Harnessing of low temperature geothermal and waste heat using Power Chips™ in Varmaraf heat exchangers

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Abstract

Power Chips Plc is in the final stages of developing solid-state thermal conversion devices that allow direct conversion of heat into electricity at 60-70% of Carnot efficiency. This is achieved by letting electrons tunnel across a gap of a few nanometers. Incorporating these devices into special purpose heat exchangers from Varmaraf allows large scale harnessing of geothermal and waste heat by increasing the efficiency of existing plants and making new plants feasible at lower temperatures than currently possible.

***Keywords**: Power Chips, Varmaraf, heat exchanger, tunneling, efficiency, geothermal, waste heat.*

1 Introduction

Typically, geothermal power is converted into electricity through turbines operating on the flash steam or the binary Rankine cycle. These systems, however, have a number of drawbacks that limit their usefulness. Aside from the maintenance issues associated with the mechanical operation of the turbines, availability of geothermal resources suitable for turbine-based power generation are restricted to a few geographical regions. Many other resources that offer lower thermal gradients are not exploitable even with advanced binary systems, leaving vast potential reserves untapped.

Heat exchangers incorporating thermoelectric modules offer one possibility to generate electrical power from geothermal sources. These devices convert a heat differential into an electric current. Thermoelectrics, however, are expensive and inefficient, operating at no more than 5-10% efficiency even under ideal conditions (CRC Handbook of Thermoelectrics, 2001).

2 Power Chips: an overview

A newly emerging technology, called Power Chips, is now expected to provide the advantages of thermoelectircs, at much higher efficiency and much lower cost. Power Chips are in the final phases of development, with production prototypes expected to be available later this year. Physically they are small, solid-state devices, capable of efficiently generating electricity when heat moves from one side of a diode to the other. Unlike thermoelectric devices, Power Chips exploit a quantum electron tunneling effect as their primary operating mechanism. Simply stated this means that the energetic electrons created by heating one electrode will migrate across a nanometer-scale gap, creating a useful electric current in the process. Because of the inherent high efficiency of this effect, and the use of a gap between the electrodes to prevent losses from heat conduction, our research indicates that Power Chips have the potential to offer a novel power generation solution capable of delivering 60-70% of Carnot efficiency across a wide range of operating temperatures.

Electron tunneling has been studied for many years by companies like GE and General Atomics, but the efficiency of earlier devices suffered for the same reasons that thermoelectric efficiency is limited – no materials have been identified that allow electron transmission while still providing good thermal insulation. As a result, thermal backflow degrades the temperature differential across the device and efficiency suffers – precisely the same problem that plagues thermoelectrics. In the absence of a suitable insulating material, Power Chips research turned to integrating a vacuum gap between the electrode surfaces.

Thermionic converters have incorporated gaps between the electrode pairs, but the gap spacing was on the order of 1-10 microns. In order for the electrons to cross this gap, the electrode must be raised to a very high temperature, high enough for the electrons' energy to exceed the work function of the material and thus "escape". By maintaining a much smaller gap, on the order of 1-10 nanometers, Power Chips make it much easier for the electrons to flow across the gap. Instead of thermionic emission, the electrons are able to "tunnel", hopping short distances from one electrode to another. Because the energy requirements are much lower for tunneling than for thermionic emission, our research indicates that Power Chips will be able to generate an electric current with a much lower heat gradient for an extended period of time.

The greatest technical challenge to building working devices of this nature lies in the creation of electrode surfaces that are broadly conformal. Because of the limits of polishing technology, it is not possible to create perfectly flat surfaces. This means that slight curvatures in the electrodes would prevent the two surfaces from maintaining such a small gap over their entire surface area. This issue is resolved with Power Chips by growing the electrodes in layers, separating them, and then bringing them back together. Through a carefully controlled process two surfaces can be created that have identical curvature, making it possible to maintain the necessary gap without creating areas of contact between the electrodes.

Boeing Phantom Works conducted validation of this work, and the resulting ability for electrons to tunnel across the gap, in 2001, with prototype devices achieving tunneling currents of more than 10 Amps. These devices, however, were limited in their operation by the relatively high work function (eV) of the electrode materials.

