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Krafla Magma Testbed (KMT): Engineering challenges of drilling into magma and extracting its energy

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ABSTRACT

Preparations are underway for drilling well KMT-1 of the Krafla Magma Testbed at Krafla, Iceland to sample and instrument the margin of a rhyolite magma body. The project is driven by the need to understand magmatic systems, to improve volcano monitoring strategies, and to develop next-generation, high-enthalpy geothermal energy. The planned depth of the well is 2100 m with cemented casings to 2040 m and a 8 ½" open hole section for coring to 2010 m. The geology for KMT-1 is well known and the well will be located close to IDDP-1 where magma was unexpectedly intersected at 2102 m depth in 2009.

1. Introduction

The Krafla Magma Testbed (KMT) project aims to establish the first *magma observatory* – an international, open access, scientific platform to advance understanding, monitoring, and use of magmatic and superhot hydrothermal systems. It is to be science infrastructure analogous to a telescope array, polar station, particle accelerator, or seabed observatory where a previously little know environment can be explored and understood, while at the same time developing materials and instruments that make long-term "occupation" possible.

Strategies for monitoring dangerous volcanoes aim to resolve the location, state and mobility of magma in the crust in order to assess their threat level. Efforts have ranged from ground analysis (including deformation and seismicity), gas sampling, temperature monitoring, aircraft and satellite surveys, and most recently, to tomographic imaging of volcanic structures using muons emitted from the Sun. In certain cases, shallow boreholes have been employed to measure strain associated with movement of magma, to emplace seismometers away from surface noise, and to record eruption stratigraphy. Recently, in efforts to advance understanding of the roots of geothermal systems believed to sit atop magma reservoirs, the geothermal community has undertaken several large-scale, deep drilling initiatives; amongst them, the Iceland Deep Drilling Project (IDDP) – an international venture that sought to drill into, and exploit, hydrothermal fluids at supercritical conditions (i.e., very high pressure and temperature beyond the termination of the boiling curve that separates liquid from vapor) for next-generation geothermal energy. Whereas this has not occurred during the first phase of IDDP at Krafla volcano (i.e., IDDP 1 in 2009), supercritical fluid conditions (dependent on actual fluid compositions) were successfully encountered during the second drilling phase of IDDP/DEEPEGS site at the Reykjanes peninsula (i.e., IDDP-2 in 2017). Yet, IDDP-1 was pivotal for the geoscience community, as drilling activities serendipitously intersected magma at a depth of 2.1 km. Interestingly, this finding has aided dissemination of information regarding two additional sites of magma encounters, at Puna (Hawaii, USA) and one at Menengai (Kenya), also at 2-3 km depth.

As a facility for repeated access to a magma body by the international scientific and engineering community, KMT comprises phase with at least three boreholes. The 1st phase of the project is a proof of concept, drilling a dedicated research borehole near IDDP-1. Can we recover core through the interval from the base of the hydrothermal system to magma and conduct long-term temperature monitoring through this coupling zone? These achievements would yield the first tests of models for magma crystallization and contact metamorphism and the first determination of heat flux from a magma body. In n parallel, KMT will collaborate with the sensor community to develop new temperature-resilient technologies to monitor pressure and other parameters. The borehole will be cased using new innovative, patented, flexible couplings allowing the steel to thermally expand without accumulating enough stress and strain to cause failure of the casing. Following a successful recovery of a core, the borehole will be allowed to heat up, under constant monitoring and supervision. Characteristics of thermal recovery of magma and its roof will reveal thermal properties of the material and determine heat flux out of magma after steady-state conditions are reached.

The drilling engineering team has proposed a preliminary well design and developed the criteria, which were:

- The well will be vertical to approximately 2100 m depth.
- The production casing design will include expandable casing couplings, designed by Iceland Geosurvey ISOR.
- The design will aim for two main purposes: 1) to recover a core from through the brittle to ductile, ductile to partially melted (solidus), crystals-present to ~no crystals (liquidus) boundaries solid between and molten rock and continuously monitor a temperature profile through that interval.

