Cool Chips plc

Cool Chips™
Technical Overview

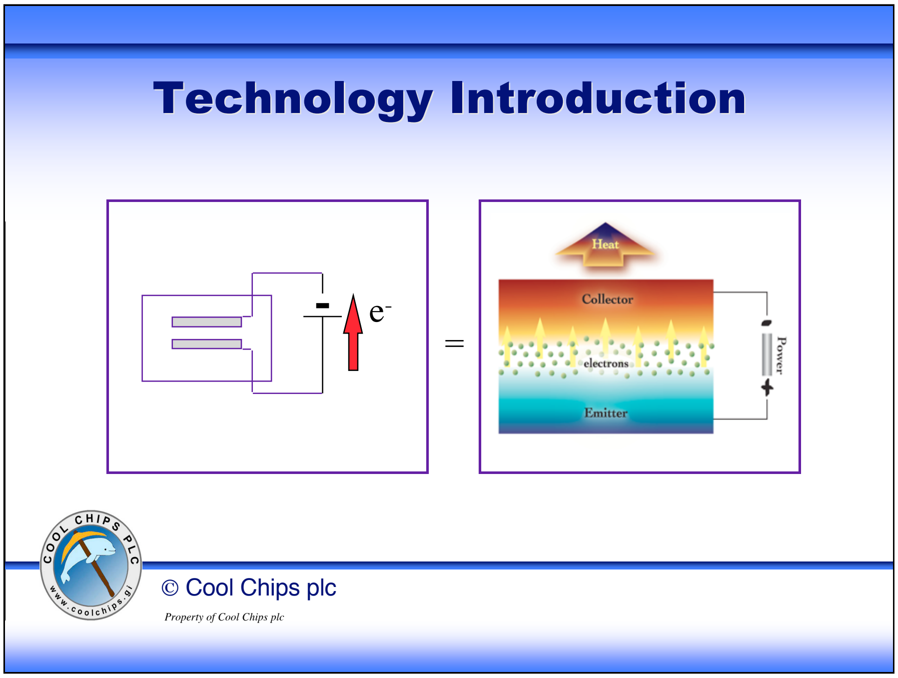
Cooling:

- Cool Chips are a unique approach to cooling, responding to a market need for cooling solutions
- Cool Chips are based on fundamentally superior science.
- Innate device advantages include:
  - High efficiency
  - Solid state design
  - Silent operation
  - Compact size for easy integration

There is no doubt that, across dozens of industries, better cooling solutions are urgently required. Compressors have been tweaked for decades, and now their improvements have flat-lined. There continue to be improvements in packaging, manufacturing, and other areas, but none of them address the core problem: the underlying technology itself is incapable of high efficiency output.

And other cooling technologies currently in use are far worse. Thermoelectrics, despite >$1 billion in research spent to date, have not cracked 8% efficiency in production (though they may achieve as high as 20-30% if recent reports are true). Still, the technology is far less efficient than compressors (40-50% efficient).

If any engineer were to make a wish list, it would be for a compact, solid-state, efficient solution which can handle very high heat fluxes and require no maintenance. Cool Chips™ is that solution.

