# THERMOELECTRIC REFRIGERATION

# Thermoelectric Refrigeration: An Introduction

- Thermoelectric cooling uses the Peltier effect to create a heat flux between the junctions of two different types of materials.
- This effect is commonly used in camping and portable coolers and for cooling electronic components and small instruments.
- Applying a DC voltage difference across the thermoelectric module, an electric current will pass through the module and heat will be absorbed from one side and released at the opposite side. One module face, therefore, will be cooled while the opposite face simultaneously is heated.
- On the other hand, maintaining a temperature difference between the two junctions of the module, a voltage difference will be generated across the module and an electrical power is delivered.

# BASIC PRINCIPLES OF THERMOELECTRIC MODULES

Thermoelectricity is based upon following basic principles:

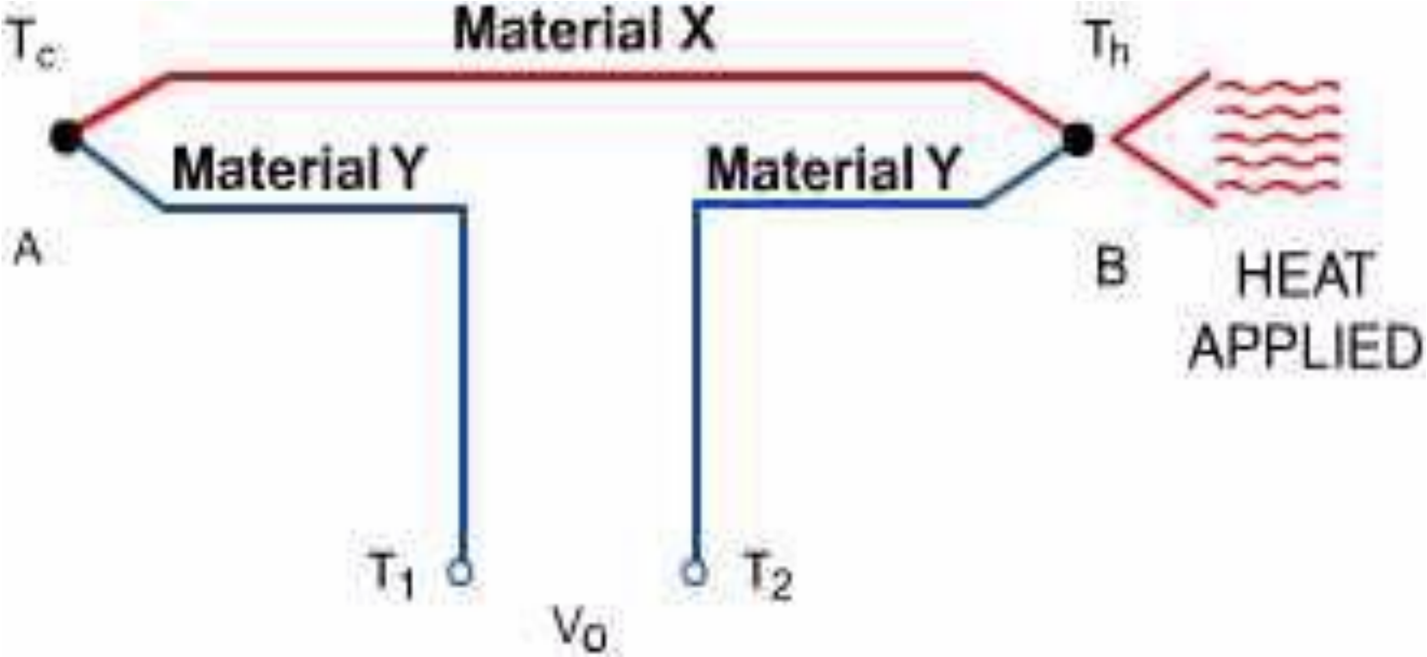
1. SEEBECK EFFECT
2. PELTIER EFFECT
3. THOMSON EFFECT
4. JOULE EFFECT
5. FOURIER EFFECT

# SeeBeck Effect:

- In 1821, Thomas Seebeck found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals, if the junctions of the metals were maintained at two different temperatures.
- Thermoelectric power supply generators are based on the Seebeck effect which is based on voltage generation along a conductor subjected to a gradient of temperature.
- When a temperature gradient is applied to a conductor, an electromotive force is produced. The voltage difference generated is proportional to the temperature difference across the thermoelectric module between the two junctions, the hot and the cold one.

