Power Chips plc

Power Chips™
Technical Overview

The Big Picture - Power

Power Chips are projected to be a superb way to extract power from waste and low grade heat.

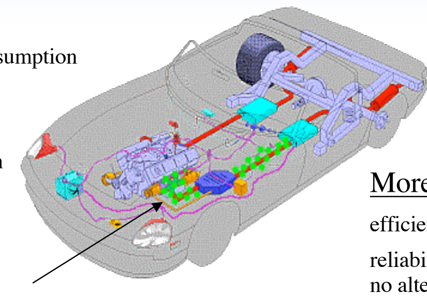
No other technology can efficiently harness waste heat

… Inexpensive to manufacture, and maintenance-free in operation
… Superior to all other existing and projected technologies
… Proprietary, allowing a 20 year head start
… Environmentally Friendly
… Robust, for use in hostile environments

Power Chips™ Applications

Automotive Waste Heat Application and Benefits

Less:
fuel consumption
weight
volume
pollution
noise



Electric power from waste heat.

More:
efficiency
reliability (no belts, no alternator)
design flexibility

Power Chips™ can be applied to the exhaust stream of an automobile, recovering considerable power.

Engine exhaust in a standard car represents up to 45% of the fuel's heating value, as compared to 25-28% which goes into the shaft. And a considerable amount of that shaft power is then diverted for uses other than turning the wheels. These parasitic losses include:

Water pump • Fan • Air conditioning • Power steering • Alternator

And these are mechanical systems, prone to breakdown, belt problems, etc.

Shaft power which is used for running components cannot be used for making the car move.

Power Chips™ would convert a percentage of the engine exhaust heat to electrical power. That power could then be used to run all the other systems electrically, without sucking power off of the shaft energy.

The result is a more efficient, reliable car, without moving to any radical systems.

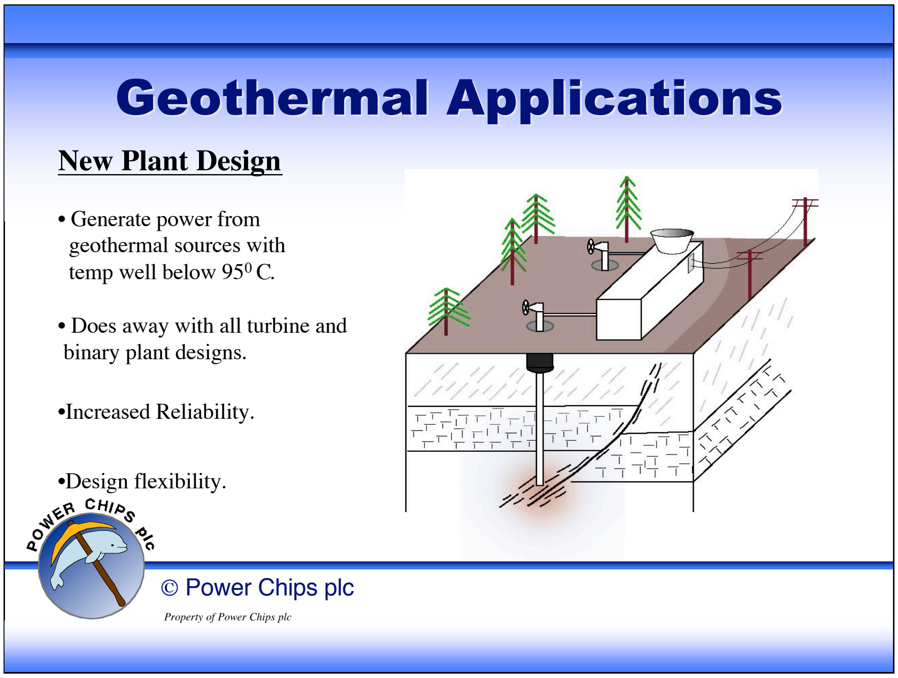
Transportation Applications

How much Power from Auto waste heat?

Power Chips, using existing packaging technology, can output up to 75kW of electrical power from a 100 kW shaft output motor, providing a <u>huge</u> improvement in fuel efficiency.

- ✓ No additional fuel consumption -- waste heat conversion
- ✓ Environmentally Friendly
- ✓ Relatively easy to integrate
- ✓ <\$20/kW is the cost target

<u>Who benefits?</u>
The producer, the consumer, and the rest of the planet



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 95^{o} C. 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

Geothermal Applications

Advantages:

- Low Costs, US$ 500 – 1000 per installed kilowatt given ΔT 60°C
- Increase power output of existing plants
- Increased efficiencies
- Retrofit any existing plant for waste heat recovery
- Environmental Advantages

•Source: US Department of Energy

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Cost

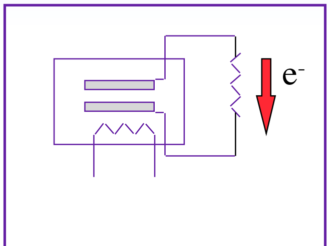
Solid state generators can be applied in a variety of applications, of which the generator itself is only a part. They can be added on to an existing plant for the purpose of increasing output or they can be the principal generator where a hot water well is present. We can therefore only discuss the 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.