2. Well Design and Drilling

The KMT-1 well is situated within the existing Krafla geothermal field that produces steam from about 18 boreholes feeding two turbine generators with a total rated capacity of 60 MW_e. The powerplant supplies electricity and hot water for the region. With a total of 47 wells drilled, the drilling challenges are well known. Some wells have penetrated the high-temperature, high-pressure steam that overlies the magma and a few have penetrated the rhyolite magma itself. While there are certainly challenges and risks drilling down to the top of the magma, they are mostly known and can either be managed or have acceptable risks. The lessons learned from operating the IDDP-1 well with 450 °C and 140 bar at the well head and the subsequent material testing in-situ in the superheated steam were taken into account in the well design of the KMT. Valuable information, such as susceptibility to corrosion of different API casing material and corrosion resistant alloys were obtained for the IDDP-1 chemistry (Karlsdottir et al. 2014, Hauksson et al., 2014, Karlsdottir et al. 2015). The IDDP-1 steam contained H_2S and CO_2 gases as well as HCl and HF which made the condensate acidic and very corrosive with low pH level (Armansson 2014, Hauksson et al. 2014). Also, examination of steel fragments from down-hole and casing material excavated from the top 10 meters of IDDP-1 well revealed extensive hydrogen damage of the API K55 carbon steel production casing material and indications of degradation of the cement casing in the well (Karlsdottir et al. 2018, Wallevik et al. 2018). Thermal cycling of the IDDP-1 well casings is considered to be the main cause for the rupture of the production casing at several locations down to 600 m depth. These failures developed at joints where the casing had been pulled down and teared from the coupling, most likely due to tension from thermal contraction (Ingason et al. 2014, Kaldal et al. 2016).

Scoping engineering has been completed. The KMT project budget includes funding for final engineering to be conducted and preparing strain-based designs for high-temperature wells. That work may change or complement the technological developments required to manage each of these challenges, but the developments, as envisioned in the preliminary engineering, are discussed in the following sections.

2.1 Drilling Program

Drilling will proceed as follows (Fig. 1):

1. Drill 28” hole from surface to 100m. Run and cement 24”, with >0.5” wall, K-55 casing with a Portand/silica based cement from total depth to the surface.
2. Install starting wellhead and 26-3/4” 3M Blow out preventer assembly
3. Drill 22” hole with mud motor from 100m to 710m. Run and cement 18-5/8”, 99 pound/ft, L-80 casing with Portland/silica based cement (may need lightening or have backfill strategy) total depth to surface.
4. Cut off 24” casing and install starting wellhead and 21-1/4” 5M blow out preventer assembly on the 18-5/8” casing
5. Drill 17-1/2” hole from 710m to 1145m with mud motor. Run and cement 13-3/8”, 68 pound/ft, L80+1.5%Cr+0.5%Mo casing with a calcium phosphate based cement (caveat as above) from total depth to the surface.
6. Cut off the 18-5/8” casing and install the wellhead on the 13-3/8” casing, then a 21-1/4 5M blow out preventer assembly.
7. Drill 12-1/4” hole from 1145m to ~2040m, monitoring the cuttings, mud gas, and temperatures for any indication that the magma is near. Run and cement 9-5/8”, 47 pound/ft,

L80+1.5%Cr+0.5%Mo casing with a calcium phosphate based cement (caveat as above) from total depth to the surface. The L80+1.5%Cr+0.5%Mo casing material has higher yield strength than the API K55. It also contains Cr and Mo additives that increase the resistance of the steel against hydrogen damages in the form of High Temperature Hydrogen Attack (HTHA) which was considered to be the corrosion form responsible of extensive cracking and damages seen in the IDDP-1 API K55 production casing material.