$$\Delta V \alpha \Delta T$$

# SeeBeck Effect:



# SeeBeck Coefficient:

- The Seebeck coefficient is defined as the ratio of the voltage difference to the temperature gradient. If the temperature difference $\Delta T$ between the two ends of a material is small, then the Seebeck coefficient of a material is defined as:

$$\alpha_{ab} = \Delta V / \Delta T$$

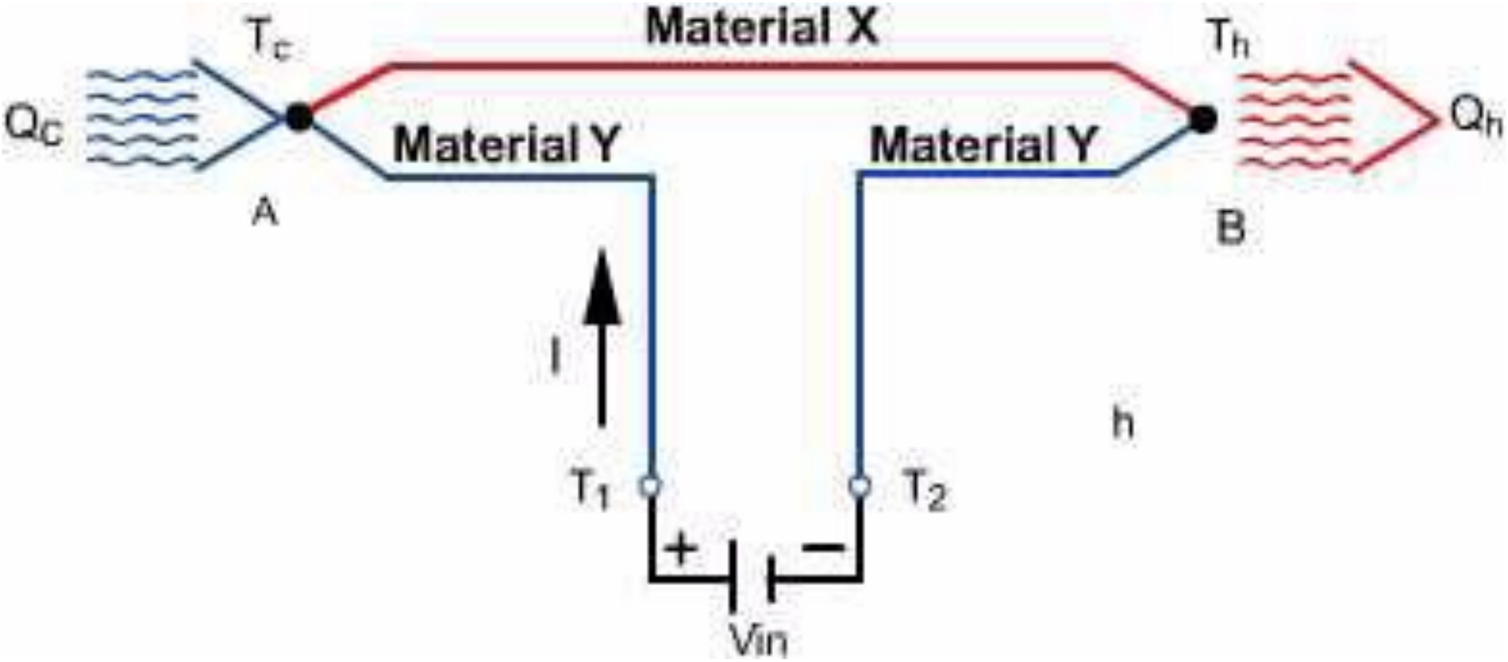
$$\alpha_{ab} = \alpha_a - \alpha_b$$

$\alpha_a$ & $\alpha_b$ is the Seebeck Coefficient with units of Volts per Kelvin for metals A & B or P & N

## Peltier Effect:

- In 1834, a French watchmaker and part time physicist, Jean Peltier found that an electrical current would produce a temperature gradient at the junction of two dissimilar metals.
- The Peltier effect is the main contributor to all thermoelectric cooling applications. It is responsible for heat removal and heat absorbance.
- It states that when an electric current flows across two dissimilar conductors, the junction of the conductors will either absorb or emit heat depending on the flow of the electric current.
- The heat absorbed or released at the junction is proportional to the input electric current. The constant of proportionality is called the Peltier coefficient.