3 From lab to manufacturing

In order to maximize the tunneling effect and to create useful amounts of electrical power, Power Chips are in the process of incorporating materials with a low work function (on the order of 1eV) into the electrodes. Research conducted at Stanford University (Stefansson, V., 1998) predicts that lowering the work function will significantly enhance electron tunneling. While this work focused on the use of tunneling to move heat when supplying an electric current, the inverse function is applicable (supplying heat to create an electric current) and provides reasonable theoretical guidelines for the capabilities of Power Chips in operation. With electrodes having a work function of around 1eV, power output is likely to be upward of 10 Watts/cm^2 at a spacing of 5 nanometers. As the theoretical maximum output predicted by the Stanford research is on the order of thousands of Watts/cm^2 (Hishinuma Y., et al., 2001), there remains an opportunity to further develop and enhance the technology.

Production of Power Chips is fairly simple; and requires no particularly rare or expensive materials. Devices are currently produced in a laboratory environment, and this is expected to continue while mass production is being readied. Initial production prototypes will be used primarily for testing and applications engineering. Mass-produced devices are expected within a year of completing current development efforts.

4 Geothermal and waste heat potential

For geothermal applications, Power Chips should provide increased power output for existing plants and enable power production where it is not currently practical. By building arrays of these devices, installations can be scaled to match available heat sources ranging from a few kilowatts to many megawatts. Making effective use of Power Chips for these applications, then, will be most dependent upon the means used to collect the heat and maintain a temperature gradient.

Geothermal plants dedicated to Power Chip arrays will be much different than existing plants. As you have seen, no magnetic induction is required to generate electricity. Power Chips require no moving parts, just heat. The Power Chip geothermal plant of the future will make flash steam cycle, and binary Rankine cycle, turbine driven plants inefficient and obsolete. We expect to run these plants at 60%-70% of the Carnot-defined maximum possible efficiency. Operating at these efficiencies changes the economics of geothermal development giving developers more electricity to sell per unit of geothermal heat. The increase in monetary return will have a ripple effect creating a greater demand for exploration and field service work. Power Chips will allow for the exploitation of geothermal resources with temperatures below 200 F. This changes many of the rules we as an industry have previously lived by. With the ability to produce power at these relatively low temperatures, “Hot Dry Rock” power production becomes a much more realistic endeavor.

Geothermal heat is a huge energy resource. It has been estimated that the total harnessable power using turbines (steam >150°C) is about 1,300 GWe and that lower temperature geothermal resources may provide about twice that using binary systems (Stefansson, V., 1998). Power Chips mounted in a suitable heat exchanger extend this even further. Therefore, the total geothermal power that can potentially be generated with this technology is on the order of 4,000 GWe. For comparison, the total installed power of all electricity generators in the world is about 3,300 GWe. It is tempting to use this figure as a basis for calculation of potential market size. It suffices to say, that even if a small fraction of this potential is realized, the economic and environmental implications are huge. Naturally, geothermal energy is only available in certain geologically active places. However, with hydrogen emerging as an energy carrier (Ogden, Joan M., 1999), the transport of energy from geothermal areas to other regions becomes a realistic option.

5 Thermoelectric generators extended to Power Chips

Varmaraf develops and manufactures heat exchangers that can accommodate solid state conversion elements. Until the Power Chips became a technical reality, the work was focused on thermoelectrics where the power conversion is achieved by the Seebeck effect. The thermoelectric modules are mass produced, mostly for cooling applications and packaged as flat cells, a few centimeters square. Inside the module, an array of bismuth-telluride crystals is connected in series and a voltage is induced in proportion to the temperature difference between the ends of the crystals. While useful electricity is generated this way, substantial heat is conducted through the crystals from the hot side to the cold, thus limiting severely the efficiency of the conversion. There are three major reasons for the fact that thermoelectrics has not been able to deliver power from heat at a cost that is competitive with traditional power generating means:

- Limited efficiency as outlined above.
- The price of the thermoelectric modules themselves has been, and still is, forbidding although higher production volumes have led to substantial price reductions.
- Effective low cost heat exchangers have not been available.

We have already learned how the Power Chips will address the cost and efficiency issues of the conversion modules themselves. Through its work on thermoelectric conversion using hot and cold-water flows, Varmaraf has developed a heat exchanger that addresses the last issue above.

