ANNEX I

Project Plan

Utilization of Supercritical Geothermal Fluid

Project ID:	**09-02-010**
Coordinator:	Guðrún Sævarsdóttir / Reykjavík University
Start date:	April / 2010
Duration:	<# of years/months>
Partners:	University of Iceland Reykjavik University Mannvit

1 Project description

1.1 General description

The Iceland Deep Drilling Project (IDDP) aims to recover geothermal fluid at supercritical conditions from deep wells. It has been estimated that such higher enthalpy sources may increase productivity by an order of magnitude compared to conventional existing wells. The focus of the IDDP to date has been on preparing the technical infrastructure to drill and test several high temperature boreholes. These efforts have included new geophysical and geochemical sensors, such as at the HITI project at the GFZ German Research Centre for Geosciences [1]; design and siting of the wellbore to properly access the geothermal reservoir and protect the well casing from the severe environment; and examinations of the properties of supercritical geothermal fluids. The MIT report[2] on Enhanced Geothermal Systems (EGS) opened the possibility that EGS reservoirs may encounter comparable pressures and temperatures, which may dramatically expand the applicability of this technology.

An identified need of the IDDP that has not been extensively explored is to assess the various power conversion or fluid utilization options possible from the geofluid once it has been brought above grade. While supercritical fluids offer increased exergetic potential compared to conventional geothermal fluids, the challenges in handling this fluid will be considerable, and the few studies that have considered this have limited analysis and are not in agreement. Fridleifsson and Elders [3] assumed binary cycles would be best suited to address this challenge. Tester, DiPippo, and others [2] have proposed several cycle types including triple expansion, arguing heat exchangers would be prohibitively expensive. No studies have yet critically assessed the equipment limitations of the various selections, with an eye towards acknowledging that reasonable sacrifices in efficiency or innovative techniques to reduce the corrosive/erosive nature of the fluid may be necessary to practically harness this resource.

Direct use of the fluid in a supercritical turbine may be the most appealing from a theoretical viewpoint, but the progression to inlet pressures of over 200 bar represents a significant new frontier for which geothermal-appropriate equipment is not currently available. Despite metallurgical advances, impurities such as chlorides or inert solids in geothermal fluids are a threat to the integrity of the turbine, and the use of fluid far from the saturation curve which may contain acidic volcanic gases creates new challenges for maintaining a steam purity that will be compatible with the plant materials. Similarly, while the use of a binary cycle may initially seem compelling to protect the turbine, this shifts the burden of exposure to the fluid to the heat exchanger, with attendant challenges of tube corrosion, challenges involving tube thicknesses and heat transfer coefficients, and fouling concerns. Alternatively, it may be more attractive, rather than for electrical generation, to use the geofluid to drive a chemical reaction, such as the production of hydrogen from the copper-chloride thermochemical cycle.

The goal of this research is to model and assess the advantages of utilizing supercritical geothermal fluid in a variety of power cycles or synthesis processes, with exploration of the design features and thermo/economic tradeoffs required in the associated equipment such as heat exchangers, scrubbers, and turbines. The proposed research is a first step towards what may develop into several branching paths spanning geochemistry, geophysics, and engineering, with many innovation and educational opportunities. The IDDP intends to flow test the recently completed well at Krafla, however as this has encountered a magma chamber it is uncertain how characteristic this will be. It is unclear under the existing circumstances when the funding will be available for additional IDDP wells in the Hengill or Reykjanes areas, although other work may proceed in Italy. Thus, the theoretical work proposed for this grant is an economical, long term strategic complement to these drilling programs to maintain momentum and help build a conceptual framework for how best to utilize this resource. The Fluid Handling and Evaluation (FHE) group of the IDDP, which includes the major Icelandic utilities and consulting firms as members, has previously identified further fluid utilization research as a helpful contribution to their efforts, and results would be freely disseminated to the group. If the FHE were able to share actual completed well data, these would be incorporated and evaluated in the study.

1.2 Scientific – and/or Technical objectives

It is instructive to consider a curve of the saturated pressure versus temperature for water (Figure 1) to appreciate the new frontier that the IDDP represents. On this curve are indicated some typical resource pressures and temperatures for conventional geothermal plants – ranging from the relatively low temperature utilization of hot water at Chena Hot Springs, Alaska by a binary cycle, up to relatively high pressure steam (~20 bar), such as is encountered at the Reykjanes plant. The vast majority of research on plant technology has focused on these conventional hydrothermal resources; generally below temperatures of 250 ^{o}C. The inset of figure 1 is an extension of the saturation curve up to the critical point (374 ^{o}C, 221 bars for pure water). We can see from this how radical a departure from existing plant designs the use of supercritical fluid technology would require.

