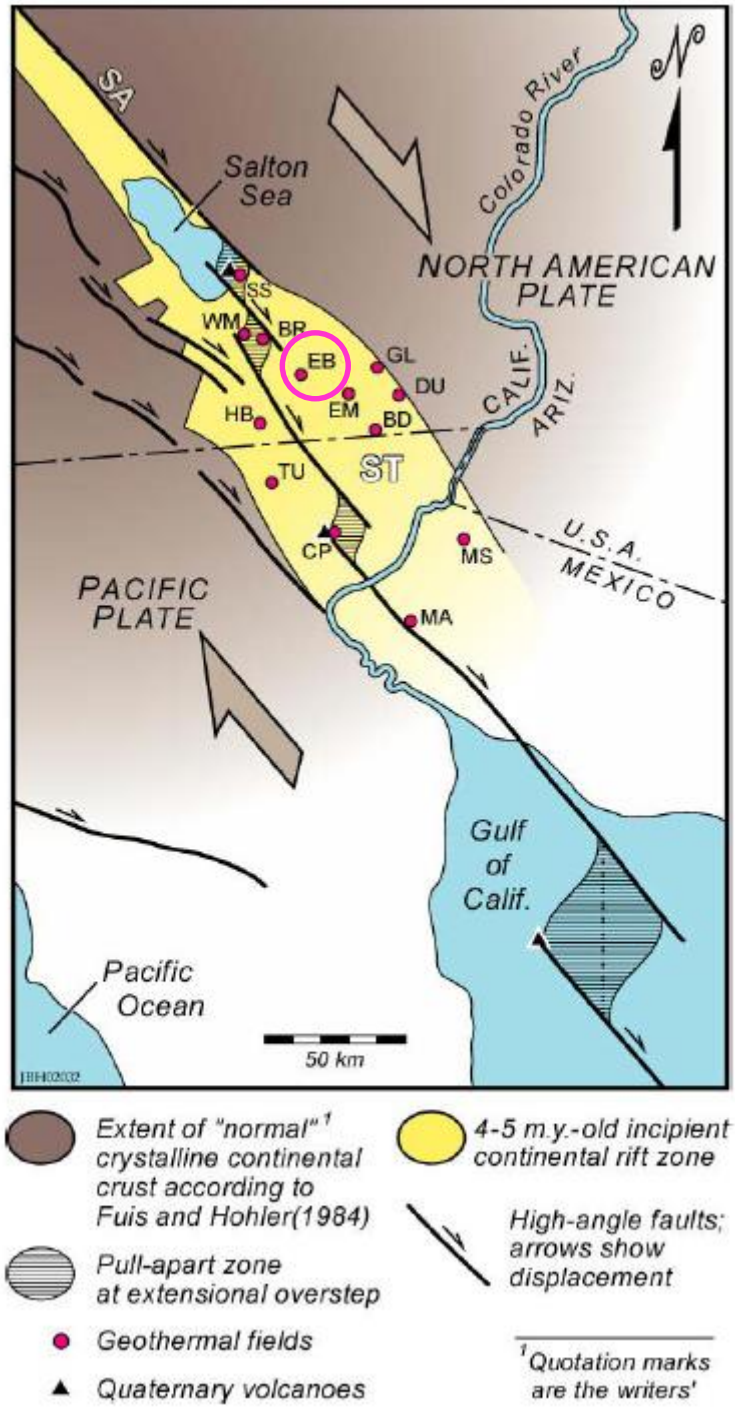
Appendix Q

Generalized Geology of the Imperial Valley Geothermal Areas



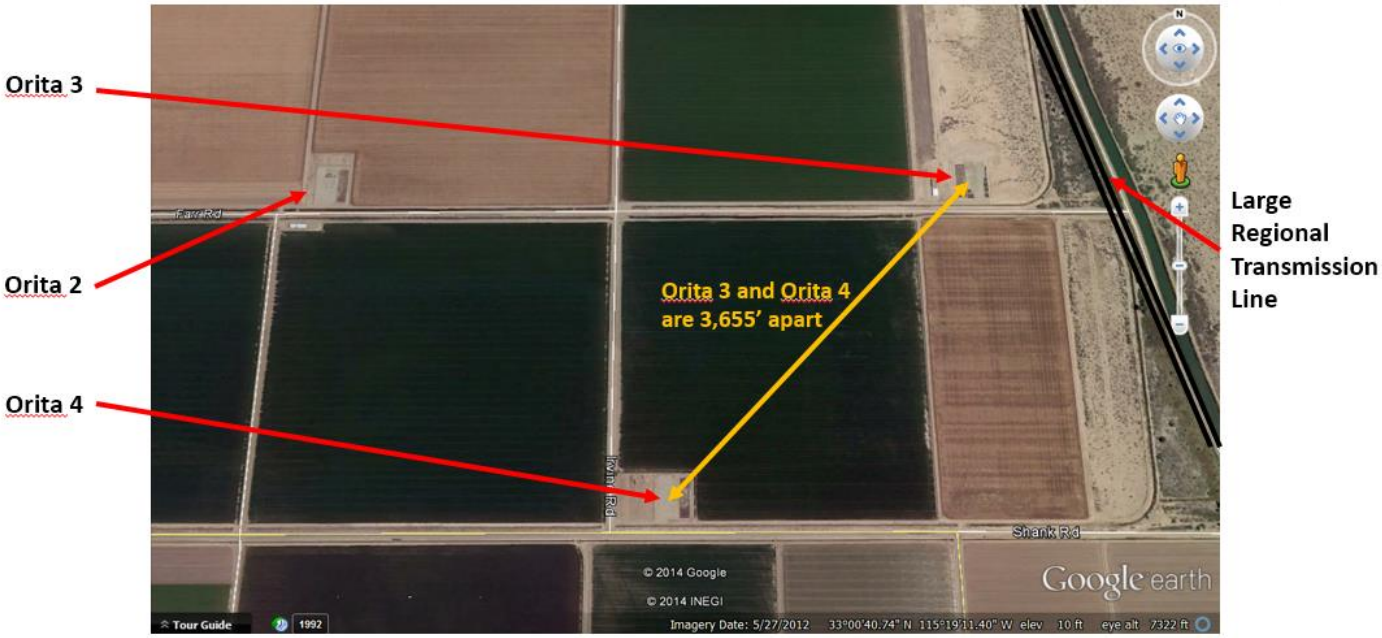
Appendix R

Location of the East Brawley Field



Appendix S

Location of the Orita Field



Appendix T

Spending Plan for Phase II

Category	$ 000	Total
Drilling costs		
Engineering	$75	
Project management	$188	
Horizontal drilling consulting	$503	
Drilling and associated services	$2896	
Materials	$1270	
