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In Situ - Vaporisation Of Geothermal Water In Low Permeability Rock And A Saline Environment

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ABSTRACT

A method is proposed to produce steam from hot but low permability rock in a saline environment without putting at risk the the bore-hole and plant. Mineral precipitates (scaling) could be avoided by injecting freshwater into the low permeability rock, thereby replacing saline brines within a defined rock district around the bore-hole.

The injected freshwater will be shut in and heat up to rock temperature. Subsequently, in situ-vaporisation will be initiated by a sudden reduction in pressure. Steam will be generated and flowing to the surface, where it can be harnessed by turbogenerators. The sudden reduction in pressure will be provided by a specific patented equipment that has been described by Herr (2002). Once the slowly prograding vaporisation front has reached the brine-filled rock domain, the water content of the brine will be turned to steam. The dissolved mineral contents will precipitate and be left in the rock. Crystallisation of salts is kept away from the well-bore and adds more heat to the rock.

1. INTRODUCTION

A method is being looked for that is capable of transforming water into steam in suitable rock at great depth. Sufficient heat must be present for vaporising formation water and reinjected water. The brine in place cannot supply a long-lasting steam generation.

The necessary rock temperatures are well over 200 °C. Experts from ENEL (Italian energy company) in 2002 had rated 250 °C as the very lower limit for such processes. It has to be kept in mind that ENEL at that time had to cope with a different economic situation. Steam production for electricity generation had to compete with fossil fuels when these were plentiful and relatively cheap in 2002.

In Germany, however, boosting energy production from renewables is of high priority. This includes geothermal energy. There is assistance in direct and indirect form in order to build up a noteworthy geothermal power production capacity. Geothermal power is fed into the public grid at guaranteed prices. This might provide the opportunity to evaluate new approaches in geothermal power production. The restrictions as seen by ENEL in 2002 may not stringently apply to Germany. Fossil fuel prices have increased considerably

It is intended to transform water to steam in deep rock because steam will flow to the surface (no pumping) and produce more energy per unit weight than thermal water could. One kg of steam mass at a temperature of 180 – 200 °C will provide an electrical generation capacity of about 0.5 MW. 10 kg/s steam would allow for a 5 MW-plant.

In comparision, binary cycle plants have to handle much larger volumes of hot water for the same power production capacity. About 70 l/s with 200 °C have to be produced to supply a 5 MW electrical capacity. The basic advantage of in situ-vaporisation seems evident, but technical solutions to realize the approach are not readily available.

2. IN SITU-VAPORISATION (ISV)

The term vaporisation is used to define the transition from a liquid to a gaseous state, in this case from liquid water to gaseous water (steam). Related to technical processes, such as desalination of seawater or producing steam from hot watery liquids in geothermal power plants, the term flash is generally used. The author prefers to make a difference from these technical processes and prefers to use the term vaporisation for steam generation in the deep rock domain.

Under specific geological and petrophysical conditions very hot water under high pressure is already being vaporised (resp. flashed) at depth. This is achieved by reducing the pressure that is usually exerted by the weight of the water column on the deep hot water, thus keeping it from boiling.

In Tuscany, there are two ways to reduce the pressure on the deep hot water resource:

- As there is a high concentration of carbon dioxide in the hot water, the gas will dissolve from the water when standing in the bore hole for a while after drillhole completion. CO_2 will build up a free gas phase in the bore-hole that has been closed pressure-proof on the surface. During the course of of a few months, the gas will accumulate and build up pressure. The increasing pressure is gradually pushing the water table downwards to hotter zones, thus heating up the water. The water table can be lowered by up to 500 m by this method. In addition, the water table table in this area is situated a few hundred meters below the surface.

After some months, the lid on the bore-hole will be opened. The gas escapes and the pressure is lowered very fast. In most instances the pressure dependent boiling point will be reached and the liquid content of the bore-hole will flash. It will be blown out of the hole within 10 to 15 minutes. Subsequently steam production sets in the rock. It still carries some liquid phase with it for a while. Later, formation water further away from the bore-hole can take up sufficient energy for complete transformation to steam from the hot rock the water has to pass through.