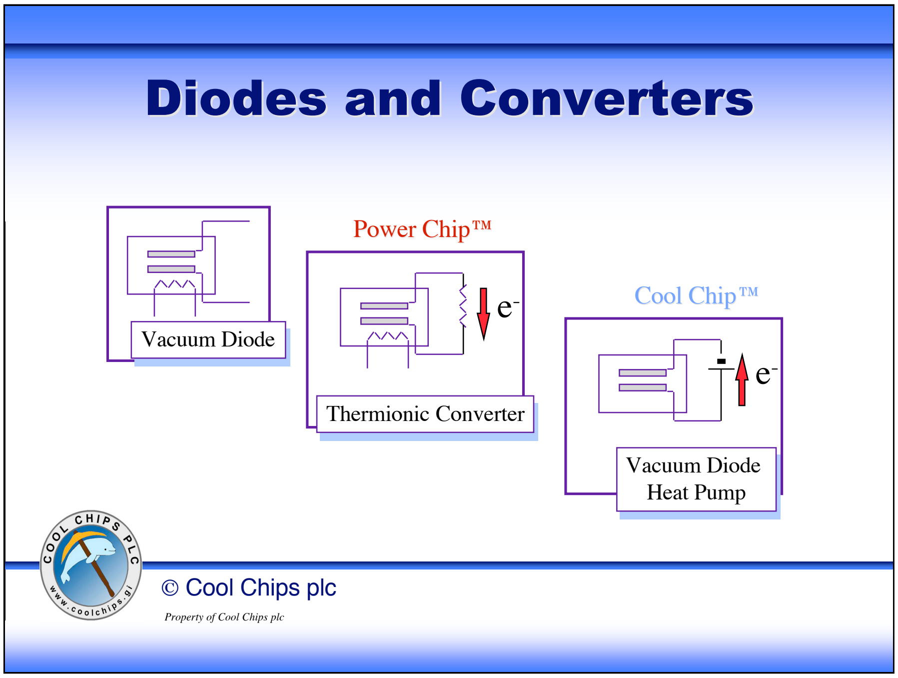


Cool Chips™ can be shown as a simple schematic using a classic diode.

Cool Chips™ are based off of a technology called a Thermionic Converter. Thermionics are an old technology; invented about 1900. Significant development occurred in the US during the 1950s and '60s, by companies like GE and General Atomics. The development effort was virtually abandoned by the mid-1970s. The reasons were simple: the devices did not work unless the two large plates were very close (microns) together, and in a time when semiconductor technology was still undeveloped, this meant hand-assembly. Complicating this was the second factor: in order to function, the thermionic converter required a cesium environment. Cesium is very difficult to work with in hand assembly. So while the technology was moderately efficient, it was not economic.

Borealis has solved both of these problems. We can mass-produce, using semiconductor-grade equipment which did not exist in the 1970s.

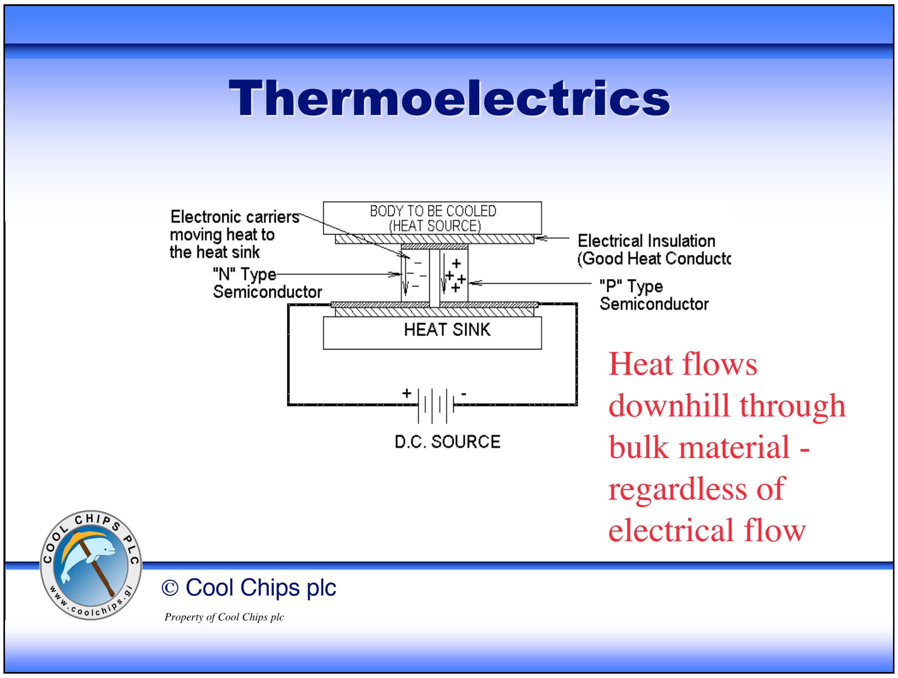
Cool Chips™ create a thermal difference (pump heat) from inputted power. Because of our solutions, we can operate at low temperatures, something which classic thermionic converters could never do. And so we have the Cool Chip™.



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 Thermionic Converter 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. The thermionic converter harnesses a thermal differential to create electrical output power.

The Cool Chip is the Power Chip in reverse. Instead of creating power from a thermal difference, the Cool Chip creates a thermal difference (cooling) from electrical power.

