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Submarine Geothermal Generation

Gerardo Hiriart L. and Iván Chávez M.

GEOKERI S.A. de C.V., Mexico City

ghiriart@enal.com.mx ; ichavez@ghsdesarrollos.com

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ABSTRACT

The abundance of submarine hydrothermal vents in the ocean ridges have been described in the specialized technical literature. Some techniques for practical use of this heat have also been suggested in many places. This paper starts with a complete description of a submarine Organic Rankine Cycle power plant, based on previous work published by the author. Then a new concept is presented where all the elements of the power plant are encapsulated in several small tubes capable of resisting very high pressure under the sea, including some floatation/sinking tubes to bring the plant to the surface for maintenance, using a compressed air system (like in the submarines). A new idea for collecting the heat from hot sea floor is accomplished without touching or disturbing the ecosystem of the vents; it is done by driving piles or tubes in the sea soil where the heat is extracted by means of a concentric tube that circulates pure demineralized water. The design and construction of such a device is at the laboratory stage looking forward to having the first submarine geothermal power plant. Several innovating features of the design are presented.

1. INTRODUCTION

The abundance of deep-sea hydrothermal vents has been widely reported (German and Von Damm, 2004) and the importance that such an exploitation could have to produce useful electricity has been studied for the vents near the Azores islands (Pedamallu, 2019) and a preliminary assessment was presented of the geothermal resource potential of several Azorean hydrothermal vent systems finding that there is a huge potential as high as 150MWe of all the vents in the system.

Several ideas to transform this heat into electricity have also been reported (Hiriart et al., 2010; Yu Xie et al., 2016; and Aryadi et al., 2016); we are convinced that this research must continue to finally arrive to a practical solution to generate electricity under the sea. The applications can go much farther than just to produce electricity, it can also be an economical solution to produce hydrogen, from electrolytical technology, directly from the very high temperature water of the vents, reducing the energy consumption per mass of hydrogen produced (Shnell et al., 2015) and also to make use of the high pressure under sea to immediately pack or bottle the gas into its metallic containers or to directly charge the batteries or the hydrogen tanks of long distance research submarines.

Two important concerns have appeared regarding previous basic designs. The first one is related with the possible impact in the ecology of the hydrothermal vents if the Submarine Generating Device (SGD) touches or even if it just disturbs the fauna and flora of the surroundings. In this paper we present a radically different approach. We stay away from the vents or smoke chimneys and make use of the heat that swipes up in their vicinity also associated to the ocean ridges that transmit heat from the crust to the sea floor (Jorgensen et al., 1990; Lonsdale et al., 1980) and extract the heat from the "boiling sands" by nailing down tubes that contain in its inside another concentric pipe. With this series of vertical heat exchangers, as explained in this article, heat from the sand is transferred to the demineralized water that runs inside the pipes and, after gathering the hot water from the nailed pipe it is taken to the main heat exchanger of an ORC generation station. It is important to notice that in the design we describe gathering heat from the "boiling sands", the heat transfer coefficient from the sea floor to the nailed pipes can be quite high since hot sea water is always flowing up, and sometimes bubbling, because of the flashing when the pressure decreases along the sand bed. Also notice that we use as primary fluid, demineralized water to avoid any accident that could pollute the surroundings, as could be the case if one uses thermal oil. Scaling and fouling in the heat exchangers become negligible and doesn't affect the heat transfer from the sand to the pure water. To stick 20 meters pipes in the sand is not difficult; it can be easily done accompanying the nailing process with a strong water jet from a pump at the surface. The main challenge in this design is to find a place of sea floor, usually in the vicinity of the hydrothermal vents, with very high temperature "boiling sands"; one of such places could be the Guaymas Basin in the Gulf of California (Jorgensen et al., 1990; Lonsdale et al., 1980). In our study we had to suppose a heat flow along the sea bead to complete in a very conservative way, our calculations.