- If the CO_2-pressure on top of the water-column cannot push the water table deep enough, the weight of the water column could also be reduced by injecting compressed air into the water at sufficient depth. The density of the water column and its weight is reduced to below boiling pressure. Boiling sets in and the water column is blown out of the hole as in the aforementioned case.

These cases demonstrate how in situ vaporisation may work when aiming at steam generation for power production. There are other cases of steam generation and blow-outs that have happened unintentionally. The probably latest such case has been reported from Geodynamics' Habanero Project (Cooper Basin, Australia). In order to recover a tool from the bore-hole, the pressure unintentionally had been lowered below the boiling point, leading to a blowout. Temperatures at 4,400 m depth were around 250 °C.

Another example had been reported from Hungary, where in the Fáb - 4 geothermal well a steam-water blowout occurred that lasted for 6 weeks. The estimated pressure at the bottom of the hole was 76.3 MPa. The sections that produced steam were at 3,698 – 4,239 m depth. Obviously, overpressured formations had led to the blowout. Such formations do occur rather frequently in Hungary. The reservoir-temperature had been set at 200 – 210 °C. Once vaporisation commenced, a watery phase was co-produced with the steam (hot water with 160 °C representing 80 % of the mass and steam representing 20 % of the mass). The liquid phase had cooled down from the original reservoir temperature of 200 – 210 °C. The cooling was a consequence of producing steam. The liquid phase lost enthalpy to the steam.

The pressure loss in higher sections of the bore-hole lead to precipitation of the dissolved solids (scaling), mostly carbonates. Though the liquids had only low contents of TDS (27.2 g/l, mainly NaCl), scaling had largely closed the upper part of the $9^{5}/_{8}$" casing. The amount of fluid was 5,000 to 8,500 m³/d (Pap, 1999). The fluid production was thus at a range of 57.9 – 98.4 l/s.

3. BASIC REQUIREMENTS FOR ISV

3.1 Temperature

For producing sufficient steam at a pressure that can supply a turbogenerator with a meaningful capacity, high temperatures have to be looked for.

A temperature of 250 °C has been considered as the very minimum by Italian experts. At this temperature, the maximum steam pressure would be at around 40 bar. However, this value is a theoretical one as the steam has to flow a fairly long distance from the point of vaporisation to the turbogenerator. Pressure losses are inevitable. They will occur in the rock, where permeability is low, but permeability must be low if the concept is going to work.

Additional pressure is lost in the bore-hole, as well as in the piping system between the bore-hole and the turbogenerator. These parameters cannot be presented as values as details for a project cannot be presented yet.

In Germany, temperatures of ≥ 250 °C can earliest be expected at a depth between 5,000 and 6,000 m. This might be possible only at a few locations with very favourable geologic settings, but it should not be ruled out entirely.

More realistically is the application in Iceland, Italy, and Turkey, where temperatures of ≥ 250 °C could be expected at 3,000 m depth in specific geologic environments in a number of areas. An outstanding example for high temperatures in Italy is the San Vito No.1 well near Naples, where 420 °C had been encountered at 3,046 m depth in a hypersaline low permeability environment (Cataldi et al.).

3.2 Permeability And Porosity>

Rock with temperatures of ≥ 250 °C at a depth of 3,000 m and below will most likely not be as porous sediments at lesser depth and lower temperatures are.

The porosity has little chance of being provided by pores sensu stricto, as they occur in sedimentary aquifers. Instead, the porosity in all probability can only be provided by fractures. The connected fracture porosity should, according to our present understanding, be in the range of 1 – 2 % of the rock volume, the permeability of 10 – 20 mD, perhaps slightly higher. This would yet have to be calculated for a few theoretical cases.

