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Submarine Geothermics; Hydrothermal Vents and Electricity Generation

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ABSTRACT

Ocean Ridges are areas with extremely high heat flow, where temperatures above 300 °C can be reached at shallow depths. These high temperatures make them a good target for exploitation of geothermal energy. Therefore, innovating designs to generate electricity installing a little submarine on top of the vent with a binary cycle plant have been developed as part of the activities of the IMPULSA project of the Universidad Nacional Autonoma de México (UNAM), which is focused on the utilization of renewable energy sources for desalination of seawater. Here, we present the results generated by the project for the exploitation of submarine vents and describe the designs that include calculations of the efficiency of every component.

The plants were designed based on typical values of the vent parameters, and a rough calculation is made about the electricity that could be generated from this renewable resource. The importance of the vents from the ecological and biological point of view restricts the amount of areas that could be used to generate electricity without any drilling, and it is considered that only 1% of the already known sites might be exploited. Under those conservative assumptions, some 130 000 MW of electricity could be generated. That is almost the same amount of geothermal power that could be generated inland with all the actual and new techniques to generate electricity. We conclude that prototypes must be tested and exploration of suitable sites must be performed for future electricity generation from hydrothermal vents. One important result, obtained with this research, is that from one hydrothermal vent, up to 20 MW of electricity can be produced with a simple method that does not affect the ecosystem.

1. INTRODUCTION

Searching for new sources of sustainable energy is a very important concern in this moment. Solar, wind, biomass, ocean and geothermal energy are receiving important support from many countries, and from key organizations as the IPCC and WEC. The development of geothermal energy to produce electricity begun long time ago (Cataldi *et al*., 1999) in Larderello, Italy, and the number of countries that generate electricity with this renewable resource capable of sustaining production independently of the climatic conditions and at a price not related to the ups and downs of the price of oil has increased. At this moment 24 countries are running geothermal power plants having a total installed capacity of 10 000 MW (Bertani, 2008) and the prediction for 2050 geothermal electricity production with the present technology is of around 58 000 MW of installed classical geothermal power, around 500 TWh/y (Bertani, 2008; Sanyal, 2009).

Even though this numbers might represent only a few percent of the whole electrical matrix for 2050, it is important to highlight that geothermics is a continuous dispatchable source of energy, and that with the new developments of advanced techniques to extract heat from nontraditional volcanic hydrothermal sources, such as deep hot dry rock (EGS) those numbers increase drastically. Recent studies (MIT, 2006) have shown that geothermics is not only the traditional hydrothermal reservoir, where meteoric water of the aquifer is heated by a volcanic source. DOE (2008) discusses MIT report, and points out that just for the USA the heat stored in the earth at depths between 3 to 10 km is so large that if only 2% could be transformed into electricity, by drilling deep wells and then fracturing the reservoir to mine out the heat injecting water or even CO_2 in gas stage, more than 100 000 MW could be generated. This number can be extended in a preliminary way to the world to obtain some 130 000 MW (DOE, 2008).

The Universidad Nacional Autónoma de México (UNAM) supports research of renewable sources of energy as part of the multidisciplinary project IMPULSA, whose main aim is seawater desalination using renewable energy (Alcocer and Hiriart, 2008). Geothermal is one of the most important renewable sources to be investigated by the IMPULSA project and specific studies have been performed to identify a new submarine hydrothermal manifestations and to develop pioneering methodology to produce electricity in a sustainable way. There are some 67 000 km of Ocean Ridges, 13 000 of them have been already studied discovering more than 280 sites with geothermal vents. Some of them with a thermal power of up to 60 MWt (Lupton, 1995) but there are some of them really gigantic as the one in Rainbow with an output of 5 GW_t (German *et al*, 1996; Marteinsson *et al.*, 2001; Humphris and Fornari, 2001; Thurnherr and Richards, 2001; German and Von Damm, 2004). In Mexico, in the Gulf of California, there are numerous sites where hydrothermal vents have been reported some of them with temperatures over 360°C in front of Guaymas (Von Damm *et al*., 1985); additionaly, shallow hydrothermal vents are common within the Gulf of California and on the Mexican Pacific coasts (Canet and Prol-Ledesma, 2007). The abundance of submarine hydrothermal systems within Mexican economic zone supports our interest to develop new techniques for their exploitation, which will be presented here.