8. Test the casing and drill out the shoe and drill 10 m of new formation.
9. RIH with coring assembly and take a 10 m core.
10. If total losses occur (such as occurred at 2070 m in IDDP-1), begin continuous coring.
11. If there are no losses, alternate drilling and coring until the first sign of approaching the magma-hydrothermal coupling zone. Core continuously from there with the minimum objective of reaching liquidus rhyolite magma (at least a portion of the core will be all glass). Use appropriate drilling rates for the circulation rate, based on thermal modelling, to keep equipment cooled and the magma quenched. At some point, further progress in “making hole” will not be possible due to walls closing or magma upflow (as in IDDP-1) during tripping to retrieve core.
12. Retrieve cores.
13. Reopen the hole with the coring bit, without the core barrel.
14. Run the thermocouple to the bottom of the well, rig down and release the drilling rig.
15. Continue injecting water to keep the magma quenched and run the sensor package.
16. Rig release.

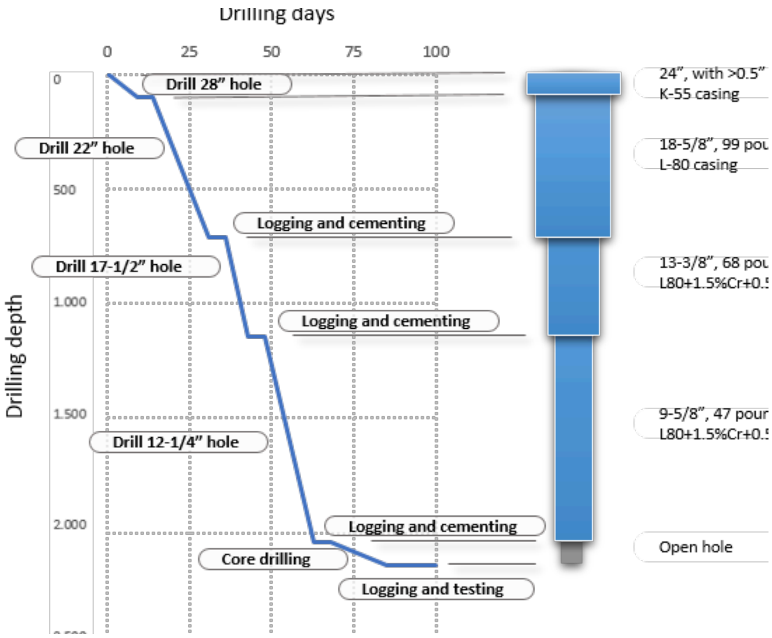

Figure 1: Preliminary drilling plan for KMT-1.

The drilling will cease upon encountering the total loss zone, known to overlie the magma reservoir. By changing to coring when total losses occur, formation samples will be recovered every 10 meters before entering the magma.

2.2 Coring

Coring magma is possible if it is quenched to a glass, using drilling fluids. Under such a solid state, the glass (i.e., frozen-in magma) can be cored like any other rock. This has been demonstrated many times in sampling lava lakes in Hawaii, with excellent core recovery. Extensive thermal modelling has already been done to assure the magma will be adequately quenched prior to coring; in doing so, the temperatures are maintained below the thermal limits of the coring equipment with the borehole fluids maintained below their boiling point at *in situ* pressures. More thermal and finite element stress modelling is underway to define the thickness and strength of the quenched magma around the borehole, forming essentially a temporary glass casing.

When cores are retrieved, the drilling fluid ceases to circulate; it is estimated that it will take approximately 1 day to retrieve the core and re-insert the drill string in the well. During this time, the quenched-in magma will reheat and may remobilise, flowing slightly up the borehole, until it until it reaches a depth at which the surroundings are too cold to inhibit further flow. The quenched-in magma will be cored using a 10 m long barrel. This will allow additional sampling of the magma, however the most critical information will come from the cored section through the chamber ceiling to and including the first of the magma. This interval has a thermal gradient $\geq 20^{\circ}C$, so there will be major changes in phase assemblage and melt fraction even within a single barallel length. Among three penetrations of magma by IDDP-1 and sidetracks, the maximum upflow was 9 m.