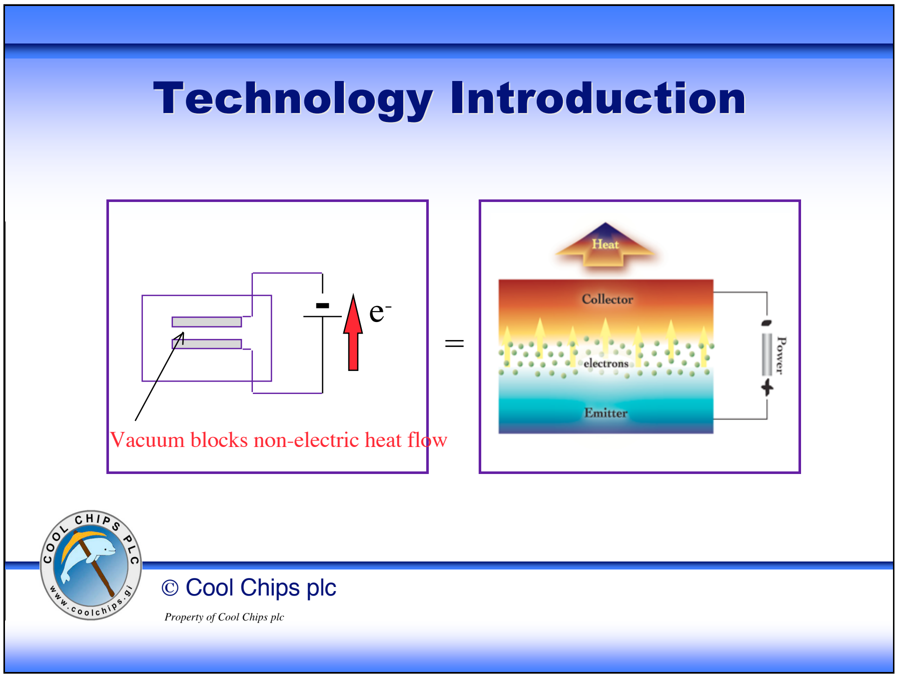


Thermoelectrics also has a long pedigree. Using a combination of the Seebeck, Thomson and Peltier effects, cooling occurs when electricity flows through materials and specific junctions. Classic thermoelectrics work, but with very low efficiency.

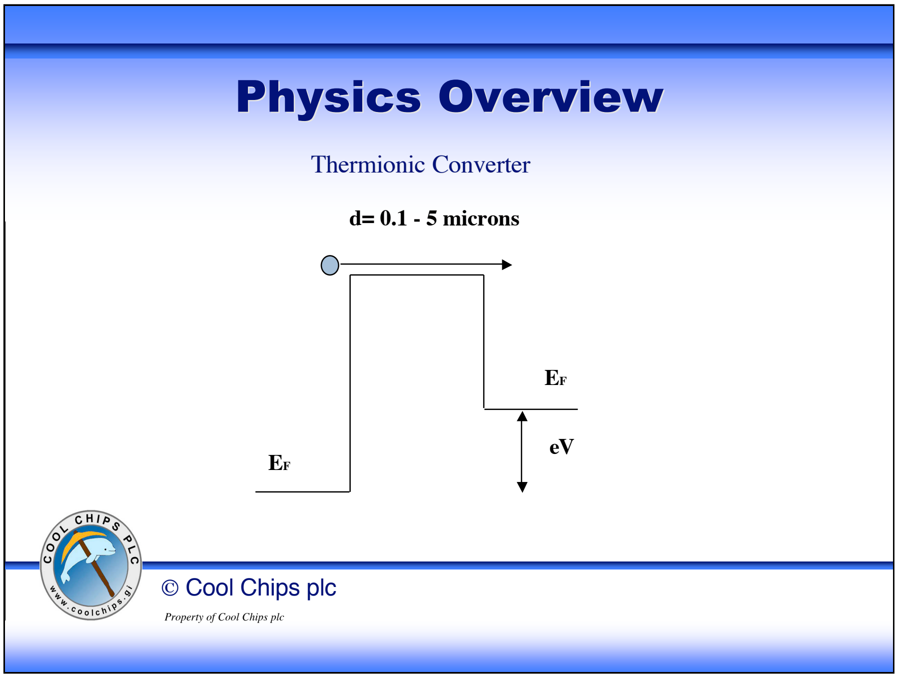
The reason is simple. Heat will flow through any material, and does not require electrons to do so. So as soon as one side becomes colder than the other, then natural conduction will seek to equilibrate the two sides. As a result, efficincies, expressed as a percentage of the Carnot-defined maximum, 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 dubbed “unobtanium”.