The other important innovation in this paper is that all the components of the SGD can be manufactured and tested in a well-suited workshop and then introduced in 18 to 24" pipe that can support very high pressure under the sea. Also, provisions are made to include several tubes, ballasted with water when immersing the SGD and with a simple compressed air camera to displace the water when floatability is needed to bring up to the surface the SGD. This modular arrangement is a very practical solution for a basic design that can be improved with better ideas of industrial design and from the submarine industry.

The SGD is designed to be installed vertically to make use of the natural convection of the cold water of the sea floor inside the condenser tubes.

Some basic calculations of every piece of the equipment are presented to have an order of magnitude of them. Of course, much more detail calculations must be carried out, based on the real characteristics of the sea floor.

2. DESCRIPTION OF THE GENERAL ARRANGEMENT FOR THE SGD

The SGD can be subdivided into two main components (figure 1): The system that collects the heat from the sea floor that here we call it the *heat pump* (HP) and the other is the power plant itself were electricity is generated by a binary Organic Rankine Cycle (ORC) that here we call *the power plant* (PP). The HP consists of two coaxial pipes (CP) buried, or nailed down, into the hot sands and a demineralized water pump (P1). The objective of this pump is to extract heat from the ocean floor using demineralized water as heat transport fluid. Cold water is pumped into de outer ring of the CP and hot water is extracted from the central pipe.

This hot demineralized water then enters a series of tube type heat exchangers (HX) where it transmits its thermal energy into the main working fluid (isobutane) for the power cycle. The working fluid enters (isobutane) the HX at high pressure, as subcooled liquid, and exits as saturated steam.

This steam is used in a steam turbine (T) which is connected to an electrical generator (G) in order to transform mechanical energy into electricity (E).

The working fluid exits the turbine as superheated steam and goes then to a condenser (C) at a lower pressure in which cool ocean water, by natural convection, extracts heat from this superheated steam until saturation of the liquid is obtained.

Finally, a second pump (P2) rises the pressure of the working fluid form the low condensing pressure to the high HX´s and T pressure and the cycle starts anew. In the final array of the SGD both pumps are placed together in one single module called pumping module.

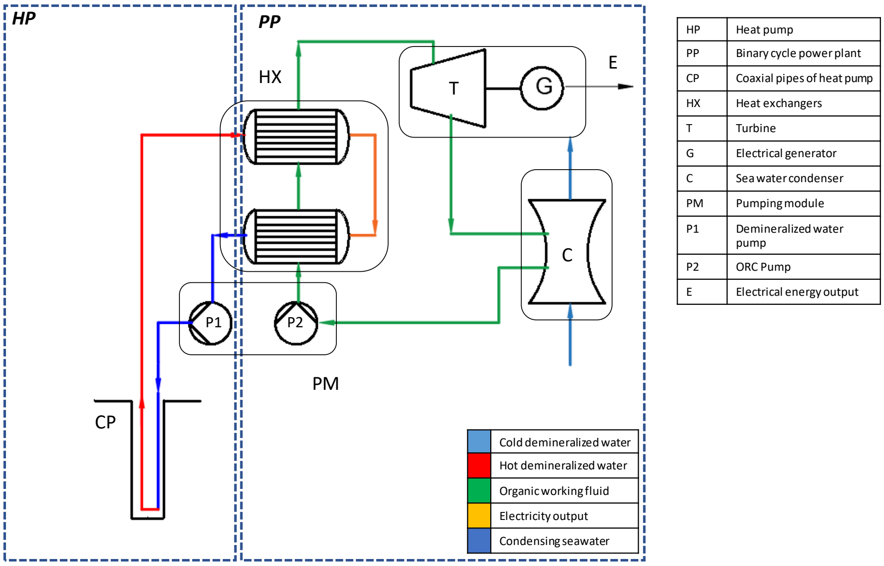


Figure 1: Main components and process lines for the SGD.