The core bit is of the impregnated type and has large cut-outs that allows flow up to 40 l/s of water to be circulated. It is important that water will be circulated while tripping in and out of the hole to efficiently cool the barrel. A coring specialist will be on site to assemble the core barrel and provide advice to the driller during the coring operation. The drilling crew will receive the assembled core barrel on site and are responsible for its care and operation. Once the core barrel is out of the hole the crew will place the barrel on a truck for transport to a warehouse by the Krafla station.

Figure 2 shows results from numerical modelling that coring into 900°C Krafla magma with the tool developed by IDDP is entirely feasible. For plausible fluid flow and penetration rates, the bit face is held below 100°C, the coring tool is kept well below its operating limit of 220°C, magma is quenched ahead of the bit and before entering the core barrel, nowhere in the borehole does the circulation fluid reach the boiling point. The portion of the magma margin that can be sampled by coring will be limited because with increasing depth the hole will tend to close during drill string trips to retrieve core.

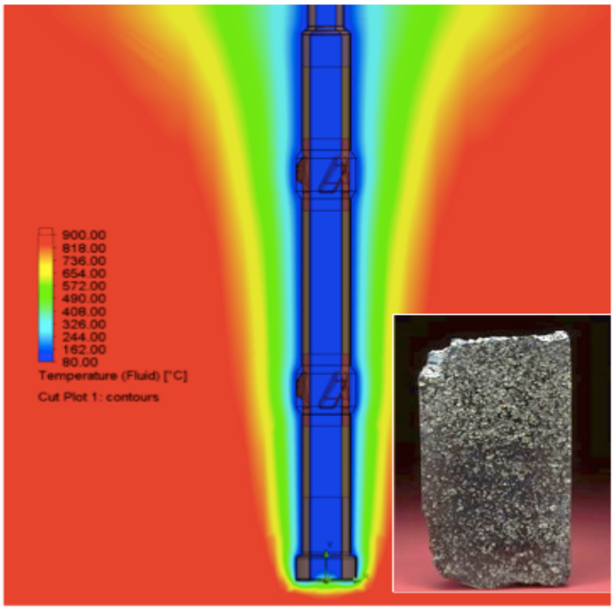

Figure 2: Numerical model of IDDP coring tool in Krafla magma at likely penetration rate of 2.5 m/h and fluid flow of 25 L/s. Red is magma, green and cooler is glass, blue is ~200°C and below. By J-C Su, Sandia Natl. Labs. Inset shows KI core with downward transition from crystal- to melt-rich.

2.3 Casing Design

One of the design premises to be established for the well is high-temperature, corrosive gasses and corrosive fluids. This affects the selection of number and depth of casing strings, casing depth and materials. The casing design assumes four cemented casing strings and the open hole diameter would be 8 ½”. This will allow sufficient fluid circulation for adequate cooling and control of the well. The casing setting depths and wall thicknesses are based on NZS 2403:2015, the New Zealand Standard Code of Practice for Deep Geothermal Wells but will be optimized for the conditions at the actual well site, when the location is confirmed.

In current, conventional wells, each segment of the casing is screwed together; when temperature increases (if fluid circulation ceases or during flow tests) thermal expansion results in significant stress build-up which may exceed the casing strength, thus causing yielding, buckling and failing. In order to foster the development of next-generation high-enthalpy geothermal energy, new flexible coupling solutions to secure each segment of casing have been designed, which permit free axial motion during thermal expansion, thus preventing the building up of excessive stresses that may jeopardise their structural stability. This novel solution will be tested and optimised for wider application during KMT.