Cool Chips has “discovered” unobtanium -- the perfect thermoelectric material. It is, in fact, the absence of material at all. A vacuum is electrically conductive, yet thermally insulating.



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 (Cool Chips has built centimeter-scale chips which have 0.5 micron gaps). The manufacturing 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, 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. Cooling at these elevated temperatures is not generally useful.

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

Introducing Avto Metals

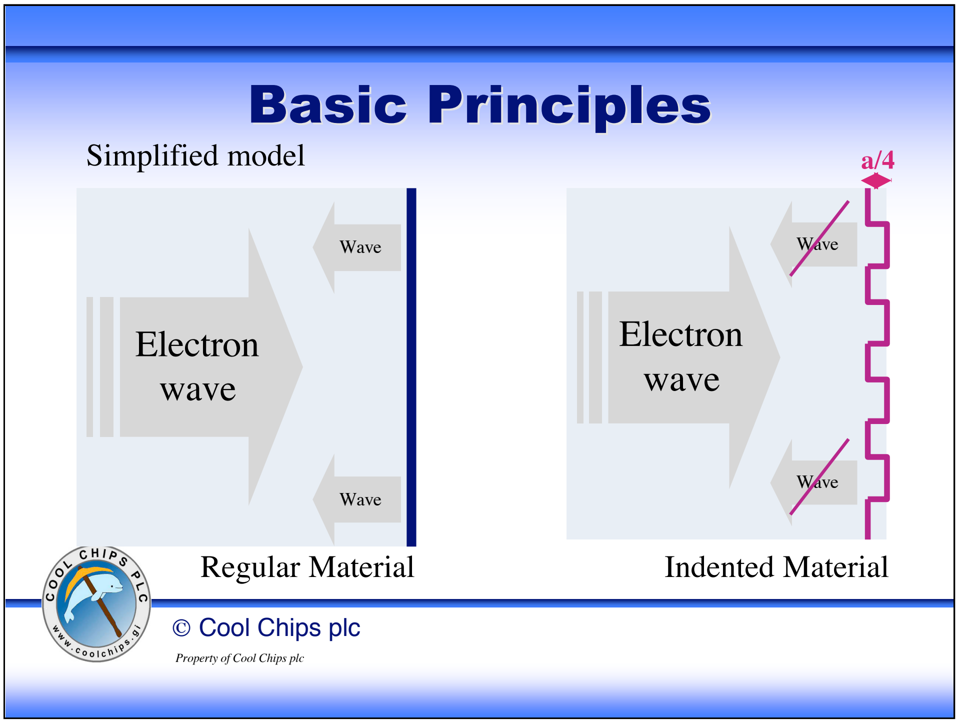
Nanostructures dimensions are approaching the wavelengths of the electrons in the solid.

Super lattices and resonant tunneling structures use these wave properties.

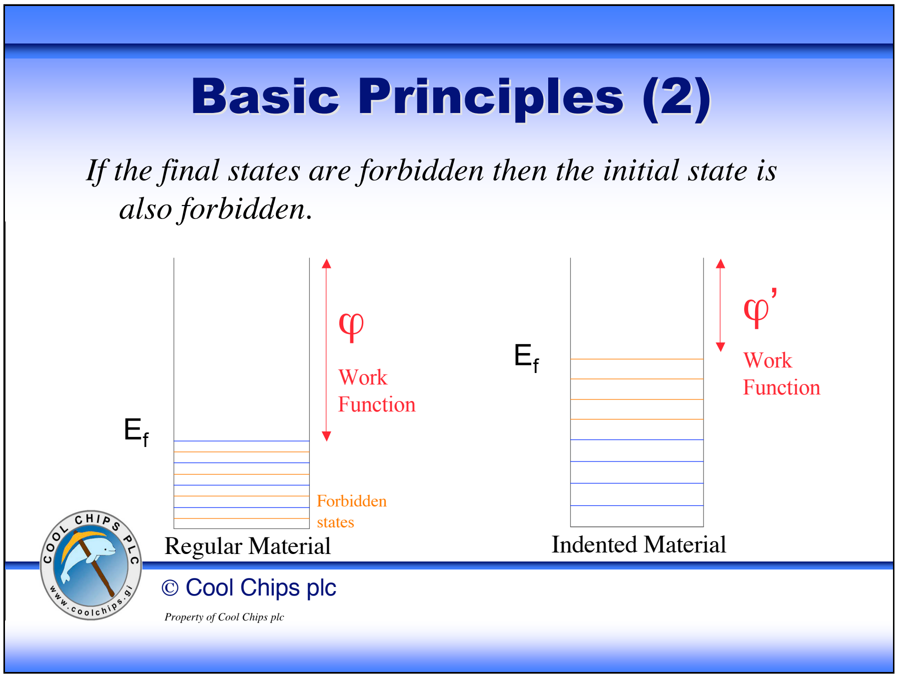
Smaller dimensions, enable new methods for reducing the electron volt work function of a surface.