3. HEAT EXTRACTION FROM THE "BOILING SANDS" OF THE SEA FLOOR

With the objective to evaluate the best scenario in the extraction of heat from the boiling sands a numerical analysis was made using the software FEFLOW. A fixed array for the heat pump was selected, consisting of two coaxial pipes of 4" and 2" nominal diameter of carbon steel. The analysis was made considering a variable mass flow of demineralized water, and also, a variable length of the nailed pipe. The parameters used in this analysis are shown in table 1.

Table 1 Parameters used for analysis of heat pump

Parameter	Value
Geometry	Coaxial (annular inlet)
Inlet pipe nominal diameter	102mm (4")
Outlet pipe nominal diameter	51mm (2")
Thermal conductivity of pipe	50 W/m-K
Thermal conductivity of hot sands	2.3 W/m-K
Inlet water temperature	20°C

The analyzed model was a 500m hot sands cube with constant temperature boundary conditions on 4 of its 6 sides of 180°C. At the bottom of the cube a boundary condition representing a convective mass flow of hot water was simulated as flowing water at 200°C and 0.15m/h of speed in an upward direction. All the insides of the hot sands cube including the top face were subjected to an initial temperature of 180°C. The nailed pipe is in the center of the top face of the cube. The schematic of the heat pump is shown on figure 2. The thermal conductivity for the hot sands was taken as a normal value of 2.3 W/m-K. The variation of outlet temperature as function of depth and mass flow rate was evaluated for a steady state condition.

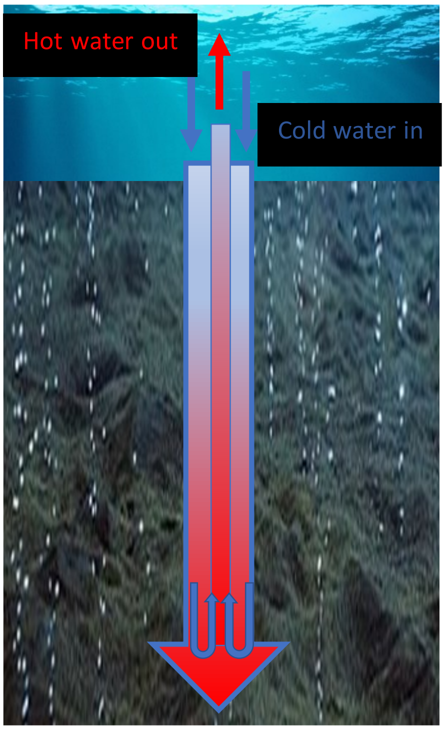


Figure 2: Schematic of the heat pump.

In figure 3 are show the results for the outlet temperature of demineralized water as function of depth for different mass flow rates.

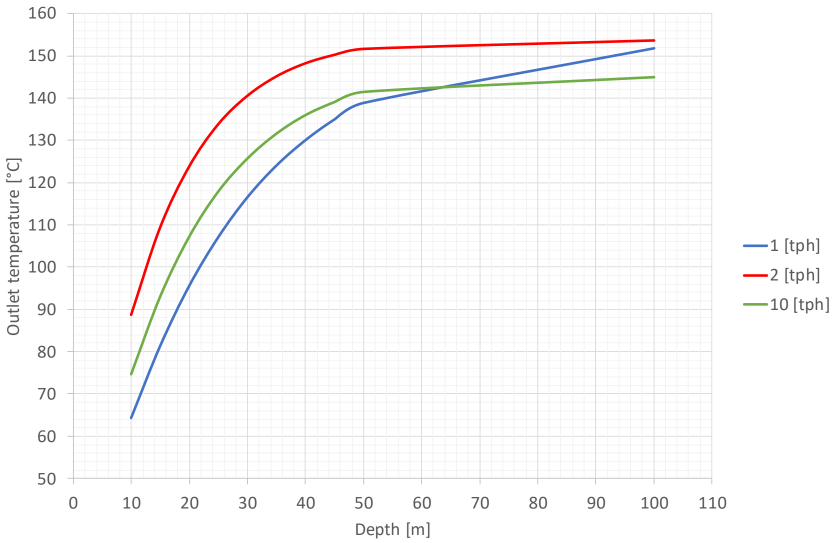


Figure 3: Outlet temperature as function of depth for different mass flow rates.