Conclusion

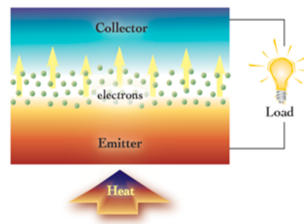
Operating at high efficiency; with lower capital costs, and a greater pool of potential heat sources changes the economics of geothermal development. Power Chips could help make geothermal development much more attractive financially; and open the field for the pursuit of resources, such as regions of "Hot Dry Rock", with temperatures below 95° 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

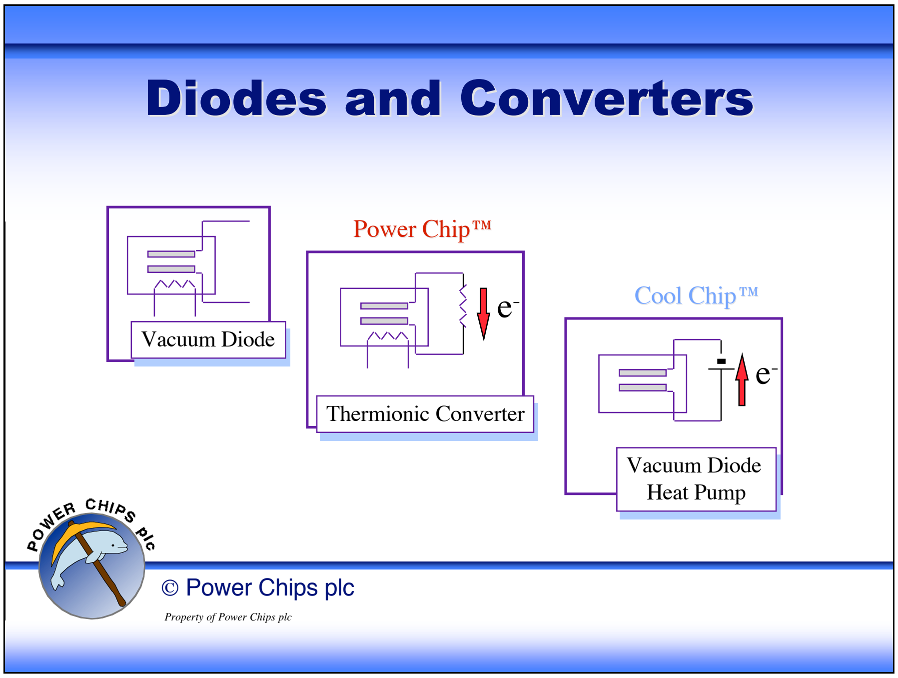
Technology Introduction

Power Chip



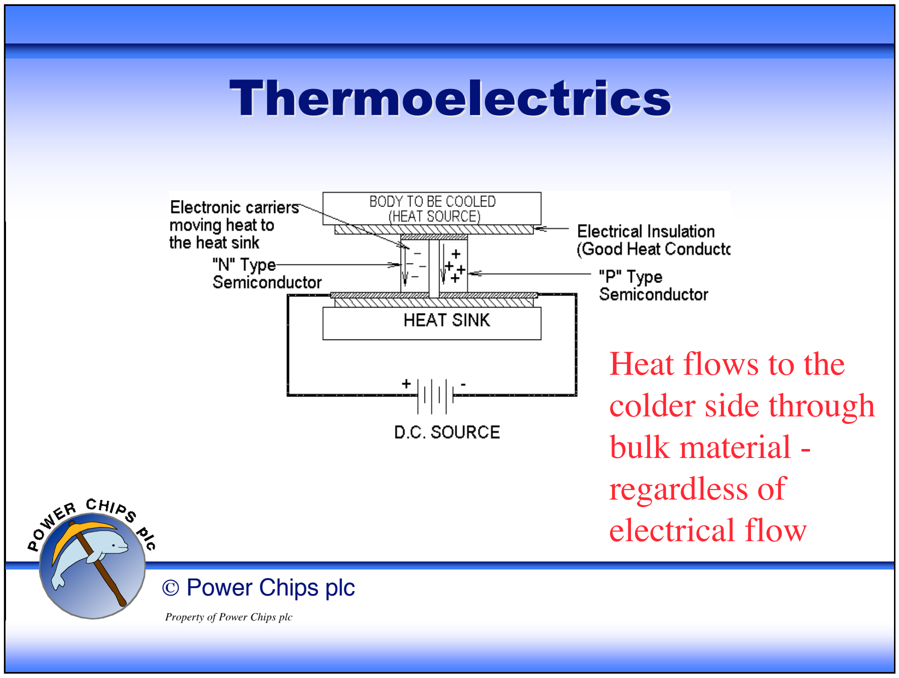
Thermionic Converter





The classic vacuum diode is on the top left. Used in vacuum tubes, television screens and numerous scientific instruments and tools, the vacuum diode is a highly mature technoligy.

The Power Chip™ is in the middle. Conceived at the beginning of the 20th century, the thermionic converter was proven to work in the 1950s, but largely abandoned by the early 1970s because of materials and manufacturing issues.   The thermionic converter harnesses a thermal differential to create electrical output power.