This University research takes into account the ecological implications of extracting heat from a hydrothermal vent (Rodriguez, 2008) and it has focused in particular places where generation of electricity could be obtained with no harm to the ecosystem. From the engineering point of view, taking into account environmental preservation, our goal is to find out how much electricity could be produced, so we will quantify the useful heat contained in the main oceanic ridges, and we will base our preliminary assessment of the heat power of the hydrothermal vents in the data gathered by Baker and German (2004) and Pelayo *et al*. (1994).

This paper presents our proposal for sustainable exploitation of the geothermal energy contained in the submarine hydrothermal vents for electricity production and an estimation of its impact in the future production of energy for this resource.

2. STUDIED HYDROTHERMAL VENTS

The submarine hydrothermal systems that have been considered in the IMPULSA project are located within the economic zone of Mexico, within the Gulf of California and on the Pacific coast; they include deep and shallow vents (See figure 1). The hydrothermal vents present in the Gulf of California are related to the divergent boundary between the North-American and the Pacific plates: the East Pacific Rise; and the shallow vents are mostly related with deep penetrating meteoric water heated by the high geothermal gradient (Canet and Prol-Ledesma, 2007). Off the Pacific coast of México, the shallow systems have been reported off Punta Banda (Vidal et al., 1978) and Bahía Concepción (Prol-Ledesma *et al*., 2004) in Baja California Peninsula, and Punta Mita, in Nayarit (Prol-Ledesma *et al.*, 2002a, 2002b) (Fig. 1). Unlike shallow systems off the Western Pacific Margin, which are distributed along island arcs, Mexican examples do not show clear links with modern volcanism. The shallow systems are located in continental margins presently affected by intense tectonic extension, with anomalously high geothermal gradients.

The submarine hydrothermal system in Bahia Concepcion (Prol-Ledesma *et al.*, 2004) was chosen to test electricity generation prototype-models directly on top of a hydrothermal vent. This site was selected because it is at a shallow depth in a very calm zone, easy to work and dive. The area with submarine and intertidal hydrothermal activity extends 700 m along a stretch of rocky shoreline in the western coast of the bay. The cliffs are configured by a system of normal faults that allows hydrothermal fluids to rise to the surface (Forrest et al., 2003). Two types of surface manifestations are found in this area: (1) a zone of diffuse hydrothermal fluids submarine venting (gas and water) through the sediments of the seabed, at depths between 5 and 15 mbsl; and (2) a cluster of hydrothermal springs and bubbling vents in the intertidal zone (Canet *et al*., 2005a, 2005b). These manifestations are all NW-SE aligned. The temperature of vent discharge is up to 87 °C in the submarine diffuse area and 62 °C in the intertidal hot springs, and pH is 5.9 and 6.7, respectively. The exsolved gas is composed largely by CO2 (44%) and N2 (54%), although it contains CH4, Ar, He, H2, and O2 in minor amounts (Forrest *et al*., 2003). Helium isotopes (R/Ra = 1.32) are compatible with a mantle-derived component (Forrest *et al*., 2005). Thermal water is a sodium-chloride type and shows high concentrations of Ca, Mn, Si, Ba, B, As, Hg, I, Fe, Li, HCO3, and Sr with respect to seawater, and chemical geothermometers (Na/Li, Na-K-Ca and Si) yield reservoir temperatures of ~200 °C (Prol-Ledesma *et al*., 2004).

Further work is planned to take place in the Wagner Basin (Northern Gulf of California), which was selected for the installation of the prototype since it is less than 200 meters deep and a few kilometers from the resort of Puerto Peñasco (Prol-Ledesma *et al*., 2008). Recently, a cruise in the Oceanographic Ship "PUMA" of the UNAM University was organized, in front of Puerto Peñasco, where an abundance of flares where found. See figure 2. Unfortunately, detailed observations of temperature and heat flow were not obtained (Birosta et al., 2008). Large-scale gas seepage and fluid ejection features were observed from the edges of the active pull-apart Wagner and Consag basins, at water depths between ~65 and 150 m. Anomalous temperatures were measured in the sediment samples, which point out extensive thermal anomalies related with the gas venting that occurs mainly through N-S synsedimentary faults and fault-propagation folds that are believed to derive from the Wagner Fault. Presumed mud volcanoes are sub-rounded, domed bathymetric features, several hundreds of meters across, underlain by gas-charged sediments and surrounded by gas vents. Release of CO2-rich gas is the main driving force of the venting, similarly to the neighboring onshore manifestations in the Salton Sea (California, USA). This gas interacts with the thick sedimentary sequence, producing fluid expulsion features on the sea floor (Canet *et al*., 2009).

