A Proposal to Develop Ultra High-enthalpy Geothermal Systems in the USA

by Wilfred A. Elders, Dept. of Earth Sciences, University of California, Riverside, CA 92521, USA.
(wilfred.elders@ucr.edu).

In October 2013, thirty scientists, engineers, and policy makers gathered at the University of California conference center at Lake Arrowhead in the San Bernardino Mountains of southern California at a workshop to discuss developing a program to produce electrical energy from very high-enthalpy geothermal fields in the USA (see http://csdworkshops.geo.arizona.edu/Lake_Arrowhead_CA.html). Two attendees from New Zealand, two from Mexico, and one from each of Iceland, Italy, Philippines, and Russia participated in the workshop, which was convened by Wilfred Elders of the University of California, Riverside. The workshop had two objectives, firstly to discuss scientific and engineering studies of active higher-enthalpy hydrothermal systems, and secondly to stimulate collaboration between academic scientists, government agencies, and industry (Elders, 2013). Such collaboration is highly desirable because research on active hydrothermal systems requires access to boreholes whose costs far exceed budgets normally available to academic scientists. It is industry that drills the wells that access and produce geothermal resources.

Although the USA is currently the world leader in generating electricity from naturally occurring geothermal resources, future growth is limited by the economics of competing sources of renewable or non-renewable energy. For example, a geothermal well between 2,000-3,000 meters deep, and costing several million dollars, typically produces a mixture of hot water and steam at 200-300°C that can be used to generate only about 5-10 MWe of electric power. The theme of the workshop was to explore the feasibility and economic potential of increasing the power output of geothermal wells by an order of magnitude by drilling deeper to reach much higher pressures and temperatures, where water exhibits *supercritical* behavior. The critical point for pure water occurs at 220 bar and 374°C. Exceeding such pressure-temperature conditions requires drilling to depths of 4 to 5 km. Supercritical fluids have higher enthalpy and greatly enhanced rates of mass transfer relative to conventional lower-temperature geothermal resources. An aqueous geofluid at supercritical conditions with a temperature of 400°C and a pressure of 250 bar has more than five times the power producing potential than a hydrothermal liquid water geofluid at 225°C (Tester et al, 2006). Not only do such fluids have higher enthalpy than conventional geothermal reservoir fluids, but they also exhibit extremely high rates of mass transport due to the greatly enhanced ratios of buoyancy forces to viscous forces in the supercritical state (Fournier, 1999; Hashida et al., 2001).

The USA is falling behind in the development of such high-enthalpy geothermal resources, whereas, as was explained at the workshop, plans for resource assessment and drilling into higher enthalpy geothermal systems are already underway in Iceland, New Zealand, and Japan. There is also considerable potential for similar developments in countries that already have a large production of electricity from geothermal steam, such as the Philippines, Indonesia, Mexico, and Italy.

Figure 1. The flow of the well IDDP-1 into a rock muffler produced dry superheated 450°C steam with only 0.1-0.2% of non-condensable gases. Initially corrosion products gave the steam a dark color but after a few minutes it became clear and transparent. The condensate had a pH 2.5-3 due to its HCl content. However experiments on wet scrubbing to remove acid gases from the dry steam were very successful. (Photograph courtesy of Kristján Einarsson).

The national program that has made the most progress in researching high-enthalpy resources is the Iceland Deep Drilling Project, (IDDP). The January 2014 issue of the international journal *Geothermics* is dedicated to the IDDP (see also www.iddp.is). It contains 15 papers, mostly dealing with the first IDDP hole drilled in the Krafla caldera in northeast Iceland in 2009. The well IDDP-1 was the first in a planned series of 4 to 5 km deep wells to be drilled in the search for supercritical geothermal resources. However, drilling the IDDP-1 was terminated at only 2.1 km depth, short of its target, when 900°C rhyolite magma flowed into the well, creating the hottest geothermal well in the world. **Figure 1** shows sub-critical, superheated steam flowing from that well at a temperature of 450°C at the surface and at pressures sufficient to generate ~ 38 MWe (Friðleifsson, Elders, and Albertsson, 2014). Planning is underway to drill the next well in the series in the Reykjanes geothermal field in southwest Iceland in 2014-2015.

Most of the new geothermal developments proposed in the USA involve relatively small, moderate-temperature, geothermal systems. In contrast, development of higher enthalpy geothermal systems for power production has obvious advantages. Although drilling to reach these deeper, higher enthalpy geothermal reservoirs is more expensive, the higher productivity per well should offset this by reducing the number of wells needed for a given power output. With higher temperatures yielding higher power outputs per well, fewer wells are needed, leading to smaller environmental footprints for a given size of power plant.

One approach to mitigating the cost issue is to form consortia of industry, government and academia to share the costs and broaden the scope of investigations. This is the approach taken by the IDDP, which is funded by a consortium of Icelandic energy companies and the Icelandic Energy Authority, a government agency. Furthermore the science program of the IDDP was largely supported by the US National Science Foundation (NSF) and by the International Continental Scientific Drilling Program (ICDP), an agency funded by a consortium of some 50 countries.