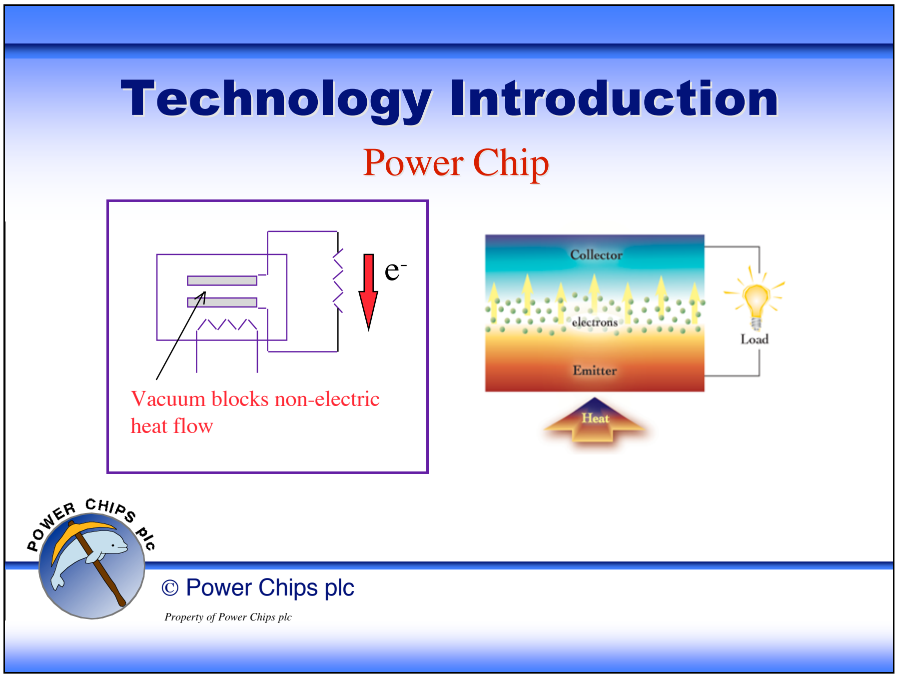


Thermoelectrics also has a long pedigree. Using a combination of the Seebeck, Thomson and Peltier effects, power is generated as heat travels through materials and junctions. This is because some of the heat travel as energy within electrons, creating power. However, thermoelectrics are inefficient.

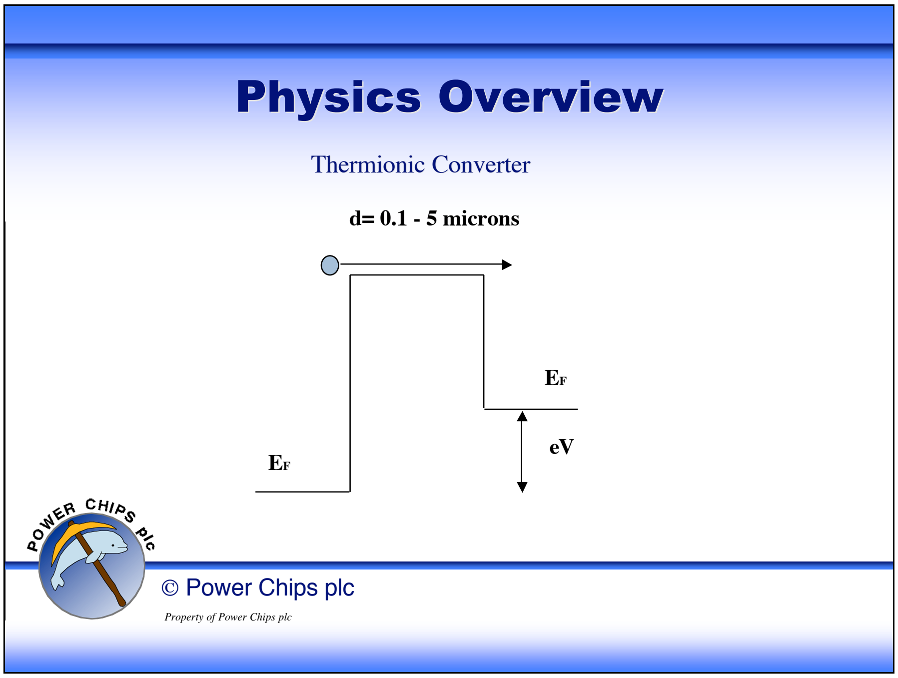
The reason is simple. Heat will flow through any material, and does not require electrons to do so. It is analogous to a hydroelectric power plant which is powered by a dam. Some of the heat (the water) flows through the turbines, generating power. But a thermoelectric dam does not block the heat flow very well, so the “water” flows pretty freely through holes in the dam as well as over the top. Any water which travels across the dam but does not go through the turbine is wasted. Thermoelectric materials are like a dam, with heat leaking through to the other side.. As a result, efficiencies, expressed as a percentage of the Carnot-defined maximum, do not exceed 5-8%.

For decades, researchers have hunted for the ideal material which would make thermoelectrics efficient. That material would conduct electrons (and their energy) with ease, yet be a very good thermal insulator.

The best bulk material found for thermoelectrics was found in the 1950s: bismuth telluride. Since then, despite many hundreds of millions of research dollars spent, a better bulk solution has yet to be found. It has been suggested that the perfect material, one with both excellent electrical conductivity properties, and superb thermal insulation, might as well be



A vacuum conducts electrons very well, but blocks most heat flow. And voila! Unobtanium is not a specific material, but the **absence** of material.



The Thermionic Converter, to minimize space charge, has a distance between the plates on the order of 0.2-5 microns. This is a gap which can be readily built using modern semiconductor technology (Power Chips has built centimeter-scale chips which have 0.5 micron gaps). The <u>manufacturing</u> problem which ended research in the West by the early 1970s has clearly been solved.

However, the other problems remain. In order to get an electron to jump over the barrier at low temperatures, it must have a low work function. The lowest work function materials are based on Alkali metals such as cesium, and they approach 1 eV. Most metals are in the 4-5eV range. At 4-5eV, copious emission does not occur until the cathode is very hot -- hotter than 2000°K. Some metals melt before they emit electrons. Thoriated tungsten, which is used for cathode ray tubes, is heated to 1,950°K.

So thermionics requires a very low work function material in order to make a useful device.