6 Heat exchanger design challenges

When it comes to harnessing geothermal and waste heat, the most applicable device would be one that uses hot and cold water as the medium for transferring heat from the original heat source to the conversion device and transferring heat from the conversion device for disposal. This is because in many cases, such fluid loops are already available or they can be established at low cost using proven hardware. On the cooling side, air-cooling is hardly an option because of the very limited heat transfer that occurs on the metal/air interface in cooling fins or heat sinks even under forced convection. When heat must be dumped at only a few degrees higher temperature than the surrounding air, an extremely large heat transfer area is called for, with high cost unavoidable. Cold rivers, lakes and cooling towers may be the best way to dump heat for this application. The effectiveness of cooling towers is due to the evaporation that is involved and carries away the bulk of the heat. The design objectives for a heat exchanger that is suitable for thermal conversion are primarily the following two:

- Maintain the temperature at both the hot and cold work surface of the conversion device as close as possible to the hot and cold fluid temperatures, under heat conduction through the conversion device and adjacent material.
- Minimal total cost of the heat exchanger because with no moving parts and negligible maintenance required, it is the capital cost of the generator that determines the production cost of each kilowatthour.

What determines the success in achieving the first objective is the heat transfer coefficient at the interface between the fluid and the wall of the flow channel and the total thermal resistance from the inner surface of the flow channel to the work surface of the conversion device. The more heat conducted per unit area through the conversion device, the higher demands are placed on these external factors. While very high thermal conductivity through the conversion device is desirable in principle, as this also gives most electrical output, a difficulty arises in maintaining the temperature difference across the work surfaces of the conversion device. In plate heat exchangers, it is also important to maintain as high heat transfer at the channel wall as possible. The classical plate heat exchanger design addresses this by corrugating the plate separating the fluids, thus inducing turbulence that enhances the heat transfer. In a heat exchanger that accommodates flat thermal conversion devices, this is not possible without resorting to expensive machining on one side while keeping the other side flat. Furthermore a uniform surface pressure must be maintained across the heat exchanger plate layers, with the conversion devices arranged in between hot and cold channels, so as to achieve good thermal contact between the devices and the flow channels. Varmaraf's design addresses all these challenges successfully in a unit that that is layered like a plate heat exchanger but includes the thermal conversion devices, namely thermoelectric cells or Power Chips. The unit has four ports, two for hot water, in and out and another two correspondingly for cold water just like normal plate heat exchangers.

An important feature of this design is how it addresses the second design objective, namely low cost. Varmaraf's design calls for minimal machining and offers the possibility to use special metals, such as titanium, without unreasonable cost.

7 System design issues

It is a basic characteristic of solid-state generators that they cannot benefit from economy of scale in the same way as, for example, turbine systems, where several components enjoy eightfold increase in useful volume while the enclosing material is only quadrupled with a doubling of a linear dimension. If a double size solid-state generator is called for, twice the number of conversion devices must be applied and the heat exchange area doubled, hence also twice the investment. Consequently, the cost advantage of the solid-state generator over steam or binary systems is greater at the lower end of the power scale. There are other important advantages:

- The solid-state generator is perfectly modular and scalable and can be delivered in single watts or in megawatt installations.
- This modularity also provides redundancy since larger installations will be made of parallel units of identical design. This enhances the reliability and maintainability of the plant.
- It is perfectly suitable for harnessing water at temperatures where even binary systems are not applicable.

There are a number of optimization issues in determining the best system configuration. The optimal result is in most cases heavily dependent on performance parameters and costs. At this early stage of the systems development such results are not available yet but the questions are well defined. These relate to the minimal temperature difference for economic harnessing and influence of auxiliary components, such as pumps, on total system performance.

The most appropriate system configuration is also strongly dependent on local conditions. In some cases, the hot water may be sufficiently pure and void of dissolved minerals to allow it directly into the generator unit. Here, the tradeoff is between using the water directly and running the risk of some fouling and corrosion or set up a secondary loop with the associated losses. On the cooling side, the question is about the availability of a river or lake into which the heat could be dumped with due consideration of the environmental effects of the heating although no material contamination would be involved. Without a cold reservoir, a cooling tower is probably the best bet. Deposits could also be factor on the cold side if a reservoir is used, depending on the water chemistry.

8 Cost

Solid state generators can be applied in a variety of applications, of which the generator itself is only a part. They can be added on to an existing plant for the purpose of increasing output or they can be the principal generator where a hot water well is present. We can therefore only discuss the capital cost of the generator itself, to which the cost of other components, including inlet and outlet piping and electrical inverters must be added. Based on Varmaraf's heat exchanger design and expected cost of the Power Chips, it is reasonable to expect that the cost of the generator is US$ 500-1000 per installed kilowatt, based on water with mean temperature difference of 60°C.