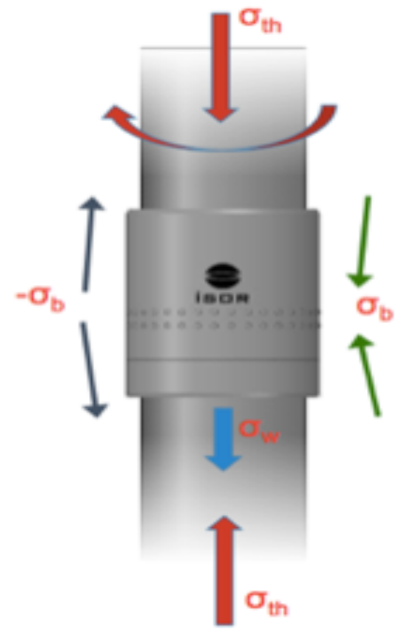

Figure 3: Slip coupling designed by ISOR to accommodate thermal expansion, to be tested in KMT-1. Courtesy of ISOR.

Full-scale prototypes have been tested and validated in the H2020 project GeoWell. Ongoing H2020 project DEEPEGS will further validate the function of the Flexible Coupling. The GEOTHERMICA supported project GeoConnect will validate the flexible coupling concept in real geothermal environment (*in situ*), the integrity of cemented annulus and the casing using flexible couplings in a surface experiment. Following positive results of these tests, the plan for KMT-1 is to use this casing design to demonstrate and test its function.

Cement will hold the casing in place, while the temperature will change from ~20°C (when injecting or drilling) to ~500°C (when monitoring thermal equilibration of magma during Phase 1 or flow testing during Phase 2). Finite-element modelling will help quantify the strains and provide input into the material selection process. Technical extension of the testing equipment to handle the temperature increase anticipated at Krafla will be required to complete the testing required for the KMT-1 well. The casing will be inspected at the end of the project.

As the steam from the well will be rich in gasses other than H_2O, especially H_2S, CO_2 and HCl, the material selected will be resistant to brittle cracking caused by hydrogen penetration into the metal structure (HIC) and sulphide stress cracking (SSC). Metals such as L80 is dedicated API grade, suitable for acidic service environment and has proved to be suitable material.

To prevent long-term contact of the casing with the corrosive fluids from the condensed steam, nitrogen or air will be compressed into the casing, pushing the water level to the casing shoe, buffering the chemical composition of the well, and minimising corrosion.

2.4 Cementing Techniques

Portland cement is conventionally used in boreholes. When water is added in exacting proportions to cement blends, the cement hydrates and sets. In geothermal boreholes, cement often contains retardant additives to ensure it sets slowly and homogeneously. Extensive use of this material under a range of conditions has provided a thorough knowledge of its setting and properties (e.g., strength, porosity, permeability (i.e., ability to let fluids through)). Yet at temperatures above ~80 ˚C, the cement dehydrates which reduces its mass, creating voids (pores), weakening the material, thus increasing its permeability, and jeopardising its structural integrity (Zhang and Ye, 2012). The permeability and long term durability of the Portland /silica based cement mixes could be improved further, for example, with a micro-silica addition of around 5%, according to investigations of such mixes in relation to the IDDP-2 well New calcium phosphate refractory cements, resistant to several hundreds of degrees Celsius, are currently being developed and tested which will enable prolonged structural stability of the cement casings in high temperature boreholes like KMT-1. The current plan to assure competent cement placement in KMT-1 includes reducing the cement density so its pressure does not exceed the minimum principal stress in the rock or risk of collapse of the casing. Several cementing methods will be considered such as, cementing from the bottom to top followed by filling the annulus from top if the cement subsides, stage tool or reverse circulation method, where the entire length of the casing is cemented from the top down. The final cementing design and method will be chosen during the design phase of the drilling program. Testing and improving high temperature cements is one of the goals of the KMT facility to follow drilling of the first borehole, KMT-1.

2.5 Well Head

The lower part of the wellhead consists of a master valve of the expanding gate type, an expansion spool and a casing head. No kill-line valves will be below the master valve as experience in Iceland has shown to require maintenance so instead the valves will be positioned above the master valve. Also learned from IDDP-1, any outlets increase the risk of condensation of steam resulting in heavy corrosion. The upper part consists of valves, flanged connections for quenching the well in case of an emergency, flanged connections for compressing nitrogen or air inside the casing, outlets for monitoring pressure and temperature on the wellhead, lubricator to adopt thermocouples and lubricator to run logging tools down the hole. The lower part will be installed while the rig is on the well and the upper part will be installed after the rig has been demobilised.