Introducing Avto Metals

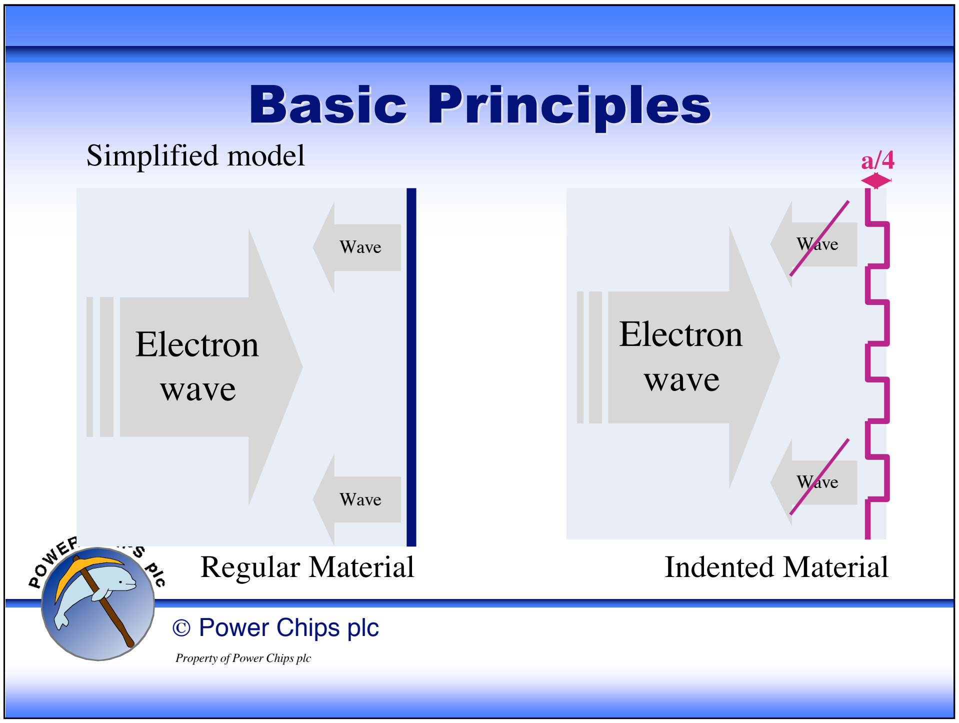
Nanostructures dimensions are approaching the wavelengths of the electrons in the solid.

Super lattices and resonant tunneling structures use these wave properties.

Smaller dimensions, enable new methods for reducing the electron volt work function of a surface.

The solution to a lower work function material which enables low temperature Power Chips can be found in Avto Metals.

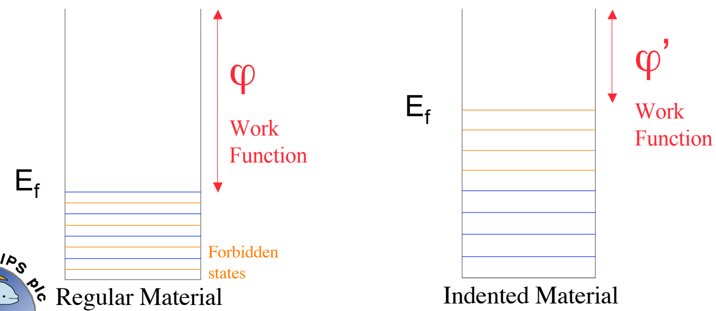
Avto Metals take advantage of newer technology which allows us to make small structures on the surface of a material. These structures interact with the wave properties of electrons, to change the electronic behaviour.



With an appropriately indented material, certain wavelengths can be cancelled out, just by modifying the surface. These principles can be found everywhere waves are studied -- from wave tanks to acoustic research to optics.

Basic Principles (2)

If the final states are forbidden then the initial state is also forbidden.



As a result of certain states being forbidden, electrons are forced to a higher energy level. The work function - the amount of energy needed for an electron to leave the surface -- has dropped. And Power Chips that work at low enough temperatures to recover waste heat become achievable.

Limiting Factors

Limiting factors in practice

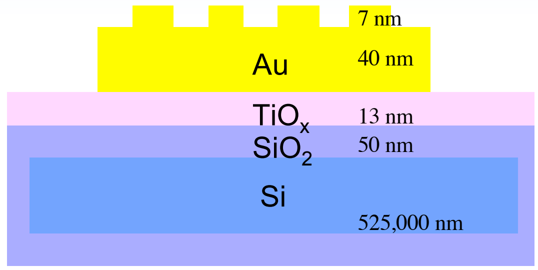
The surface roughness should be less than the electron's de Broglie wavelength.

To avoid scattering at grain boundaries, single crystals are preferred, though amorphous solids are acceptable.

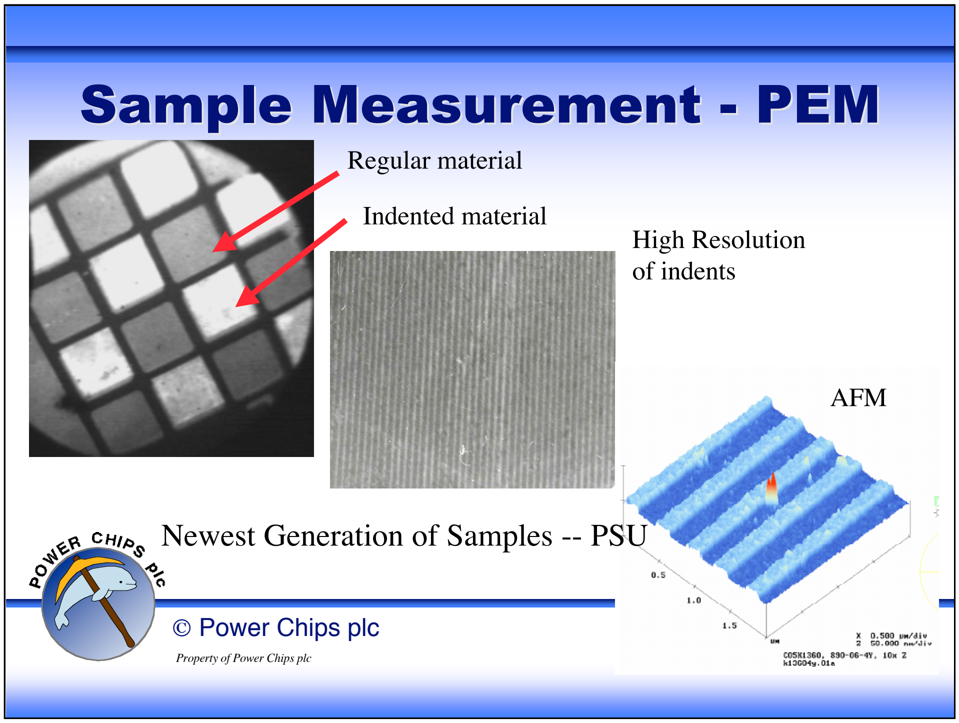
Different geometries for measurement PEM/KP.