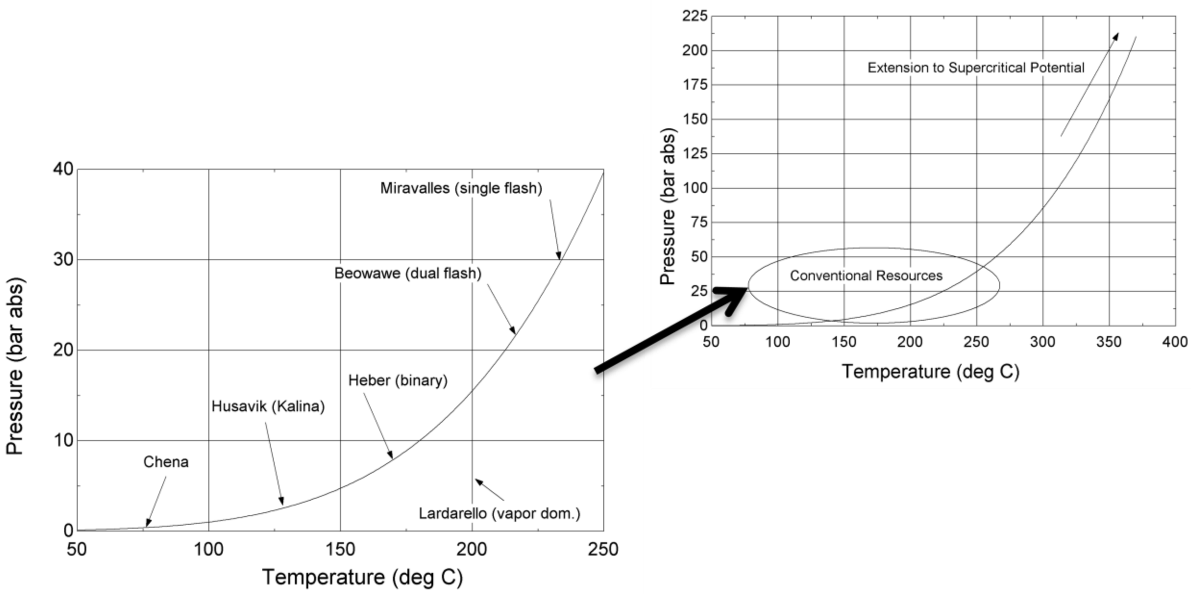

Figure 1: Saturated pressure-temperature relationship for water showing conventional regimes and capability for extension to the critical point

Many new geothermal above grade initiatives focus on accessing lower-temperature hydrothermal resources, such as the LOW-BIN project or the PureCycle; or on EGS. The thrust of the IDDP into high grade hydrothermal resources represents a different path. Improvements in drilling technology and

EGS reservoir engineering may bring more and more of these high temperature resources into play. This will require significant new engineering approaches and equipment to be developed to deal with the fluid.

The team working on this project aspires to bring the following aspects into sharper focus and attempt to quantify some of the challenges and benefits, such as but not necessarily limited to:

a. ***What would appropriate power plant configurations be, and how would these vary with different regions of high superheat/supercritical resources?*** This aspect would be investigated with cycle modeling using Engineering Equation Solver (EES), evaluating power output and exergy destruction pathways per unit of geofluid for various options.
b. ***What are the incremental advantages in plant costs that an IDDP plant could offer, or what are the major challenges to making these more economical?*** A reference "conventional" plant would be designed, and the sizes of major equipment and systems compared to the various IDDP options to gather a relative perspective on the possible advantages of the IDDP configurations.
c. ***What would be the appropriate steamfield configurations?*** The current study would need to identify key assumptions regarding geofluid production per well, evaluate wellhead properties given down hole conditions, and likely leave other aspects as open but intriguing questions, highly reliant on well testing and additional reservoir engineering that would need to be covered in a separate study.
d. ***Are binary cycles with a "clean" water working fluid and conventional steam turbine technology feasible?*** A heat exchanger satisfying the power cycle design investigated in (a) would be designed and thermoeconomically evaluated.
e. ***Can moderate superheat dry scrubbing techniques be extended to high superheat/supercritical zones, or are there other technologies that can be used to protect equipment from acidic volcanic gases?*** If heat exchangers will be impractical, a technical/economic evaluation of scrubbing and direct turbine admission will be required.

1.3 Innovation / Entrepreneurship

Current technology does not have the potential to receive supercritical geothermal fluids and properly utilize the enthalpy carried with it. Therefore technological development and innovation is an inherent part of making it possible to utilize this heat source. The IDDP has ambitious goals that are intertwined to the international EGS programs to the extent that very hot dry rock resources may develop similar pressures and temperatures and require similar abovegrade utilization options. As a result the scope of applicability for this plant equipment will be expanding at a pace commensurate with improvements in drilling depth and technology worldwide, radically expanding the customer base for applicability of geothermal power, and correspondingly, Icelandic expertise.