Subtotal drilling costs		*$4,931*
Surface equipment		
Piping, valves, controls, orifice plate	$915	
CO2, delivered and compressed	$48	
Site preparation	$25	
Subtotal surface equipment		*$988*
Testing		
Fiber optic monitoring cable	$150	
Consulting	$200	
Subtotal Testing, etc.		*$350*
Subtotal		***$6,269***
Contingency (11.7%)		*$731*
Estimated Total Project Cost		**$7,000**

Appendix U

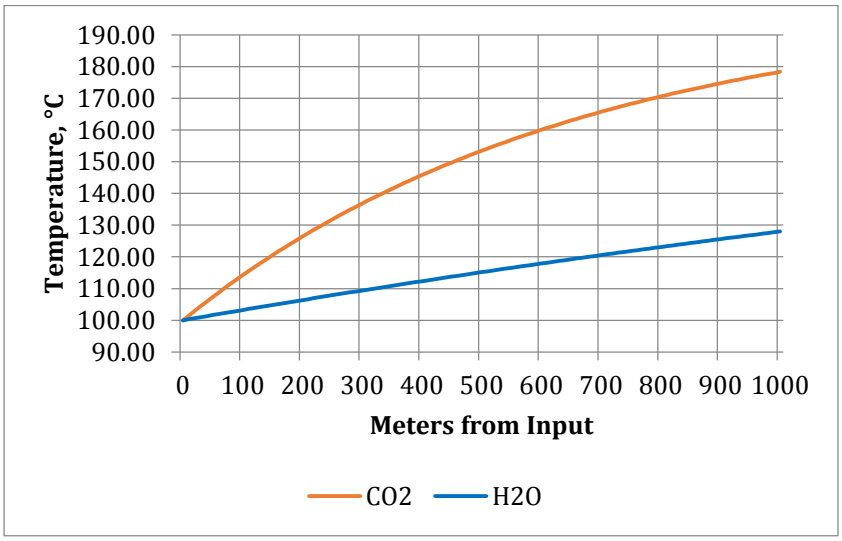
Spreadsheet for Modeling Heat in Horizontal Pipe