The solution to a lower work function material which enables low temperature Cool 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.



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.

Limiting Factors

Limiting factors in practice

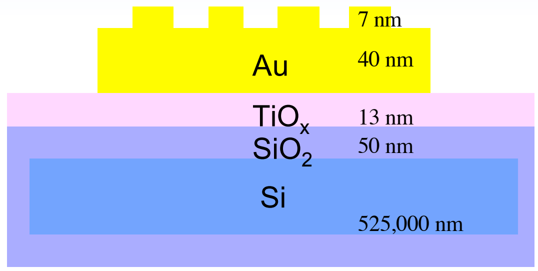
The surface roughness should be less than the electron’s de Broglie wavelength.

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

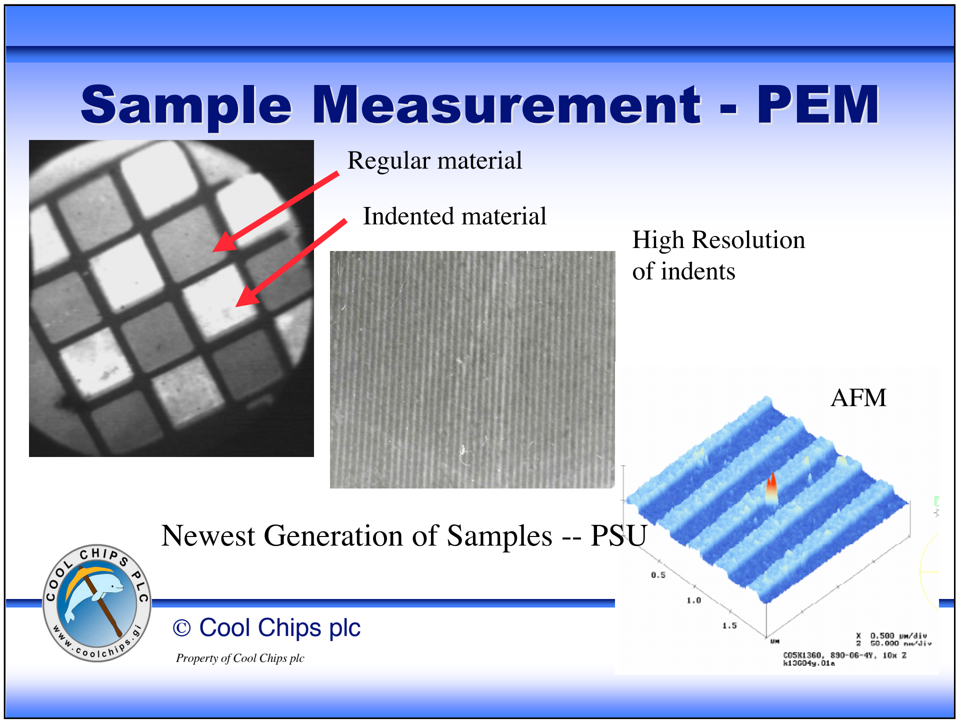
Different geometries for measurement PEM/KP.