We find a logical result; the outlet temperature goes up with deeper (longer) nailed pipes. However, output temperature is more sensitive to changes in depth in the first 50m of pipe. That is, going deeper as 50m doesn´t change much the output temperature.

In figure 4 it is shown the outlet temperature as function of mass flow rate for different depths. There is a maximum mass flow rate in which the highest temperature is obtained for a certain depth. For example, at 20 meters depth, the highest outlet temperature (127°C) comes around a flow rate of 3.5 tph. This could be counter intuitive because, as flow rate goes up, the time for the water to exchange heat with the hot sands goes down hence lowering the outlet temperature. But it must be taken into account that at lower flow rates the heat transfer phenomenon between the hot sands and the water is mainly conductive due to low velocity of the flow rate. As flow rate goes up convective heat transfer takes a preponderant role having the effect of improving energy transfer. As flow rate increases, a maximum of energy transfer efficiency is reached, passing which the outlet temperature goes down because of residence time of water in the heat pump.

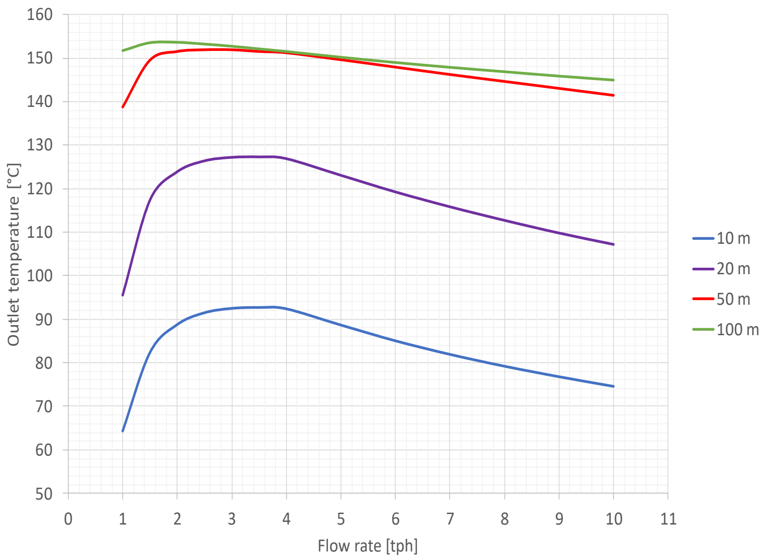


Figure 4: Outlet temperature as function of flow rate for different depths.

In figure 5 the thermal power obtained from the hot sands is plotted as function of mass flow rate for different depths.

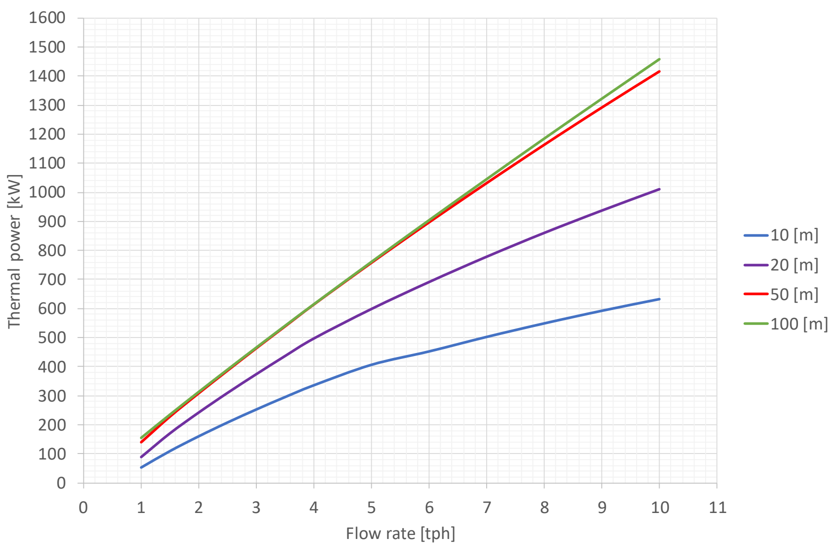


Figure 5: Thermal power as function of flow rate for different depths.