The size and pressure class will be 12” ANSI 2500 for all wellhead components except for the master valve, which will have ANSI Class 1500 body but ANSI Class 2500 flanges which is the strongest manufactured for this bore size.

All lower part components of the wellhead, including the master valve, will be cladded with corrosion-resistant material to improve the integrity of the components.

3. Logging

To ensure full characterization of the hole, wireline and/or memory tool logs will be run in all section of the hole below the 24-inch-diameter conductor pipe. Loggings tools will include gamma, neutron, resistivity, sonic, and caliper in upper sections of the hole at temperatures below about 150°C. Flowing into the hole during logging (as described below) will act to cool the hole and allow use of these tools where formation temperatures well above the tool limits.

Additionally, acoustic televiewer logs will be run. These logs can be run in temperatures up to ~300 C. Cement bond logs will be run after cementing each string of casing.

For logs run in high-temperature sections of the hole, flasked tools will most likely be required. In 2012, Sandia National Laboratories performed unpublished laboratory-based tests on commercial heat flasks (Dewars). As supplied, the Dewars were rated for operation to 400 ºC and they performed as specified by the manufacturers. Testing was performed to 440 ºC (the limit of the tube furnace capabilities) and only after several temperature cycles did the data indicate unit failure. These results are supported by recent work in IDDP-2 (Iceland Deep Drilling Project: Well no.2) where pressure-temperature logs were successfully run to temperatures of 426 °C. Coupling Dewars with the electronics used in high-temperature logging tools can allow operation in environments well above the capabilities of the native electronics. Commercial vendors can support this development.

Logging will be done through a pipe (lubricator) extending from the rig floor to position below the BOP´s. The annular BOP will be closed around the pipe while logging. The pipe will have a seal at the top for the wireline and the pressure rating will be API 5M. A minimum flow of 30 l/s will be maintained on the kill lines at all times.

4. Instrumenting the Well

To monitor continuously the temperature through the roof of magma chamber a string of thermocouples (TC) will be installed (Figure 4). The idea is to core into the magma and then leave TC in the hole which may become submerged in magma with time, or at least remain as close to magma as possible. The actual method and requirements will depend on the temperature modelling, which will determine the time it will take the magma to remobilize relative to the time required to place the thermocouple in the well. These will be the highest direct temperature measurements ever made in a borehole. Return to thermal equilibrium will reveal thermal properties of the roof zone, and thereafter the heat flux out of the magma.

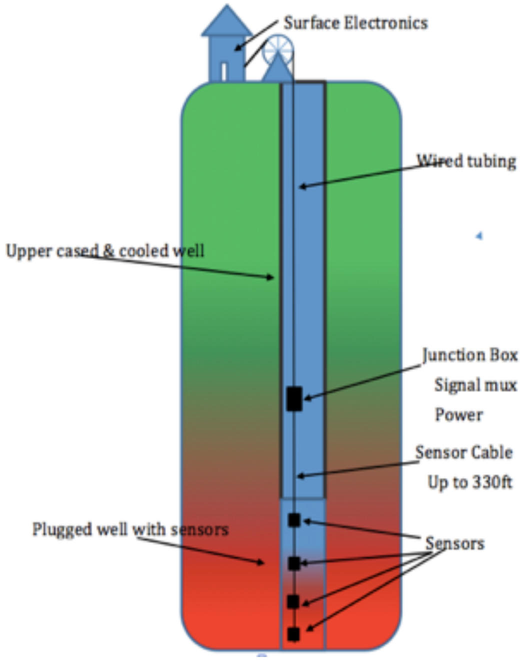

Figure 4: Concept of long-term monitoring of the magma-hydrothermal boundary. A string of sensors, in Phase-1 thermocouples, is connected to an electronics package in a higher, cooler, level of the well.