Our goal at the IMPULSA project will be to have a commercial deployment in front of Guaymas where depth is over 2000 meters and temperatures of the vents are above 360°C (Von Damm *et al*., 1985).

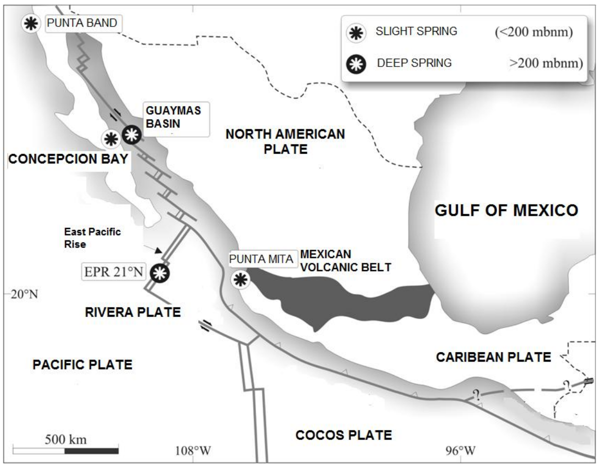

Figure 1: Prospective submarine hydrothermal systems in the Pacific Ocean and the Gulf of California within and nearby the economic zone of Mexico.

3. ESTIMATION OF THE POTENTIAL GEOTHERMAL POWER OF THE HYDROTHERMAL VENTS

According to some studies, (Baker and German, 2004) there are 67 000 km of Ocean Ridges that are constantly recharging their thermal activity by the uprising of magma. They represent 30% of all heat released by the earth. So far 13 000 km have been studied representing 20% of the global ridges of the world. There have been reported 280 sites of hydrothermal vents along the ridges, most of them are at a depth of 2000 to 2 500 meters.

Baker and German (2004) define a parameter called *Fs* Site frequency that is the number of sites per 100 km and presents a table with the factor *Fs* for different regions that he explored. One can approximate those numbers from the graphs he presents as *Fs*=2 for the already explored part of the global ridge, that is 260 hydrothermal vents sites. Considering Baker and German's definition of plume incidence *ph* as the fraction of ridge crest length overlying by a significant hydrothermal plume and taking an average of his values one might take a conservative *ph* =0.3

Now, one can calculate that 13 000 km of explored ridges with a ph of 0.3 gives the equivalent of a long active ridge of 3 900 km long. Being quite speculative on the amount of heat that comes out of this equivalent vent, and based in some extend on Baker`s words that " ...on super fasts ridge sections, vent sources can be so extensive that plumes are continuous for upward of 100 km along axis" an average width of this equivalent vent as 10 cm and a flow out at a velocity of 1 m/s at 250 °C, one gets a heat flow of 400 TW thermal using as a sink temperature 30 °C. We can check the results obtained with these daring assumptions with the work reported by Baker *et al*. (1989). He calculates 350 thermal MW per axial meter for a mega plume, whereas we obtained here only 100 MWt, which is 25 % of his value because we are considering all vents and not only "mega plumes".

If we can transform all that heat with a conservative thermal efficiency of 4% (as it is shown in the next chapter), one gets an electrical power of 16 000 GW (16 millions electrical MW). Assuming that only 1% of the vents could be utilized in practical applications, 160 000 MW of electricity could be generated.

We do not propose to install 160 000 MW in the main hydrothermal vents, but we are pointing out that the geothermal resource from hydrothermal vents is of the same order of magnitude of the Enhanced Geothermal Systems (EGS) , doubling the actual prediction for geothermics as renewable energy. We believe that the possible use of the thermal energy that exists in the hydrothermal vents ocean ridge around the world should be studied more carefully, especially to discover its practical transformation into electricity and its impact in the environment.