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

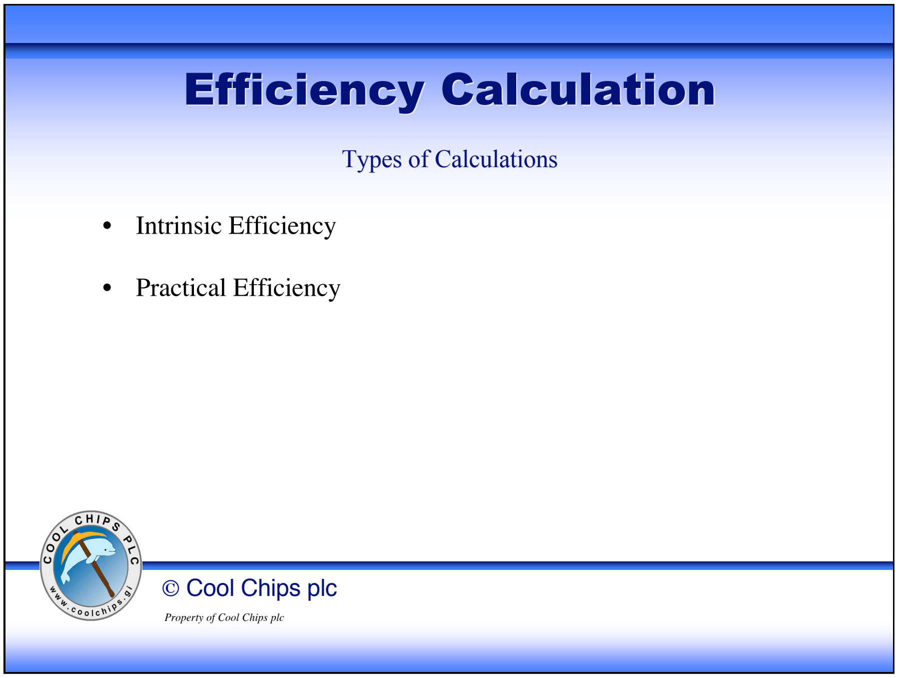


Current test samples use gold, since it does not form an oxide layer which would hide the resulting effect. Production devices will use other materials.



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 cooling mechanism

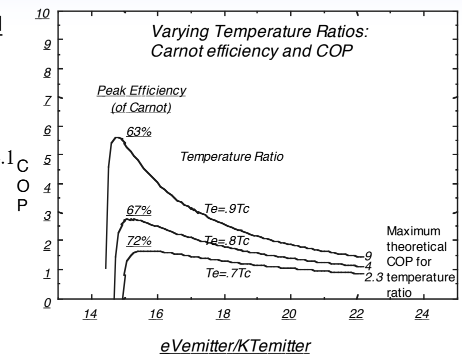
2: The practical efficiency, allowing for losses which occur in real-world devices. These figures are only rough estimates, but they allow for some general conclusions about the efficiency of the Cool Chips™ technology.

These will be taken in turn.

Intrinsic Efficiency Limits

$$COP = \frac{[\theta^3(\alpha+2) - \exp(\alpha-\beta)[\alpha\theta+2]]}{[(\beta-\alpha\theta)[\theta^2\exp(\alpha-\beta)]]}$$

if eVcollector/KTcollector = 14.1



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 Cool 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. The above graph can be well understood by referring to 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 Cool 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
Radiation losses are negligible (<1%)

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. For Cool Chips parameters, the loss is on the order of 1% of Carnot.

Radiation is not a significant loss term.