We can see another logical result; thermal power is directly dependent of mass flow rate. But the most important result is that there is almost no difference in terms of thermal power between a heat pump at 50m and one at 100m.

Based on the previously shown results it was decided to try the scenario of a power plant obtaining the necessary heat form hanged pipes of 20m depth.

4. GENERAL ARRAY OF THE SGD PLANT

In figure 6 a general array of one SGD unit divided into its constituent modules is shown. Cold demineralized water is pumped from the pumping module (blue) into the 20m depth nailed pipe. Hot water comes out and is directed towards the heat exchanger module (red) where it transfers its heat energy into the ORC working fluid. This heat exchanger module consists of a preheater and an evaporator. The preheater rises the temperature of the working fluid to the saturation point and the evaporator changes its phase to saturated steam. The working fluid is next directed to the turbogenerator module (green) where a vertical ORC turbine coupled to an electrical generator produces electricity. The exhausted superheated steam goes next to the condensation modules (purple), where cold sea water removes heat from the working fluid until it reaches the saturated liquid phase. These condensers use natural convection as motive force for the cold sea water, they have a curved shape to help the convection process by means of generating a differential pressure between the inlet and outlet of the sea water. The condensed working fluid is then pumped from the pumping module (blue) to the heat exchanger module and the power cycle starts again. The pumping station has two sections inside the same vessel, one for the demineralized water and other for the working fluid. All the instrumentation and control devices for the SGD are inside the turbogenerator module. If one module needs maintenance or repairs the ballasting and floating module (orange) controls the process for it to float to the surface by means of a compressed air system.