Thermocouples are the temperature sensor of choice for temperatures above 800°C. The popular K-type thermocouple is rated to 1350°C. Other thermocouple types are rated >2000°C. The base concept is to run 4 thermocouple cables down to the bottom of the well inside Incoloy tubing. Each TC termination will be spaced 2-10M providing 4 measurement points. The pressure tubing needs to be 3/8 inch in outer diameter to house multiple thermocouples. The large tubing also benefits pulling a vacuum on the tubing and cable to reduce humidity captured in the tubing during assembly. Once the vacuum has been created, the tubing is flushed with dry Argon gas. This process significantly increases the operation life of material exposed to geothermal temperatures.

There is a need to perform laboratory testing to determine the maximum possible length of the thermocouple cable. The allowable length of thermocouple cables is a function of the distributed signal loss through the insulating material. The longer the cable can be made the greater the probability of success and greater the accuracy to be expected. At least two types of thermocouple insulation at elevated temperatures will be tested: magnesium oxide and ceramic fiber.

Once the loss factors for insulation have been identified, a research for the availability of Chromel-Alumel K-type (1300°C) or higher rated TCs based on platinum or tungsten will be carried out.

If it is not possible to run the thermocouple wire the entire distance up the well, HT SOI amplifiers will be used to amplify the thermocouple signals and provide local temperature and pressure measurements. At the surface, a high-resolution ADC and Arduino processor system will calculate the thermocouple temperature values and verify the system performance and general health. The HT SOI electronics have been oven calibrated up to 280°C running barefoot. These electronics don't require a flask or any heat shield. The ICs are manufacturer qualified for continuous use at 225°C for 5 years. Expected operating life at 275°C is greater than 6 months. Perma Works, will test everything inside the tool for hydrogen effects at temperature up to 400°C. The electronic components have been eliminated, that can be affected by free hydrogen. The pressure housing is rated for 10,000 psi@ 300°C. Deployment requires placement of the thermocouple sensor tubing, the HT SOI tool and the wired tubing to the surface. This requires a logging crew with tubing experience.

The most robust high temperature survey and monitoring system for geothermal rock masses is a combined distributed fiber optic and fiber optic point sensor array system. Fiber Optic sensors have many applications and can operate in very high temperatures. Optical point sensors have today, using commercially available polyimide coated fiber, been long-term tested to 320°C by Paulsson, Inc. Gold coated fiber can operate to 700°C, platinum coated fiber is claimed to tolerate 1450°C. Packaged in small Inconel tubes without fillers, the fiber sensors will tolerate very high temperatures subject only to melting temperatures of materials used. Darkening of the fiber due to hydrogen is a factor that must be incorporated into the design of the fiber optic sensor systems. Fiber can measure temperature, acoustics and strain using distributed sensing technologies with the fiber sensor interrogating instruments placed in the well. Fiber optic point sensors include optical accelerometers and optical pressure sensors. Arrays can be built using these point sensors – not as many sensors as with the distributed sensor technologies – but much more sensitive and much more accurate.

5. Geothermal Energy Developments

The importance of a magmatic source cannot be overemphasized. It has high energy density because of its high temperature and latent heat of crystallization and it convects, replenishing heat lost to production. Also, its roof fractures with cooling, keeping open access by advective aqueous fluids. But sustainable systems will require improvements in casing alloys, fluid management, cement, and – again – extreme sensors to monitor source and well conditions.

Government expenditures for volcano monitoring are high because monitoring is labor intensive, involves great uncertainties, and hence needs redundancies. In contrast, the largely private sector expenditures for geothermal energy are capital-intensive for drilling and infrastructure and probably much larger. Yet they have achieved only about 0.3% of global electricity production. This is because conventional geothermal is inefficient, tapping mere whiffs of steam at 250^{o}C from the ~1000^{o}C magmatic furnace below, and not always conveniently located. Tapping superheated or supercritical steam from adjacent the heat source could boost energy transport to the surface by an order of magnitude and efficiency of conversion to electricity by 3.5 times. When combined with the advantages of continuous operation (bed load), absence of need to transport either fuel or waste, limited carbon emission, and advances in long-distance HVDC power transmission, geothermal energy could change the electrical energy game completely.