# Peltier Effect:



## Peltier Coefficient:

When a current is made to flow through a junction between two conductors A and B, heat may be generated (or removed) at the junction. The Peltier heat generated at the junction per unit time, Q , is equal to;

$$Q \alpha I$$

$$Q = \pi_{ab} I$$

$$\pi_{ab} = \pi_a - \pi_b$$

where ($\pi_a$ & $\pi_b$) is the Peltier coefficient of conductor A & B, and I is the electric current (from A to B).

## Thompson Effect:

- The Thompson effect governs the cooling and the heating of a material carrying a current and subjected to a temperature gradient.
- It states when an electric current is passed through a conductor having a temperature gradient over its length, heat will be either absorbed by or expelled from the conductor.

$$\frac{dQ}{dx} = \tau I \left[ \frac{dT}{dx} \right]$$

- Whether heat is absorbed or expelled depends upon the direction of both the electric current and temperature gradient.

## Joule Effect:

When electrical Current I flows through a conductor of resistance R, there is dissipation of electrical energy. This is well known joule effect. The energy dissipated is given by;

$$Q_J = I^2R$$

## Fourier Effect:

If the ends of any element are maintained at different temperatures, the heat transfer from the hot end to the cold end is related by;

$$Q_{cond} = U(T_h - T_c)$$

$$U = \frac{kA}{L}$$

The cooling and heating effects due to thermoelectric effect are given by;