In order to preserve the wave properties of the material, then conditions should be ideal: both the surface and backplane should be otherwise smooth. The corrugation needs to be as crisp as possible. And the material should minimize wave scattering by using either single crystal or amorphous materials.

Current Test Samples

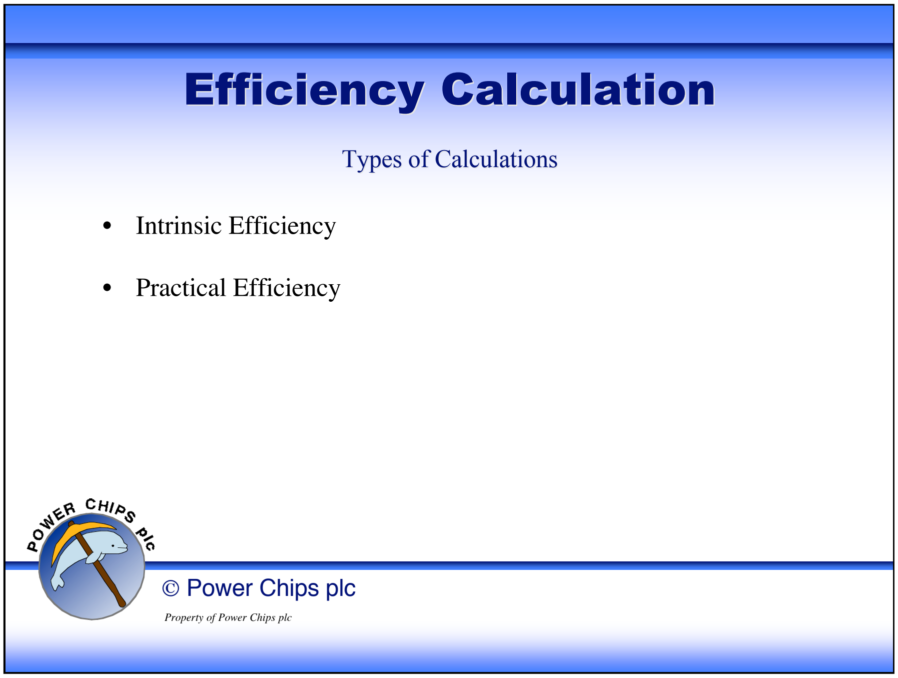


Current test samples use gold, since it does not form an oxide layer which would hide the resulting effect. Production devices will use other materials.



The corrugation seen in the atomic force microscopy image on the right can also be seen optically in the middle. The Avto Metal effect, showing regular gold compared to corrugated gold, can be seen in the Photo Emission Microscopy image on the left.

The acceleration voltage was 15 kV, the illumination source an HBO 100 mercury short arc lamp incident on the sample surface at a glancing angle of 15 degrees from horizontal. The lamp spectrum was filtered using a 280 nm low pass filter, corresponding to a photon energy of 4.4 eV. The final image was projected onto a microchannel plate image intensifier and recorded with a video camera. The images were captured from video tape.



The efficiency of the devices can be understood as two separate pieces:

1: The intrinsic efficiency, considering only the physics of the power generation mechanism

2: The practical efficiency, allowing for losses which occur in real-world devices. These figures are only rough estimates, but they allow for some general conclusions about the efficiency of the Power Chips™ technology.

These will be taken in turn.

Energy Balance for Power Chips

eVemitter + 2KTemitter - energy carried away by one electron emitted from the emitter
eVemitter + 2KTcollector - energy given to the emitter by one electron emitted from the collector

$$\eta = \frac{(Jemitter - Jcollector)(Vemitter - Vcollector)}{Jemitter(Vemitter + \frac{2KTemitter}{e}) - Jcollector(Vemitter + \frac{2KTcollector}{e})}$$

$$Ja,c = ATa^2,c\exp(-eVa,c / KTa,c)$$

$$\alpha = eVcollector / KTcollector,$$

$$\beta = eVemitter / KTemitter$$

$$\theta = \frac{Tcollector}{Temitter}$$

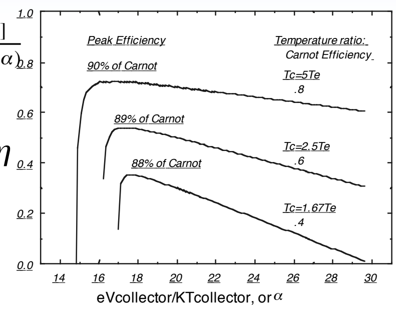
Thermionics has been in the field for over a century now, and considerable work was done in the middle of the 20th century within the field. As a result, the mathematics of thermionics has been well understood for some time.