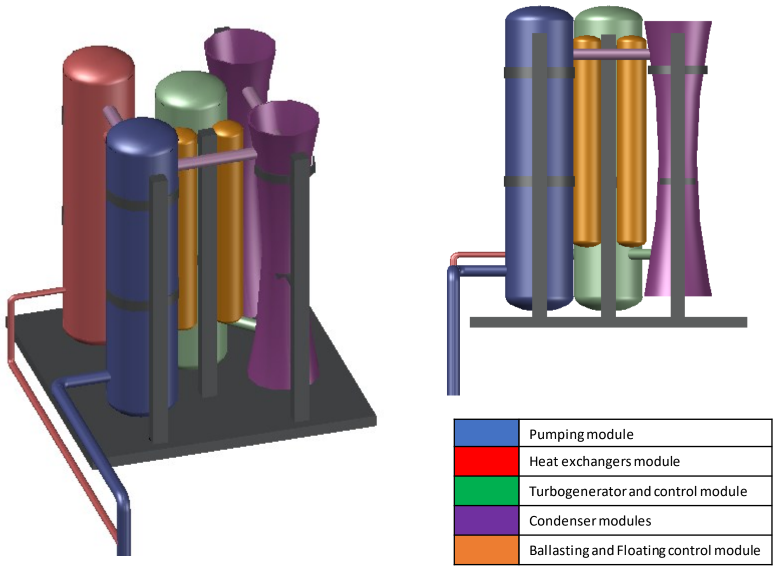


Figure 6: General array of SGD

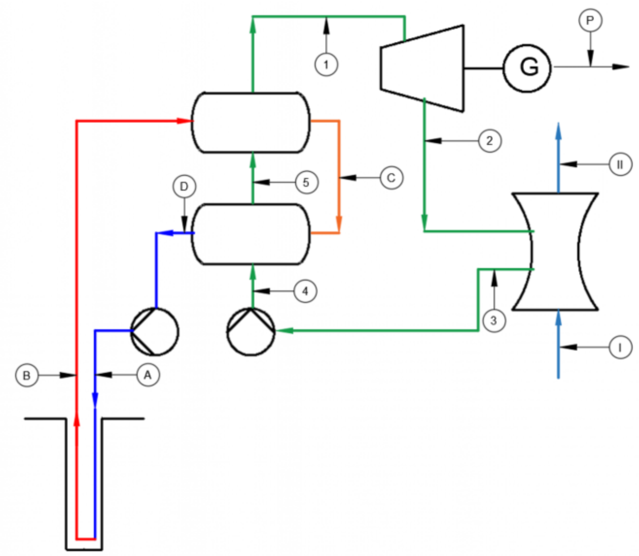
5. HEAT BALANCE OF THE SGD

The hanged pipe for the proposed SGD has a depth of 20m and the power cycle is an ORC with isobutane as working fluid. The mechanical efficiency of the turbine is selected to be 40%. Some other important parameters for the heat balance of the SGD are shown in table 2.

At the start of the operation of the SGD the demineralized water enters the heat pump at a temperature of 20°C and exits with 103°C, after entering the ORC it exits at 60°C thus producing less power than in normal operation. In normal operation the water at the outlet of the ORC exits at 60°C goes through the hanged pipe and comes back at 128°C thus giving the normal power output of 36kW. For condensation, sea water at 20°C was used as cooling fluid at a depth of 2000m. The diagram of the heat balance and thermodynamic properties of the different fluids are shown on figure 7.

Table 2: Design parameters for SGD.

Parameter	Value
$\Delta T_{pitch\ point}$	5°C
Turbine efficiency	40%
Electrical generator efficiency	95%



Point	Fluid	Flow rate (tph)	Pressure (bara)	Temperature (°C)	Entalphy (kJ/kg)
A	Demineralized water	10	3	60	251
B	Demineralized water	10	3	128	538
C	Demineralized water	10	3	82	345
1	Isobutane	8	13	77	654
2	Isobutane	8	4	52	636
3	Isobutane	8	4	30	271
4	Isobutane	8	13	30	272
5	Isobutane	8	13	77	397
I	Sea water	133	200	20	103
II	Sea water	133	200	25	123
P	Gross electric output	36	kW		

Figure 7: Heat balance for proposed SGD.

Using the heat balance results, the general array of the SGD shown on section 2 was obtained in which vessels of 24” diameter and 2.5m length were used. There is one pumping module inside which we have the pumping station for the heat pump and the pumping station for the ORC organic fluid. We have one heat exchanger module inside which we have the preheater and the evaporator of the ORC. In the middle of the array we have the turbogenerator and I&C module inside which we have the ORC turbine, electrical generator and all the control and instrumentation necessary for the operation and sending to maintenance of the SGD. And finally, two condensation modules which use sea water as condensation medium for the ORC working fluid. That is, for a total gross generation of 36kw the SGD would require 5 modules.

6. SOME IMPORTANT FEATURES

The proposed SGD can give a gross output of 36kW using one 20m long nailed pipe in hot sands of nearly 180°C and using demineralized water as heat transport medium.

The SGD proposed uses a non-conventional and widely spread geothermal energy source that is not currently being exploited. It has the advantage not touching nor disturb the hydrothermal vents because it uses the heat from surrounding hot sands as power source

The thermal energy is extracted from the hot sand bed by means of spikes or nailed tubes that penetrates 20m in the soil. Demineralized water is circulated inside a concentric tube to extract heat and sent it to the ORC power plant, few meters away.

The process of nailing down into de sand the 20m pipe presents no major technological challenge as is technology that has been already tested in real life applications.