4. EVALUATION OF THE EFFICIENCY OF A SUBMERGED POWER PLANT

This chapter concentrates in finding out how much electrical energy can be produced from a hydrothermal vent using an encapsulated plant, see figure 2, like a submarine containing an organic Rankine binary plant inside, as described in (Hiriart and Espindola, 2005). In the external part of one extreme of the submarine there is a heat exchanger in the form of a conic coil, to be installed exactly at the top of the vent in a way that the hot water flows naturally through the coil, touching as much surface of the tubes as possible. This is the evaporator of the cycle. In the other extreme of the submarine, another heat exchanger is installed in the cold water of the surrounding sea, also in the shape of a conic coil. To enhance the natural convection of the cold cooling water through the tubes of the condenser, a cover in the form a hyperbolic cooling tower is installed.

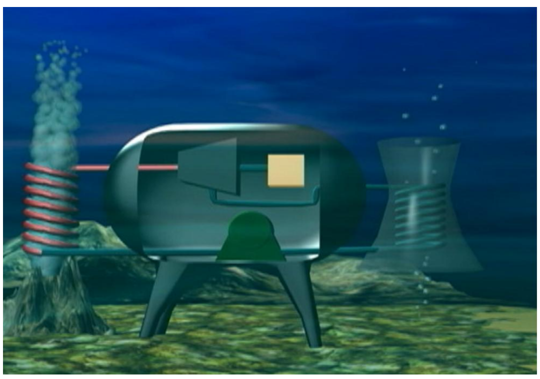

Figure 2: Schematic design of the submarine generator installed on the top of a vent.

Inside the submarine is allocated the turbine, generator, condensate pump and control system. The plant works as follows. Liquid organic fluid (low evaporation point) is pumped at high pressure to the evaporator that is outside of the submarine. The steam produced is then expanded in a high speed organic turbine which moves a generator. The exhaust of the turbine flows directly to the condenser, outside of the submarine. Vacuuming to improve the efficiency of the cycle is made with a condensate pump. This cycle has an internal efficiency of the order of 80%, which is the losses of the turbine, pumps and generator (not the cycle itself).

Another alternative, that is safer for the operation, is to use oil to transport the heat of the external heater into the submarine as shown in figure 3. The heat rejected is also transported outside the submarine by means of an oil circuit.

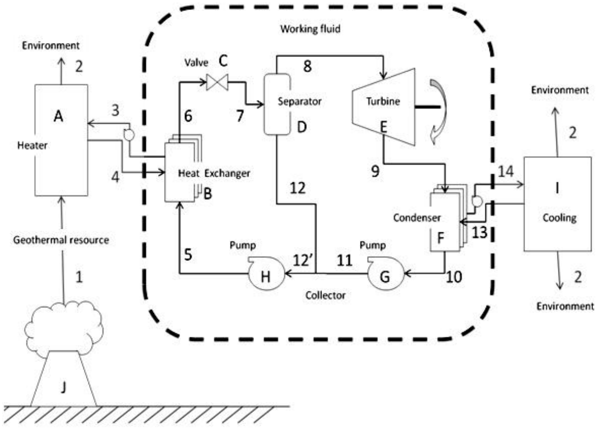

Figure 3: Diagrammatic scheme of a binary submersible generator.

Details of the calculations of the special design depicted in figure 3 are presented in Hernández (2008).The hydrothermal vent (J) flows by natural convection from 1-2. Likewise oil is cooled in the other extreme (14-13) at a heat exchanged (I). Inside the submarine, demineralized water enters under pressure (5) into a plate heat exchanger (B) coming up to (6) as saturated hot water. In (C) at the expansion valve a mix of water and steam (7) is produced. At the separator (D) the steam (8) goes to the high velocity steam turbine (E) and condensed in (F). The condensate pump (G) makes the vacuum. The condensate (11) and the separated water (12) are pumped to the heat exchanger (B) to close the cycle.

The efficiency of the heater (A) can be defined as the thermal energy captured into the oil divided by the total energy ejected from the vent (J). It is important to recognize that this efficiency is directly associated with the area or the size of the heat exchanger (A). A reasonable efficiency of a heat exchanger under this external, open flow, conditions is of the order of 10%.

The maximum efficiency that can be obtained from a thermal cycle is the Carnot efficiency; that is (1- T_1/ T_2) where T is the temperature of the cold and hot water respectively, in °Kelvin.

The maximum temperature of the hydrothermal vent is the saturation temperature of the water under local pressure which is completely related with the depth. In figure 4 it is shown the maximum temperature that the water can attend in a hydrothermal vent, and the maximum efficiency that can be reached.