The above graph shows the intrinsic maximum efficiency for a Power Chip. This takes into account electronic backflow, the amount of heat energy carried by the electrons, etc. It does not take into account practical engineering loss terms, such as losses through support walls, residual gas, electrical interconnects, etc.

Power Chips Efficiency

$$\eta = \frac{[\beta - \theta\alpha][1 - \theta^2 \exp(\beta - \alpha)]}{[\beta + 2] - \theta^2[\beta + 20]\exp(\beta - \alpha)}$$

$$if\beta, eVemitter / KTemitter = 18\ \eta$$



The above graph is taken from a classic thermionic article: “Theoretical Efficiency of the Thermionic Energy Converter” by J.M. Houston, General Electric Research Laboratory.published in the Journal of Applied Physics, Volume 30, Number 4, April 1959.

Efficiency Calculation

Practical Losses

Loss terms for Power Chips™ include:

- Radiation
- Residual gas
- Resistive heating
- Thermal backflow

As losses are temperature dependent, they are all calculated as a percentage of Carnot efficiency (maximum possible COP)

The calculations presented in this section cover all the major loss terms. To make sure the conclusions are conservative, the assumed heat flux is 3 watts/cm^2. Practical losses will be reduced with increased output.

Efficiency Calculation

Radiative Losses

Radiation losses are proportional to $T_{hot\ side}^4 - T_{cold\ side}^4$.
Dropping the temperature by a factor of 5 reduces radiation losses by factor of 625.

There is a loss of <0.1 W/cm^2 at room temperature for black box radiation. Real losses are lower.

Effect on Carnot Efficiency
Acceptable for low temperatures. At over 1200K, becomes a prominent loss term.

Any hot surface radiates heat (which is how the sun works through vacuum). But radiation is very closely tied to the temperature of the hot side.

Efficiency Calculation

Residual Gas Losses

Residual gases, a product of all imperfect vacuums, will be an additional efficiency loss term.

Effect on Carnot Efficiency

<1% due to the small distance between the emitter and collector, which is less than the mean free path of the gas electrons:

http://www.electronics-cooling.com/html/2002_november_techdata.html

Residual gases are a problem in classic thermionic converters, which have comparatively large spacing between the anode and cathode, and which had a flow of plasmas between the cathode and anode.

Fortunately, this only applies to "high pressure" gas in between the wafers. When the pressure drops to a level, where the mean free path for the gas molecules is larger than the gap, the heat conduction is given by a different "rarefied gas" formula [5] (below). In air (nitrogen) the mean free path at 1000mTorr (~ 1 mBar) is 55µm. This is a level of vacuum, which can easily be achieved during bonding.

[5] $Q_{air} = ß * A\ [m^2] * p\ [mbar]$ W/K

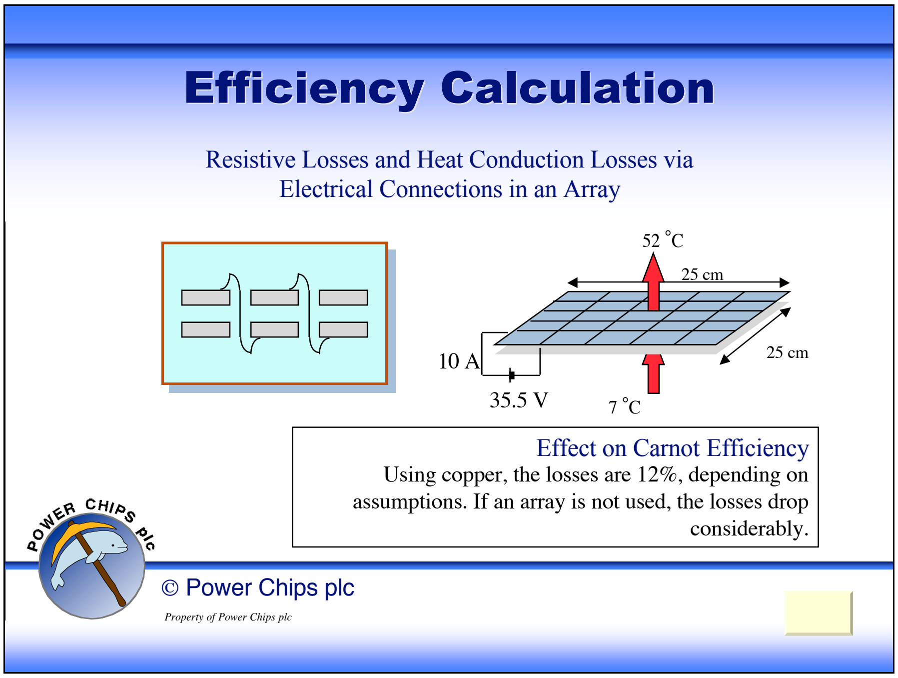
$ß = 125\ W\ m^{-2}\ mbar^{-1}\ K^{-1}$

$A = (1.8 * 10^{-2})\ m^2$

$p = 1$ mbar

$$Q_{air} = 125 * 3.2\ 10^{-4} * 1\ \text{W/K} = 0.040\ \text{W/K}$$

What this slide means is that Power Chips™ do <u>not</u> require a high vacuum environment. The space between the electrodes can be filled with an inert gas, at reduced pressure. This makes sealing the device far simpler, and certainly prolongs its lifespan.



Power Chips™ are likely to operate in an array. Because each device generates a high amperage, and a low voltage, it will be most useful to wire them electrically in series, and thermally in parallel. This keeps the amperage constant, and boosts the voltage into the normal range.

There are two kinds of losses which will occur with an array.