The main components of the SGD are well known pieces of equipment that are readily available in the market. The novel solution presented here is that all the parts are encapsulated inside a pressure resistant vessel, assembled and tested in an adequate facility ashore. A couple of ballast pipes are added to the plant to facilitate its immersion and a device with compressed air to be used to give the necessary floatability to bring it to the surface if needed for maintenance or reparation of any of the modules.

The condensers proposed use cold seawater in the surroundings as cooling fluid and don´t require additional pumping equipment as they take advantage of natural convection within its shell similar to a hyperbolic, natural draft, cooling tower.

6. CONCLUSIONS

It was proposed a geothermal ORC power plant called Submarine Generation Device (SGD) that uses heat from hot sands undersea, in the surroundings of the well-known hydrothermal vents to obtain electrical energy.

A single SGD unit consists of five modules and can produce as much as 36 kW of electrical power by nailing down a pipe 20m long into the hot sands (heat pump).

Heat obtained from the hot sands was found to be highly dependent on mass flow rate and depth, except at very long pipes where power output slightly changes

The modules were 24” diameter pipes 2.5m long and the heat balance produced an array of 5 modules.

Ample submarine areas can be farmed to escalate the power output of a certain region. The idea and great advantage of the SGD is that each module can be brought back to the surface form each SGD when necessity of maintenance and repair arises.

This was a first proposal for the use of a non-conventional geothermal resource in the sea surface. This first design can be readily improved in different areas: heat pump design and installation, ORC design and optimization, design and general array of SGD elements, scaling up of power output, surfacing system etc. It was our purpose to open the field to discussion and improvement of a new idea of geothermal exploitation.

REFERENCES

Aryadi, Y., Rizal, I., and Fadhil, M.: Electricity generation from hydrothermal vents, *5th ITB International Geothermal Workshop*, IOP Conf. Series: Earth and Environmental Science 42, (2016).

German, C., and Von Damm, K.: Hydrothermal Processes, In: Elderfield H., (ed.), *The Oceans and Marine Geochemistry*, Volume 6 of Treatise on Geochemistry, H.D. Holland and K. K. Turekian (eds.), Amsterdam, (2004).

Hiriart, G., Prol-Ledesma, R., Alcocer, S., and Espíndola, S.: Hydrothermal Vents and Electricity Generation, *Proceedings*, World Geothermal Congress, Bali, Indonesia, (2010).

Jorgensen, B., Zawacki, L., and Jannasch, H.: Thermophilic bacterial sulfate reduction in deep-sea sediments at the Guaymas Basin hydrothermal vent site (Gulf of California), *Deep-Sea Research*, **37**, (1990), 695-710.

Lonsdale, P., et al.: A High-Temperature Hydrothermal Deposit on the Seabed at a Gulf of California Spreading Center, *Earth and Planetary Science Letters*, **49**, (1980), 8-20.

Pedamallu, L., Hiriart, G., Rodrigues, N., et al.: Preliminary Assessment of Offshore Geothermal Resource Potential of Portugal – The Case of Azorean Deep – Sea Hydrothermal Vents, *Geothermal Resources Council Transactions*, Volume 42, Davis, CA (2018).

Prol-Ledesma, R., and Canet, C.: Evaluación y Explotación de los Recursos Geotérmicos del Océano, En: Low Pfeng, A., and Recagno E., (eds.), *La Frontera Final: El Océano Profundo*, (2014).

Rachel, E., and Allen, R.: Nuclear Heat for Hydrogen Production: Coupling a Very High/High Temperature Reactor to a Hydrogen Production Plant, *Progress in Nuclear Energy*, **51**, (2008), 500-525.

Shnell, J., Hiriart, G., Nichols, K., and Orcutt, J.: Energy from Ocean Floor Geothermal Resources, *Proceedings*, World Geothermal Congress, Melbourne, Australia, (2015).

Yu Xie, Shi-jun Wu, and Can-jun Yang: Generation of electricity from deep-sea hydrothermal vents with a thermoelectric converter, *Applied Energy*, **164**, (2016), 620-627.