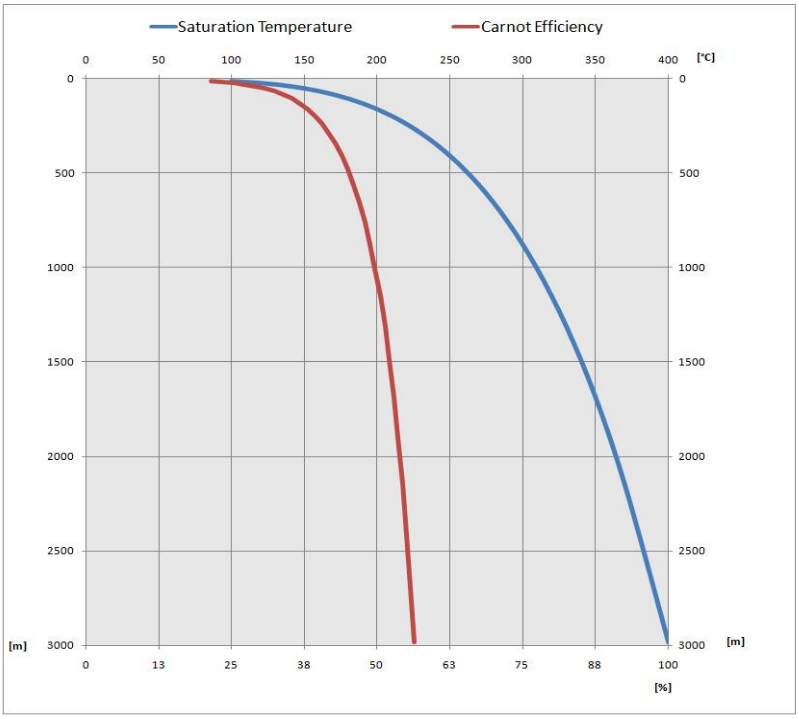

Figure 4: Saturation temperature and maximum efficiency (Carnot) as function of depth.

With those basic numbers one can calculate an approximate electrical output of a given vent flowing at the highest temperature that it can have at this depth. The total efficiency of the cycle will be (0.1) x (0.8) x (0.55 Carnot) = 4.4 %.

Regarding the vent, we will assume a vent diameter of 24" and a velocity of 1 meter per second, which becomes a mass flow of 0.3 m^3/s. If we take as an example a depth of 2000 meters, the saturation temperature will be 365 °C, so the total heat from this vent will be 450 MWt. In that case, with 4.4% overall efficiency the vent of the example could produce reasonably 20 MW.

For the purpose of this study, we can say that from reasonable medium size vent at 2000 m depth, 20 MW of electricity can be generated.

5. CONCLUSIONS

From the abundant literature that exists regarding the many surveys carried out around the world trying to map and characterize the existing hydrothermal vents in the Ocean ridges it has been found that from the 67 000 km of ocean ridges, 13 000 have been already studied.

From the descriptions of the vents, an approximation of 3 900 km of active vents has been used for preliminary calculations.

A submarine generator description has been presented which uses the hot source (the vent) and the cold sink (surrounding ocean) to run an organic Rankine cycle thermal plant, based on the work done at the IMPULSA project www.impulsa4.unam.mx of the Universidad Nacional Autonoma de Mexico, UNAM.

Detailed calculations and results of a reasonable efficiency for every part of the cycle have been presented, showing that an overall efficiency for a vent of 4% (electrical power generated over the thermal power of a vent) is a reasonable conservative value for such an installation.

Applying this efficiency to an equivalent hypothetical case of a vent of 3900 km with a slot of 10 cm and a discharge velocity of 1 meter per second showed that using only 1% of this equivalent vent to generate electricity, without any drilling, 130 000 MW of electricity could be generated.

The main conclusion is that the available (supposedly reasonable) geothermal power that could be generated from well known hydrothermal vent sites in some of the ocean ridges is of the same order of magnitude of the EGS geothermal power that eventually can be produced in the whole world.

We expect that as more information comes up from the survey cruisers which are mapping the ocean floor, much more accurate evaluations will be done and this power will increase.

The challenge of economics and environmental impact of such a project is enormous. The place where energy is generated is usually far from the consumer and also hydrothermal vents are considered almost as sacred places for the conservation of rare species. But since the technology presented here doesn´t require drilling of wells and the submarine generator does not touches the vents , we believe that one day a good solution will come up to make use in a clean and economical way of this enormous natural and sustainable resource.

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