At the workshop, presentations were made outlining projects comparable, but differing in approach, to the IDDP that are already underway in both Japan and New Zealand. The Japan Beyond the Brittle Project (JBBP) plans to drill deeper than the brittle ductile transition in a 500°C or hotter granites and thermally fracture the rocks to form permeability in the ductile zone and thus create contained EGS systems (See jbbp@jbbp.kankyo.tohoku.ac.jp). The hope is to use a combination of government and industry funding to begin drilling in two or three years.

A similarly ambitious project is underway in New Zealand, although possibly not so far advanced as the IDDP or the JBBP. Hotter and Deeper Exploration Science (HADES) is a long-term program of exploration on the North Island of New Zealand that aims to use geological, geochemical and geophysical data to assess the resource potential of deep (up to 7 km) geothermal systems in the Taupo Volcanic Zone. Preliminary indications of this "Hotter and Deeper" project suggest that by 2025, New Zealand's deep geothermal resources (3-7km) could supply at least 20% of New Zealand's electricity requirement. (See www.gns.cri.nz/Home/Our-Science/Energy-

Resources/Geothermal-Energy/Research/Hotter-and-Deeper). Conservative estimates point to the total potential of accessible deep geothermal resource in the Taupo Volcanic Zone exceeding 10,000 MWe.

The most recent assessment of geothermal resource base to 10 km depth in the USA for different categories of geological environment was reported in Tester, (ed.), 2006. The major thrust of that report was to assess the potential of Enhanced (or Engineered) Geothermal Systems (EGS) in the USA, and it greatly increased the assessment of the EGS resource base of the USA in crystalline basement rocks over earlier estimates. However, it also showed that *supercritical* volcanic EGS also has a large potential in the USA amounting to 74,100 exajoules (1 EJ= 10^{18} J) as compared to 2,400-9,600 EJ for "conventional" hydrothermal resources.

In the USA there is no comparable national program to develop such resources although there is a significant undeveloped potential for developing high-enthalpy geothermal systems in the western USA, Hawaii and Alaska. For more than a decade the US Department of Energy (and its predecessor, ERDA) had a "*Magma Energy Program*" aimed at extracting high-enthalpy energy directly from magma, using a downhole heat exchanger. In February 1990 the *GRC Bulletin* was a special issue devoted to discussing that concept (Eichelberger and Dunn, 1990). After a nation-wide study (Finger and Eichelberger, 1990), the Long Valley Caldera in California was chosen as the optimum site in the USA to drill into magma and drilling was begun designed to reach a depth of almost 7 km in order to reach a magma chamber believed to exist below the caldera. However, due to funding problems, it was abandoned far short of its target, at less than 3 km depth, where the temperature was only 120^{o}C (Bender-Lamb, 1991).

One outcome of the workshop was to form a planning committee consisting of Wilfred Elders (UCR), Peter Schiffman (UCD), Dennis Nielson (DOSECC Exploration Sciences) and Alexander Schriener, Jr. (CalEnergy Operating Corp.) to encourage the creation of a government-industry-university consortium to systematically explore, assess, and eventually develop such ultra high enthalpy geothermal resources. Not only would this yield large new sources of energy but it would permit scientific studies of pressure-temperature regimes not otherwise available for direct investigation, such as the coupling of magmatic and hydrothermal systems and associated volcanic hazards.

Acknowledgements: The author thanks the attendees at the Lake Arrowhead workshop for their enthusiasm and fruitful discussions. The workshop was funded by an NSF grant to Elders (No. EAR-005400).

References Cited:

Bender-Lamb, S. 1991. "Magma energy exploratory well, Long Valley Caldera". *California Geology*, v. 44 (4), p. 85-92.

Eichelberger, J.C. and H.C. Dunn, 1990. "Magma Energy; what is the potential?" *GRC Bulletin*, - Geothermal Resources Council v. 19, (2), p. 53-56.

Elders, W. A., 2013. "A proposed collaborative initiative to promote development of higher-enthalpy geothermal systems in the USA." Geothermal Resources Council *Transactions*. v. 37, p. 263-270.

Finger, J.T., and Eichelberger, J.C., 1990. "The magma energy exploratory well." *GRC Bulletin*, - Geothermal Resources Council v. 19, (2), p. 36-41.

Fournier, R.O., 1999. "Hydrothermal processes related to moment of fluid from plastic into brittle rock in the magmatic-epithermal environment". *Economic Geology*, v.94, (8), p.1193-1211.

Friðleifsson, G. Ó., W.A. Elders, and A. Albertsson, 2014. "The concept of the Iceland deep drilling project." *Geothermics*, v.49, p.2-8.

Hashida, T., G. Bignall, N. Tsuchiya, T. Takahashi, and K. Tanifuji, K., 2001. "Fracture generation and water rock interaction processes in supercritical deep-seated geothermal reservoirs". Geothermal Resources Council *Transactions*, v. 25, p.225-229.

Tester, J.W., (Ed), 2006. "The future of geothermal energy: impact of enhanced geothermal energy (EGS) on the United States in the 21st century". *MIT Panel Report to the US Department of Energy*, p.1-54. (see also http://geothermal.inel.gov/). ■