Low permeability is a precondition for making the concept work. Too low a permeability would restrict the steam flow to such an extent, that pressure losses would be excessive. Too high a permeability would allow the liquid phase moving so fast that it could not absorb sufficient energy from the adjacent rock to transform all water into steam. Then the liquid phase, including the dissolved solids, would enter the bore hole and lose the dissolved solids there. This could, depending on the amount of dissolved solids, render the bore-hole useless within short (as it had happened in the Hungarian bore-hole Fab-4). This is even more important once saline environments are targeted (see chapter 4.).

3.3 Amount Of Dissolved Solids

From Italian steam producing wells it is known, that TDS-contents of up to 10 g/l are tolerable for in-situ-vaporisation (A. Barelli, F. Sabatelli, /Enel, personal communication). It must be concluded, that most of the dissolved solids will remain in the rock system once vaporisation sets in, especially when the vaporisation front is moving away from the bore hole. Somewhat higher TDS–contents might work out as well, but the upper limit is not known. In the targets with higher TDS (≥ 80 g/l) the risk of scaling will be extremely high. For this reason a specific approach has to be applied that would minimize the danger of rapid scaling (see chapter 4). Higher saline environments are the rule especially when aiming at the Italian and Turkish potential.

3.4 Depth

In principle, depth is not a factor that would restrict the general applicability of in situ-vaporisation. From a standpoint of economical viability, the depth is a limiting factor for two reasons:

- deep drill holes are raising costs at an exponential rate

- large drillhole diameters are required in order to obtain a steam pressure that could drive turbogenerators

It will be difficult to apply the method beyond 4,000 m depth. The bore hole diameter is usually restricted ever more the deeper drilling goes. In Tuscany, ISV is possible at 4,000 m depth using borehole diameters of 8 ½ inch. There, ≥ 300 °C are required to produce economic quantities of steam.

There are prospective areas in Iceland, Italy, and Turkey where high temperatures could be met at 3,000 m depth, but apart from Iceland and Tuscany, the environments are saline to strongly saline. ISV would not be applicable there because of scaling effects, unless the method could be modified.

3.5 Steam Pressure And Tubing Diameters

Steam pressure is controlled by the temperature of the rock domain. A rock with 250 °C could, in a theoretical case, deliver up to 40 bar steam pressure. On its way from deep rock via the tubing to the inlet of the steam turbine, much of the pressure will be lost. At 200 °C the maximum steam pressure would be in the 20 bar range.

While at 250 °C the steam mass per m³ is around 17 kg/m³, it will only amount to around to about 8 kg/m³ at 200 °C. Still, this is a value that allows utilization. In Mexico, the Cerro Prieto project is producing electricity from steam that has a temperature of 180 – 200 °C at the turbine intake.

Such a temperature is most likely the minimum that should be considered for electric power generation. In order to keep pressure and temperature losses at a minimum, tubing on the surface has to be kept as short as possible. Tubing at the surface could be installed with fairly large diameters. Tubing insulation has to be efficient. This is no technical challenge but a matter of price.

3.6 Thickness Of Steam Productive Rock Zones

Considering the envisaged minimum electrical capacity of a steam powered turbogenerator (5 MW e), a fairly thick rock sequence is needed as a producer.

Given a (fracture) porosity of 1,5 %, an overall permeability of 10 – 20 mD, and a rock temperature of about 300 °C, the specific yield of such a rock per metre of uncased drill-hole could attain of 15 to 20 g/s per meter of bore-hole. In order to obtain 10 kg/s steam, 500 to 670 m of productive bore-hole section would be required. These are preliminary estimates, based on experiences made in the geothermal fields of Tuscany.

4. REALIZING IN SITU-VAPORISATION IN A SALINE ENVIRONMENT

In situ-vaporisation, as it has been outlined afore, so far has only been applied in low TDS thermal water environment. It will face difficulties when being tested in a saline to highly saline geological environment. At a first glance, it may even appear impossible. On the other hand, hot rock domains in volcanic or non-volcanic setting would most likely be saline to highly saline.

Such thermal waters can be used at present with the flash technique, comprising one or several stages of flashing the brines and reinjecting the cooled-off liquid phase.