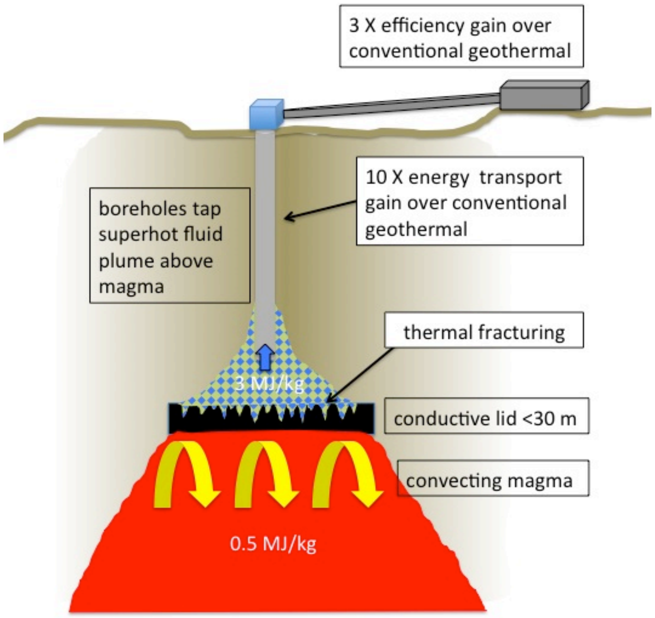

Figure 5: Depiction of power generation from "magma energy". Convecting magma continually delivers uncooled magma to thin conductive "lid" (Carrigan, 1984, 1987). Extreme thermal gradient in the lid aided by thermal fracturing transports magma energy to a superheated or supercritical plume (Scott et al, 2017), which can then be tapped for efficient power production (Tester et al, 2009).

Utilization of high-enthalpy hydrothermal systems for geothermal energy have been proposed, with drilling into supercritical systems, the original intent of IDDP-1 and the achieved goal of IDDP-2, being notable examples. The enthalpy of the super-heated steam at IDDP-1 is several times the enthalpy of a conventional geothermal system, and not significantly less than the enthalpy of the super-critical fluid in IDDP-2, although less dense. However, the important driver here is the existence of the magma. Harnessing the latent heat of crystallization from convecting magma source provides a long-term, reliable heat source, instead of trying to extract heat from a huge volume of low-heat capacity rock. A key will be discovering the origin of the exceptional permeability just above magma in IDDP-1. If this is a natural condition due to thermal fracturing between magma and a hydrothermal system or initiated by injection of drilling fluid (Lamur et al, 2018), then the extraction of superheated or supercritical fluid from just above a magma body will find broad applicability.

The testing of IDDP-2 should inform future experiments that could be carried out in the KMT-1. The rate of permeability formation, its effect on the magma body and its influence on the acid gases that evolve from the magma are interesting areas for future study. Deeper wells into higher temperatures will cost more. Having complementary experiments in IDDP-2 and KMT will inform the economics of the alternatives. Understanding the heat extraction rates and effects on the magma through the KMT experiments will guide the next steps in power generation that utilizes magma as a heat source.

6. Conclusion

The KMT-1 well design aims to provide a well to improve volcano monitoring strategy and to develop next generation of geothermal energy. In order to foster the development of next-generation high-enthalpy geothermal energy, new flexible coupling solutions to secure each segment of casing have been designed, which permit free axial motion during thermal expansion. Monitoring the temperature profile in the roof of a magma chamber will reveal actual heat flux from magma to hydrothermal system, and unprecedented observation that will test botht he promise and sustainability of Super Hot Geothermal Systems (SHGS).

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