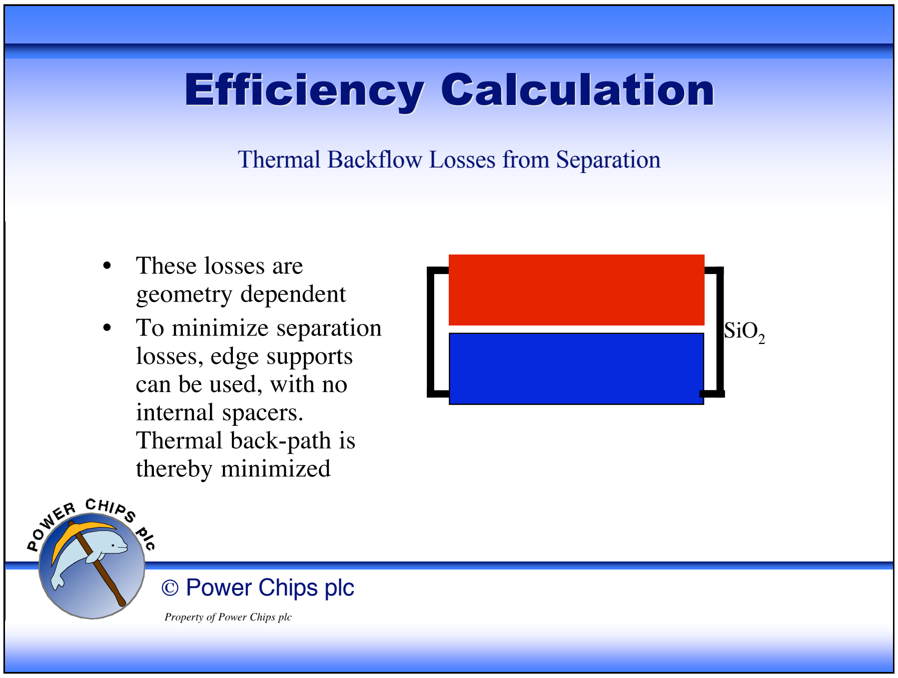
The first is that the wires connecting the chips will run from the hot side, to the cold side. They will provide a thermal backpath, which reduces efficiency. To maximize efficiency, one uses a thin wire.

The second loss comes from the fact that a lot of power is flowing across the wire. Resistive heating will occur. To maximize efficiency, one uses a thick wire.

This is a classic engineering tradeoff: find the ideal wire thickness to minimize the losses.

Using copper, the losses are on the order of 12% of Carnot. This makes the thermal connectors the largest single loss term.

NOTE: If the Power Chips are not run in series, then this loss term is practically eliminated.



When heat flows from the hot side to the cold side, and it does so through active (hot) electrons, the device is efficient. Power Chips are designed to only allow electron flow -- there is no direct thermal contact between the hot and cold sides.

But when heat can flow without the electrons carrying it with them (as it does through simple conduction), the device loses efficiency. A solid-state converter which has no gap between the hot and cold side is like a dam with holes in it. Some of the water is used to turn the turbine. Some of it just goes through the holes.

To maximize this advantage, the device should be built so as to have a long, thin, thermal pathway. Heat, in order to reach the other side, will need to travel the longest path. Efficiency is increased.

Efficiency Calculation

Thermal Backflow Losses from Separation

$$= (\Delta T)\lambda\left(\frac{A}{l}\right)$$

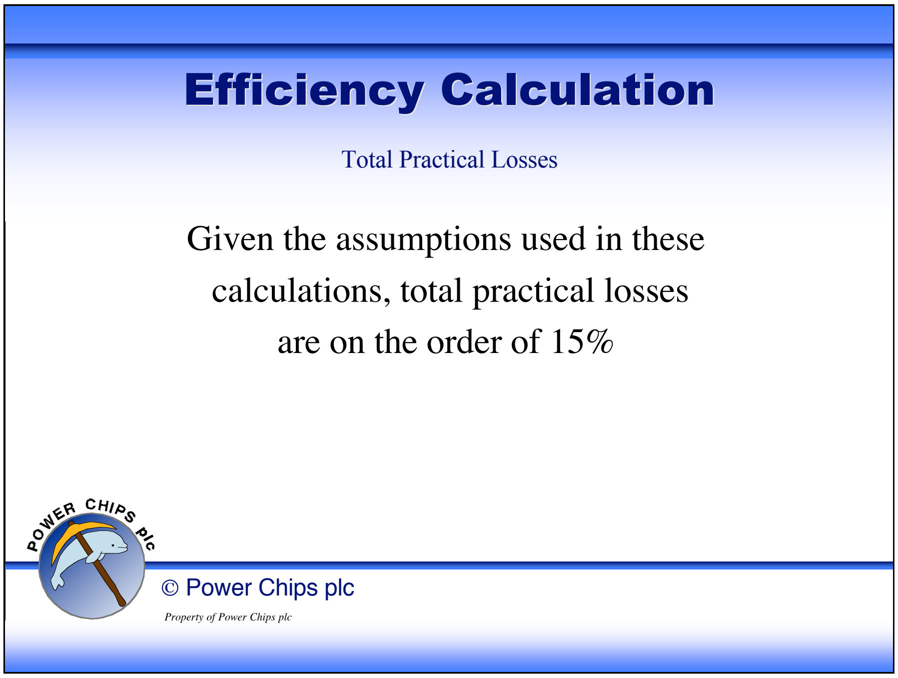
A=cross-sectional area
l = length

Geometry and materials will determine the precise separation loss. These will be selected based on device temperature range, efficiency, cost, and other requirements.

Effect on Carnot Efficiency
Production devices will vary
Prototype has a separation loss of <1.2 x 10^{-3} watts per degree Kelvin ΔT, or <1%

This loss term can be adjusted, depending on device geometry, to have high losses, or low losses. The test machine in use has a long quartz tube as the thermal backpath, and the losses are very small -- less than 1% of Carnot.