This is already done in many cases, but only feasible, when the productivity of the geothermal fields is high. To the authors' knowledge there is no low permeability highly saline field producing steam. On the other hand, these unfavourable conditions do outnumber the favourable ones by far. It seems worth thinking about ways how a solution to this challenge might look like.

Having described in situ-vaporisation as it is applied at present (Tuscany/Italy being the witness that it works), the authors would like to outline an idea that has yet to prove either its worth or its non-feasibility. As no experience is at hand, numbers and exact figures cannot be given. The authors would just like to forward the idea and possible approaches and hope for subsequent discussions.

The dissolved solids in thermal brines have been a continuous source of problems and challenges even in more conventional geological settings where the majority of difficulties had been solved by different means, most notably by pressure control and using inhibitors.

In situ-vaporisation cannot apply pressure control of geothermal liquids, as reduction in pressure is required to turn water to steam. Likewise inhibitors are not applicable for obvious reasons.

Initiating in situ vaporisation with the available technical means, as it could be done in low TDS-environments, would have severe consequences in saline to highly saline environments. A simple reduction in pressure would let saline/highly brine flow from the near well rock into the borehole, where, on the way to the surface, most of the contained dissolved solids would precipitate over the entire length of the casing or tubing. Parts of the dissolved solids would still be carried up to the surface, contained in the watery phase that has not been vaporized due to insufficient contact with the hot rock.

Only when saline brines would have to flow for a yet undetermined length and time through hot rock, the thermal energy of the rock could provide sufficient heat to vaporise all water so that the dissolved solids would precipitate within the rock itself.

That would probably happen after a while, perhaps a few days or weeks after initiating the vaporisation, but that would be too late. By then, the bore-hole would be restricted in diameter by mineral precipitates or even be totally clogged.

A means to prevent this from occuring is to inject freshwater into the potentially productive section of the bore-hole. Freshwater would have to be injected over an extended period of time.

It would have to be injected at a constant pressure and flow rate. It is intended to replace the brines that are present in the rock system, pushing them away from the bore-hole further into the rock. Fairly large volumes of fresh water would have to be used.

A simple calculation shows, that replacing brines by freshwater in a hypothetical cylindrical rock body that surrounds the bore-hole over 500 m vertical distance with a radius of 100 m, would amount to 15.7 million cubic metres. When setting the effective porosity at 1.5 %, the connected pore volume would amount to 235,500 m³.

This calculation is simplified. It does not take into account the inhomogenities of the rock and the porosity (resp. fractures). An injection rate of 20 l/s would need 173 m³/d of freshwater, 63,072 m³/a. Thus, it would take 3.7 years to replace the saline brine by freshwater by pushing the former away from the bore-hole into the rock.

This is most likely not necessary and would consume too much time. In a second example, the radius of the rock cylinder would be set at 50 m. This leads to a rock volume of 3.9 million m³ that would contain 58,900 m³ of connected porosity, 1.5 % (fracture) porosity provided. This volume is filled with brine, that could be replaced by freshwater within approximately 11 months, based on an injection rate of 20 l/s. Volume numbers are rounded.

The geometrical picture of the rock domain, the porosity of which has been flooded with freshwater after a certain time span, would by no means be of true cylindrical shape. It would most likely represent a shape that reflects the inhomogeneous permeability of the rock. The outer limit of the freshwater zone would be time controlled. It would mark the outer limit to which freshwater has advanced after 11 months of injection.

It is obvious, that domains of higher permeability would let the freshwater advance further than low permeability zones would. As regards injection rates, they must be carefully measured in order not to create additional permeability by fracturing. Some slight increases of permeability might be tolerable, but a larger scale fracturing must be avoided. Additionally created permeability would let the water flow back too fast. It could not be vaporized entirely because of insufficient heat exchange with the rock. Slower flow provides more time to take up heat from the rock system.

An injection rate of 20 l/s over a 500 m thick sequence of 10 – 20 mD rock appears achievable without causing too much of fracturing and raising the permeability excessively. It is assumed, that the freshwater injection will push back the saline water domain without mixing with the brine to a larger extent. In this respect, calculations and trials have to be carried out before testing the method in situ.