1.4 Education / Dissemination

This project has the potential to expand the involvement of Icelandic universities in the IDDP project, since regardless of the time scale for implementation or economic feasibility, it provides an ideal platform for engaging interested students and prospective workers in the field. The challenges are sizeable, but research along these paths has the potential to further expand Icelandic expertise in the various related fields of geochemistry, geophysics, and plant engineering as a "unique brand". The proposed M.S. study is intended as stand-alone, but also as a potential gateway to other interesting problems related to design using resources several times more energetic than the best currently available. The results of this specific study would be shared with the FHE group and submitted to appropriate geoscience/engineering outlets as well as forming a M.S. thesis.

1.5 Objectives and GEORG WP relevance

The IDDP is an interesting frontier of geothermal development which is prime to attract new young technical experts into the field, as this proposed M.S. project will do in accordance with the objectives of WP2. The main thrust of this work is on the heretofore lightly covered aspect of the above-ground processes and equipment needed to harness high-superheat or supercritical fluids, falling under Task 5.5 of WP5. This is related quite closely with Task 4.6 of WP4 (subsurface aspects), and is intended as a first step towards a longer-term strategic view on how to handle these resources.

1.6 References:

[1] GFZ German Research Centre for Geosciences, "High Temperature Instruments for supercritical geothermal reservoir characterization and exploitation," *Helmholtz Centre Potsdam*, June 2008 [Online]. Available: http://www.gfz-potsdam.de/portal/-?$part=sec52&locale=en [Accessed: Aug. 6, 2008].

[2] United States. Department of Energy. *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century*. Idaho Falls, ID: Department of Energy, 2006

[3] G.O. Fridleifsson and W.A. Elders, "The Iceland Deep Drilling Project: a search for deep unconventional geothermal resources," *Geothermics*, No. 34:269-285, 2005.

2 Work plan and time schedule:

A promising candidate student from HR, HÍ, or the REYST program would be engaged in Spring 2010. During that same time other funding sources such as the OR, LVP, or US grants would be explored. The student would be able to build on other preliminary studies currently underway regarding how best to configure power cycles to utilize the high temperature fluid. With options in hand, a map of reasonable parameters (pressure, temperature, gas content) over which to evaluate options would be developed. The student would perform preliminary design and costing of proposed plants/processes, with an eye towards identifying incremental improvements in plant economy that the IDDP resources may offer. If reliable geochemical data from IDDP wells become available in the course of the study, configurations could be tuned to reflect the likely conditions. Key challenges or gaps in current knowledge/technology such as heat transfer coefficients, dry scrubbing technologies for high superheat, or corrosion performance of selected materials would be identified and potentially spun off into parallel research projects. The results would be disseminated following the M.S. thesis defense in 2011.

2.1 *Time schedule:*

Subtask	Start	Finish	Deliverable/Milestone
Literature review and preliminary screening of options	Apr 2010	June 2010	Select student. Preliminary draft of options to explore, identifying gaps in current work
Cycle-level comparison	May 2010	Nov 2010	Presentation of the various cycle options
Equipment-level comparison, with identification of key cost drivers or technology challenges	Dec 2010	Mar 2011	Equipment sizing and cost estimates, including heat exchanger design and optimization assuming given fluid properties
Dissemination of the results	Apr 2011	Jun 2011	M.S. thesis defense Technical paper and/or conference presentation

3 Project Management

The project leaders are Guðrún Sævarsdóttir and William Harvey from Reykjavik University, Halldór Pálsson from the University of Iceland, and Kristinn Ingason from Mannvit. The team´s experience includes geothermal powerplant design, and research on power cycle analysis, optimization and equipment design. The financing plan shown below assumes the contributions of the time for the various researchers in proportion to their responsibilities, and the requested funding is to provide a small stipend for the graduate student.

4 Budget overview

4.1 *Financing:*

	Cost item	Requested funding		Other financing		Total
2010/2011	Salaries					7.990
	Operational expenses					0
	Travel expenses					0
	Total 2010/2011:	1.890	24%	6.100	76%	7.990
2011/2012	Salaries					4.730
	Operational expenses					0
	Travel expenses					500
	Total 2011/2012:	1.130	22%	4.100	78%	5.230
2012/2013	Salaries					0
	Operational expenses					0
	Travel expenses					0
	Total 2012/2013:	0	N/A	0	N/A	0

Grand Total	**3.020**	**23%**	**10.200**	**77%**	**13.220**