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

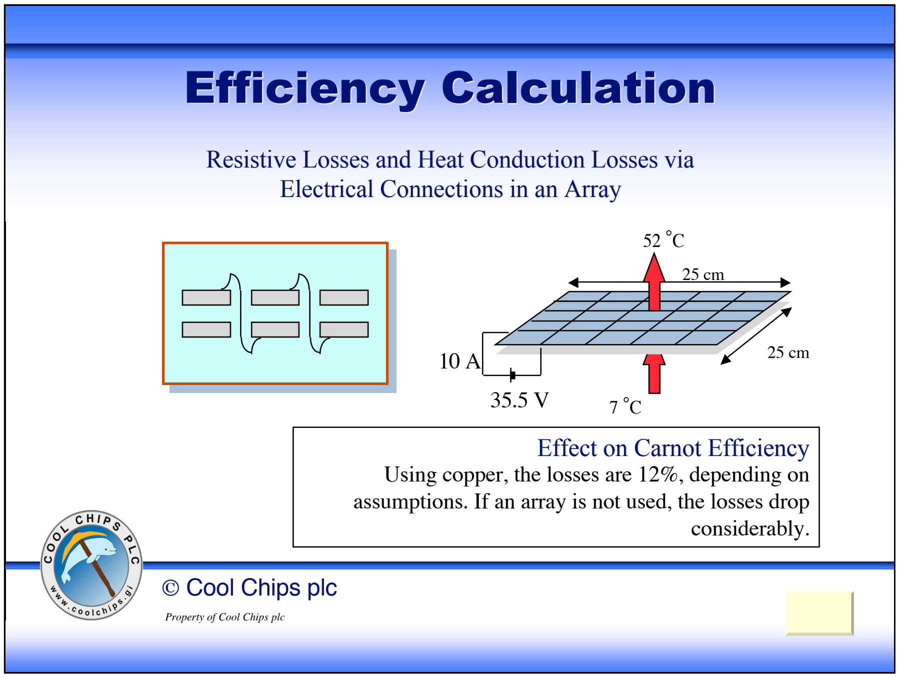
$ß = 125\ W\ m^{-2}\ mbar^{-1}\ K^{-1}$

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

$p = 1$ mbar

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

What this slide means is that Cool 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.



Cool Chips™ will operate in an array. Because each device uses 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.

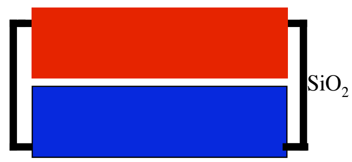
Using copper, the losses are on the order of 12% of Carnot. This makes the thermal connectors the largest single loss term.

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

Efficiency Calculation

Thermal Backflow Losses from Separation

- These losses are geometry dependent
- To minimize separation losses, edge supports can be used, with no internal spacers. Thermal back-path is thereby minimized



When heat flows from the hot side to the cold side, and it does so through active (hot) electrons, the device is efficient. Cool 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 $<1.2 \times 10^{-3}$ 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 used by Borealis 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, but keeping these losses within reasonable bounds is straightforward.

Efficiency Calculation

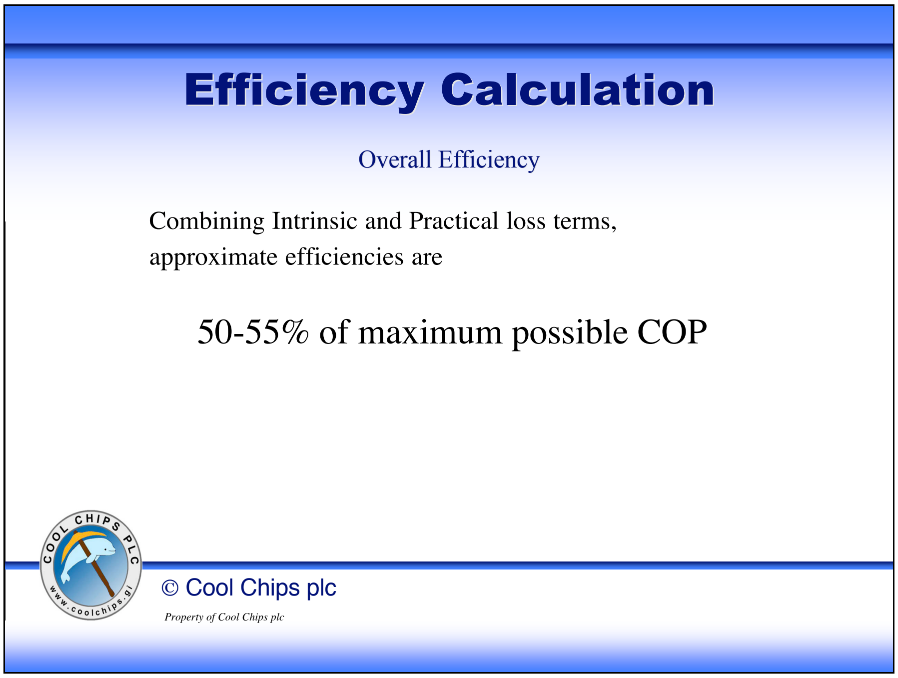
Total Practical Losses

Given the assumptions used in these calculations, total practical losses are on the order of 15%

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 cooling 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.



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

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

Compressors are 40-50% efficient. This is a mature technology, with only incremental improvements in its future.

Cool Chips™ will clearly be far more efficient than the competition.

Fabrication Cost

Cool 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 Cool Chips™, in production, will be as low as pennies per watt capacity

In addition to high efficiency, Cool 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. Cool 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. Cool 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. Cool 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. Cool Chips™ have a very small component count.

The Big Picture

Cool Chips™ will be a high margin, high volume product which is:

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