In situ-vaporisation would have to wait for the injected freshwater to be heated up to rock temperature. Tentatively, a 6 – 12 month period would be suggested. Detailed calculations have not been carried out yet and would most likely not be meaningful as the properties of a potential target are not yet known. This is a proposal, outlining an idea, that might be reviewed by others in order to work on this concept or discuss it further.

Initiating the production of steam requires a sudden reduction in pressure. The method has been briefly described in chapter 2. Once the reduction in pressure that is to trigger vaporisation or flashing, has been applied, the near bore freshwater, that has more or less been heated up to rock temperature, will stream to the bore-hole. There it flashes, turning to a gaseous steam phase which is under pressure and thus streaming to the surface. The remaining liquid phase, that is cooled off considerably, will be entrained in the steam flow and be carried to the surface, where it has to be separated from the steam.

Mineral precipitates/scaling would not be expected too any larger extent as the injected freshwater has a very low TDS-content. The vaporisation front is then slowly prograding further into the rock domain. The longer the flow-distance between the vaporisation front and the bore hole, the more thermal energy could be taken up by the liquid phase. Thus, the steam portion would increase and the liquid portion be reduced. At a certain distance from the bore-hole, that would depend on permeability and rock temperature, the liquid phase will be entirely turned to steam.

If an injection rate of 20 l/s has been maintained for 11 months, it is conceivable that over the same period of time freshwater could be vaporized at 10 l/s, possibly longer. Once the vaporisation front has reached the fresh water-brine boundary, complete vaporisation has to be achieved, in order not to transport mineralisation in solution to the bore-hole.

The mineral freight of the brine will be left behind. It will certainly fill some of the pore / fracture space but not excessively clog it up. Even high salinities, when leaving their mineral content in situ, are not able to fill the void space of the connected porosity. The crystallization of salts, mainly chlorides, would even add up heat to the system the same way it has consumed energy when being dissolved. Calculations have shown, that a dissolved content of 120 g/l NaCl (2 Mols) might provide 0.43 kWh (!) of t hermal energy per liter of brine when the salt crystallizes from aqueous solution.

5. CONCLUSIONS

It appears feasible to produce steam for power generation from low permeability rock in a saline environment without causing excessive scaling. Scaling could be minimized by vaporising freshwater which has to be injected into this rock first. As vaporisation progresses into the brine-dominated rock domain, the fairly low rock permeability restricts the flow of liquids whereas the steam could pass pores and fractures fairly easily.

The liquid phase will move so slowly that it will not reach the bore-hole where vaporisation had commenced. Water will turn to steam as there is ample of heat stored in the surrounding rock. Mineral precipitates, such as chlorides, carbonates, and sulfates, will stay more or less in place. Even high concentrations of dissolved solids will not clog up the hydraulic system, as only up to 25 % of pore and void space will be filled by the precipitates if left in place.

The scheme would only work under specific geological conditions. The permeability must be low in order to restrict the flow of the liquid phase but allowing the gaseous phase (steam) to flow. A permeability of 10 – 20 mD appears appropiate for high temperatures. The value could be higher, possibly up to 50 mD when temperatures of 200 - 240 °C are present and steam pressure would be lower. Productive bore-hole sections must be several 100 m thick in order to compensate for the low specific yield per m..

If the scheme works out, steam production would allow for a more efficient power generation as cheaper turbines and plants could be used. The pumping of large volumes of liquid would not be necessary any more and save running and equipment costs.. Temperatures of ≥ 250 °C should be envisaged, but potential is seen for the temperature range 200 – 250 °C as well.

Tubing diameters would have to be in the $9^{5}/_{8}$" range. Perhaps 8¾" might suffice, depending on the steam pressure. In any case, the steam has to be kept from losing to much pressure, as the production rate and power generation would decrease accordingly.

The scheme would only work in a low permeability-environment. There must no highly productive faults nearby or other features characterized by high transmissibility.

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