Input Values (some from other calculations)				
Parameter	**Value**	**Units**	**Value**	**Units**
Pipe diameter	7	in	0.1778	m
Hole diameter	8	in	0.2032	m
Pipe length	1000	m		
SCO2 flow rate	120	kg/sec		
Inlet SCO2 temp	100	C		
Outlet SCO2 temp	178.35	C		
SCO2 density	150.00	kg/m^3		
Water density	718.39	kg/m^3		
Energy extracted	11.47	MW		
H2O heat capacity	5.68	kJ/kg-K		

Calculated Values *Volumetric Basis*		
Parameter	**Value**	**Units**
Volume of annulus	7.60	m^3
Mass of H2O in annulus	5460	kg
Volume of pipe	21.41	m^3
SCO2 residence time	26.76	sec
SCO2 velocity	37.37	m/sec
SCO2 velocity	122.60	ft/sec
SCO2 velocity	83.6	mi/hr

Appendix V

Typical Results of Modeling Heat in Horizontal Pipe



Appendix W

Revised SOPO, Phase II

New Task 7.0 – Obtain appropriate permits

Task definition: GreenFire will obtain all required permits, including:

- *Conditional Use Permits* for both above- and below-ground activities
- A *CEQA Negative Declaration* (in lieu of an Environmental Impact Report)
- Authority to Construct for the project as a whole

and will file a *Notice of Intent to Drill Geothermal Well*

All of these permits will be obtained through the appropriate permitting agencies, in this case, Imperial County and the Imperial County Air Pollution Control District

New Task 8.0 – Horizontal drilling from existing wells to form loop

Task definition: GreenFire will use directional drilling techniques from the oil and gas industry to complete a horizontal well connecting Orita Well #3 and Orita Well #4.

New Task 9.0 – Design and construct surface equipment

Task Definition: GreenFire will design and construct surface equipment to inject, control, and monitor SCO2 behavior in the system.

New Task 10.0 – Design and install orifice plate

Task definition: GreenFire will design and install an orifice plate to accurately simulate the pressure drop expected from a turbine. It is understood that the temperature loss will not be an accurate simulation of a turbine.

New Task 11.0 – Load system, test the thermosiphon and orifice plate

Task definition: GreenFire will load CO2 into the system, bring it to the supercritical state, test the starting and running properties of the thermosiphon, and observe the behavior of the system through the orifice plate. As part of the process, we will also pressure-test the system for leaks, measuring any leakage. From the pressures and temperatures on either side of the orifice plate, we will assess the power generation capability of the system. From measurements of pressure, temperatures, and flowrates over multiple weeks of operation, we will assess the amount of heat loss in the formation, permitting an estimate of thermal depletion time.

New Task 12.0 – Project management and reporting

Task definition: GreenFire will manage the project in accordance with DOE regulations and practices, making sure that project goals are met. GreenFire will also submit all required reports, including those at the normal quarterly intervals. GreenFire will also share appropriate data with the NGDS national data system.

New Task 13.0 – Build and maintain good community relations

Task definition: GreenFire will build and maintain good relations with the Imperial Valley community, its citizens, institutions, and stakeholders.

Appendix X

Permits Required in the Imperial Valley

Permit required	Permitting agency[3]	Time req., months.	Cost, $x10^3$
For drilling well(s) – Phase II			
Conditional Use Permit (for well drilling)	Imperial County[1]	6[4]	-
Conditional Use Permit (for non-well construction)	Imperial County[1]	6[4]	-
CA Env.Quality Act Initial Study/Neg. Declaration	California EPA[2]	6[4]	-
Notice of Intent to Drill Geothermal Well	CA Div. of Oil, Gas, and Geothermal Resources[2]	6[4]	-
	Total permitting cost		**$50**

1 – In Imperial County, due to the county's experience with geothermal, the CA Division of Oil, Gas, and Geothermal Resources (DOGGER) delegates CA Environmental Quality Act (CEQA) matters to the county.