9 Conclusion

Operating at high efficiency; with lower capital costs, and a greater pool of potential heat sources changes the economics of geothermal development. Power Chips could help make geothermal development much more attractive financially; and open the field for the pursuit of resources, such as regions of "Hot Dry Rock", with temperatures below 95^{o} C. Coupled with an effective heat exchange mechanism like the solutions developed by Varmaraf, power generation from geothermal resources can become a practical, reliable and renewable means to satisfy our energy needs. The overall effect on the geothermal industry will be enormous once functional devices are deployed. Embracing this technology early is to the industry's collective advantage. In addition, there are very substantial environmental benefits as the added power generated is clean and replaces fossil fuel based generators. With deployment of the generator in the form of a fluid/fluid heat exchanger, substantial opportunities open up in retrofitting existing thermal plants of various designs for higher efficiency, as well as in building new plants, particularly in lower temperature geothermal areas.

10 References

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11 Figures

Fig 1: The figure shows a small thermoelectric generator from Varmaraf. A similar device will incorporate Power Chips™ for much higher efficiency and electrical power output. The size shown is 34 cm by 24 cm and the stack height can be extended to accommodate as many layers of Power Chips as desired. Inlet and outlet ports are hidden under the bottom end plate. This design has patents pending.

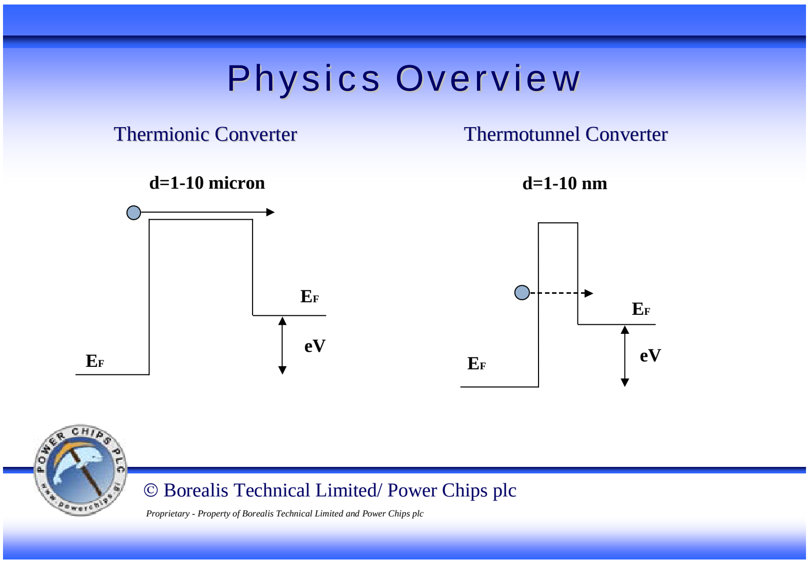

Fig 2: If the two electrodes are close enough to each other, electrons do not need to jump over a barrier. Under the well-known laws of quantum mechanics, they can 'tunnel' from one side to another. The distance must be on the order of 1-10 nanometers, or 1-10 billionth of a meter. This is much more challenging to build than a 10 micron gap.

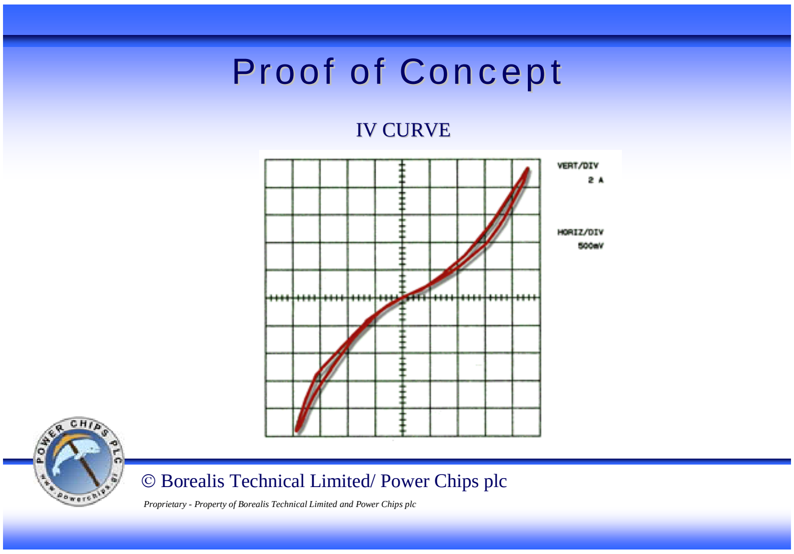

Fig 3: The Proof of Concept was achieved when tunneling currents on the order of 10 amps were measured across a gap. This measurement is several orders of magnitude more current than has ever been reported before.

Fig 4: Power Chip in comparison to US Quarter.