It is expected that production devices will have higher separation losses than 1%, depending on manufacturing cost tradeoffs.



In conclusion, assuming a 3 watt/cm^2 heat flux, the practical losses are on the order of 15% of the theoretical maximum. These are very acceptable losses, and compare quite favourably with other technologies.

As the power density increases, the practical losses will decrease, since most of these losses occur as a result of the ΔT across the diode.

On the other hand, as the ΔT increases (for high performance applications), the practical losses will increase.

Efficiency Calculation

Overall Efficiency

Combining Intrinsic and Practical loss terms, approximate efficiencies are

65-75% of maximum possible COP

Fabrication Cost

Power Chips™ are chip-based technologies, with precise, but simple construction.

- Non-exotic materials with moderate contamination tolerance
- No costly materials involved in processes
- Very small devices require small amounts of material

Marginal cost of Power Chips™, in production, will be as low as pennies per watt capacity

In addition to high efficiency, Power Chips™ are expected to be very inexpensive to make.

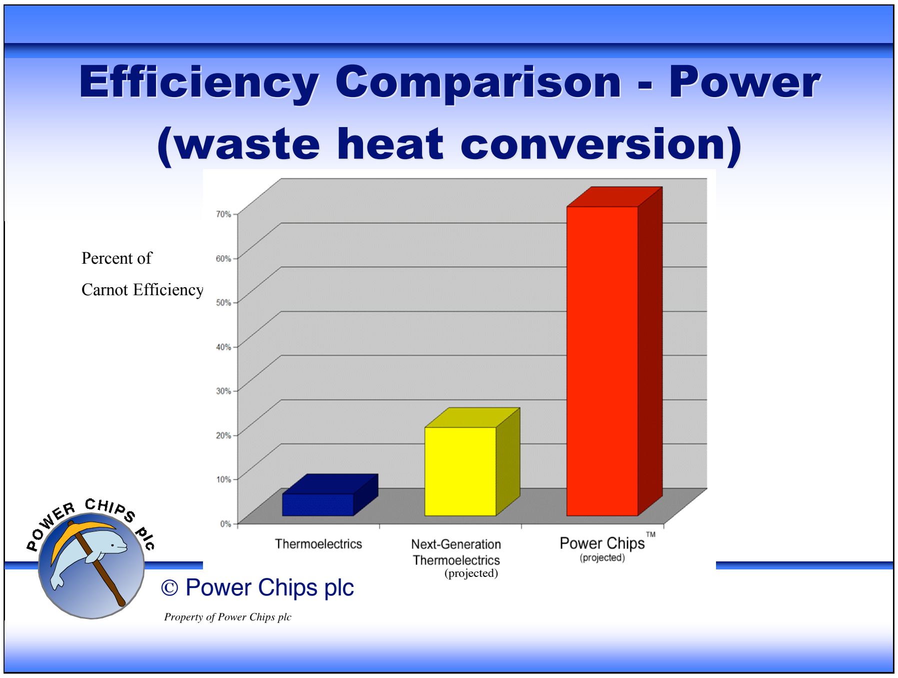
A number of factors come into play when estimating the cost of a product like a turbine or a compressor. The marginal costs (the cost of making one more unit on an already-present assembly line), are heavily dependent on the following factors:

1: Materials quantity. No device can cost less than its parts. And big, heavy machines like turbines and compressors have a lot of steel, copper and iron in them. This is an unavoidable cost. Power Chips™ use very little in the way of raw materials -- at least an order of magnitude less than the competition. A single chip will be only a few millimetres thick.

2: Material quality. As machines improve, the specifications for their components become ever more demanding. If the components must be of very high materials purity, a significant cost is added. This cost, unlike, say economies of scale, is not reduced easily. The price of 99% pure iron, for example, is far less than 99.9999% pure iron. Power Chips™ can use relatively impure materials.

3: Machining/assembly costs. The more welding, bonding, sealing, etc. which is required, the higher the costs as well. Power Chips™ are extremely simple to manufacture -- much less complicated than an Intel 386 processor, for example.

4: Component costs. The more pieces that have to be put together, the more it will cost. Power Chips™ have a very small component count.

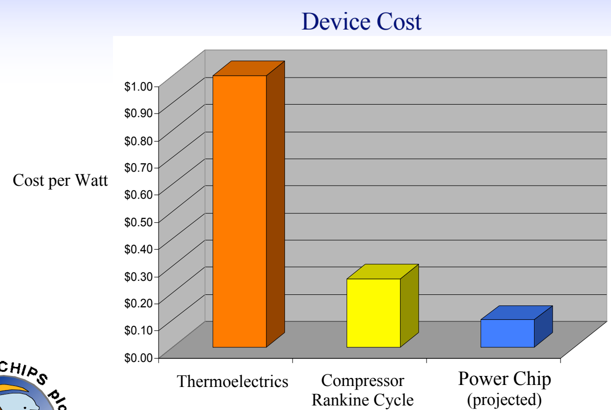


The result of these efficiency calculations show that Power Chips™ are highly competitive with other technologies.

Thermoelectrics are 5-8% efficient. If recent breakthroughs are confirmed, they may achieve 20-30% efficiency.

Primary power production (at higher temperatures) is also an excellent application for Power Chips. First products are expected to be at waste heat recovery temperatures, as the market demand is especially high.

Comparison - Cost



The Big Picture

Power Chips™ will be a high volume product which is:

… In high demand across industry
… Superior to all existing and projected technologies
… Proprietary, allowing a 20 year head start
… Environmentally Friendly