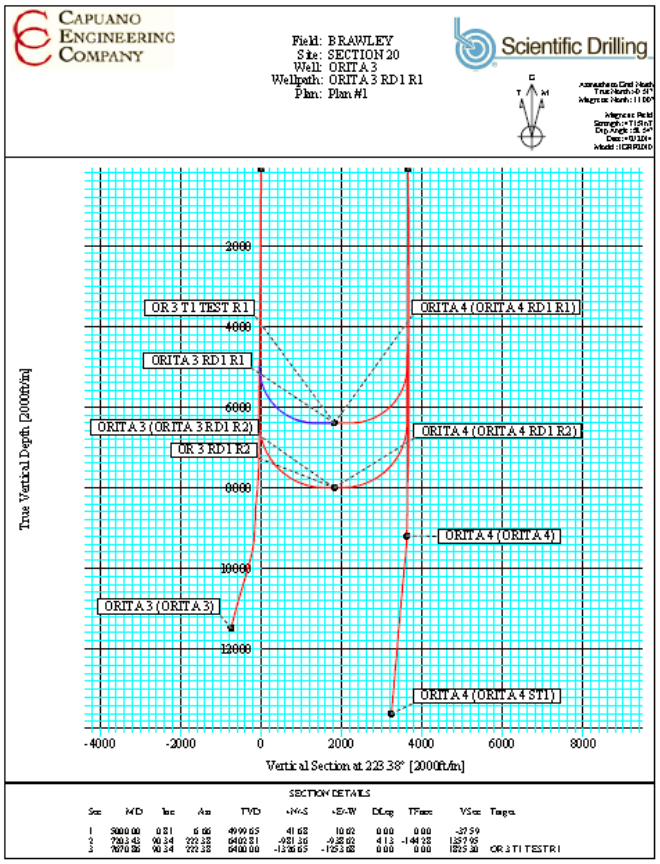
2 – For geothermal projects, California EPA delegates CEQA authority to DOGGER.

3 – Since the various state agencies have delegated their regulatory authority over geothermal projects to Imperial County due to of the county's experience with geothermal, the county is the only permitting agency with which we will have to interact.

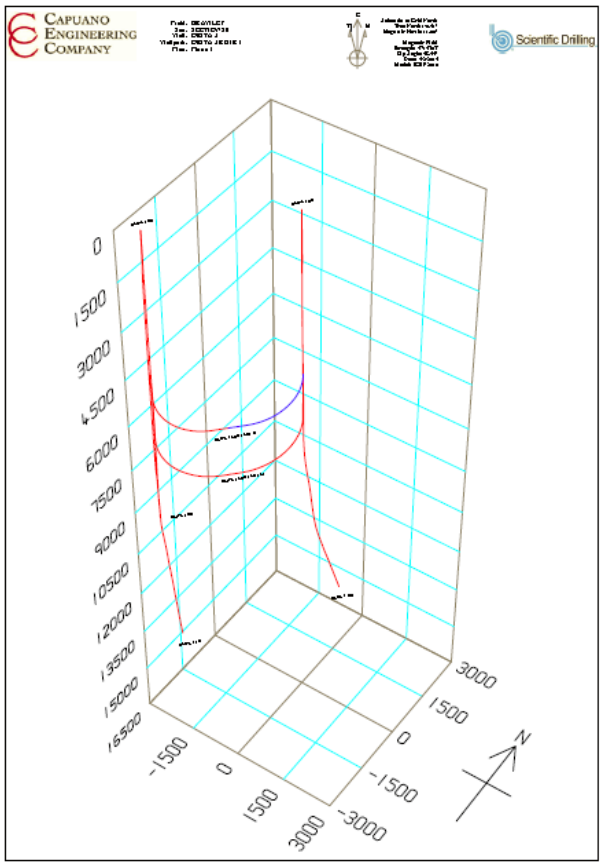
4 – These permits may be pursued in parallel, so 6 months the approximate time to obtain all necessary permits for each phase.

Appendix Y

Schematic Diagrams of Two-Well System



2-D Well



3-D Well