$$Q_c = \alpha_{ab} I T_c$$

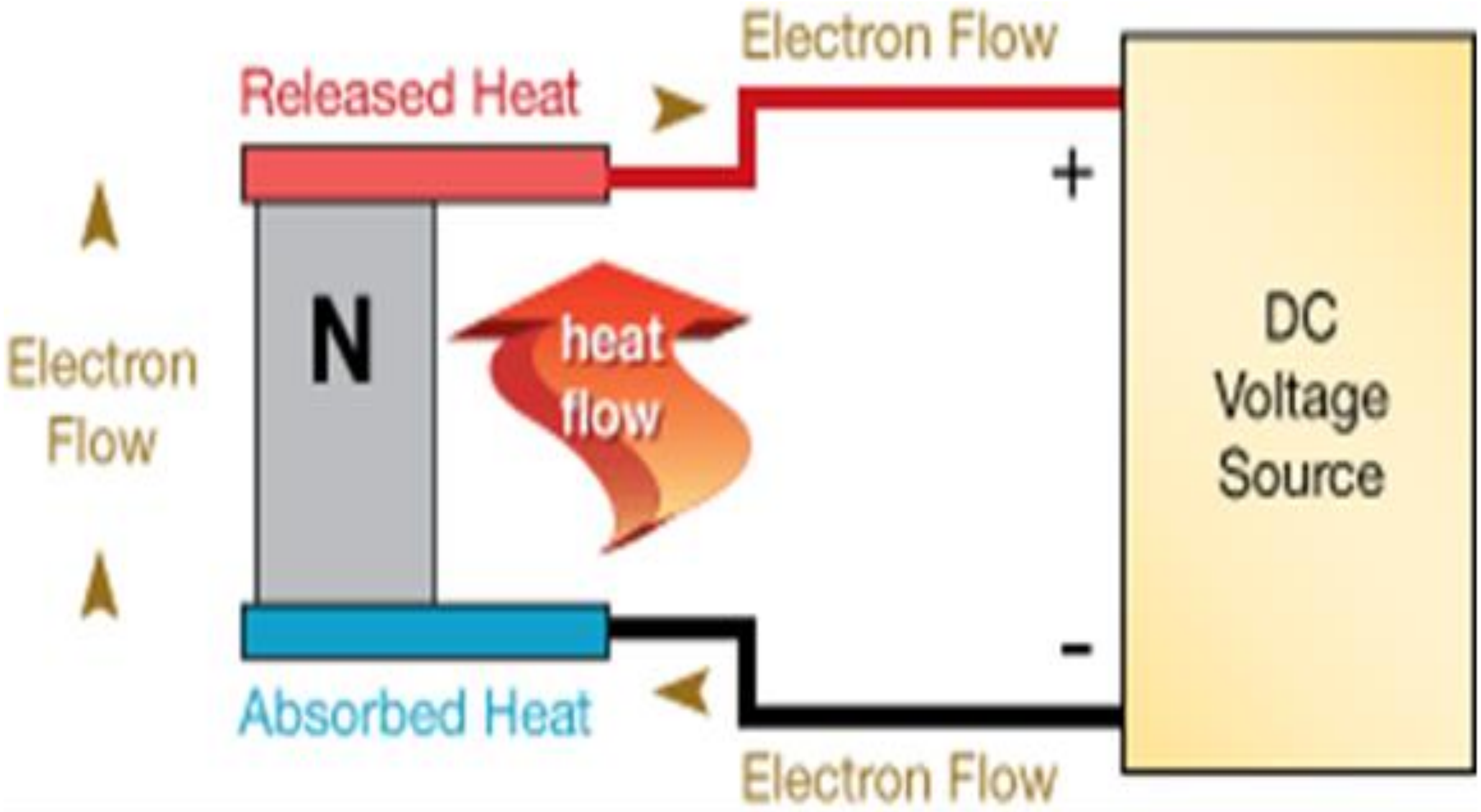
$$Q_h = \alpha_{ab} I T_h$$

# BASIC MECHANISM OF THERMOELECTRICS

# Basic Principles:

- A typical thermoelectric cooling component is shown on the next slide. Bismuth telluride (a semiconductor), is sandwiched between two conductors, usually copper.
- A semiconductor (called a pellet) is used because they can be optimized for pumping heat and because the type of charge carriers within them can be chosen.
- The semiconductor in this examples N type (doped with electrons) therefore, the electrons move towards the positive end of the battery.
- The semiconductor is soldered to two conductive materials, like copper. When the voltage is applied heat is transported in the direction of current flow.

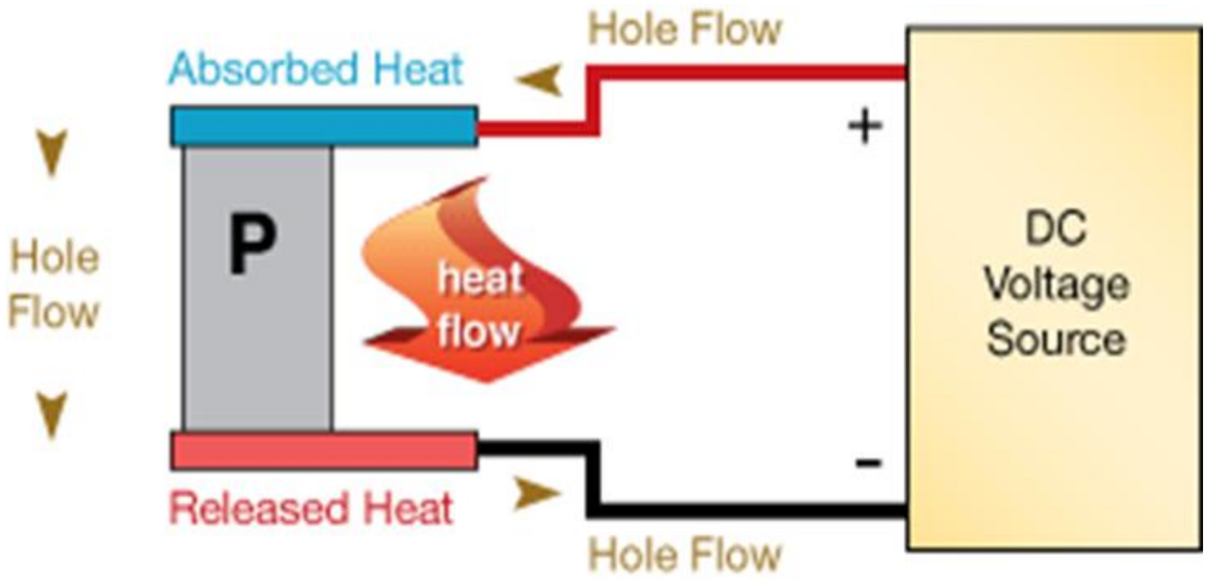
# N-TYPE SINGLE SEMICONDUCTOR PELLET



# Basic Principles:

When a p type semiconductor (doped with holes) is used instead, the holes move in a direction opposite the current flow. The heat is also transported in a direction opposite the current flow and in the direction of the holes. Essentially, the charge carriers dictate the direction of heat flow.

P-TYPE SINGLE SEMICONDUCTOR PELLET

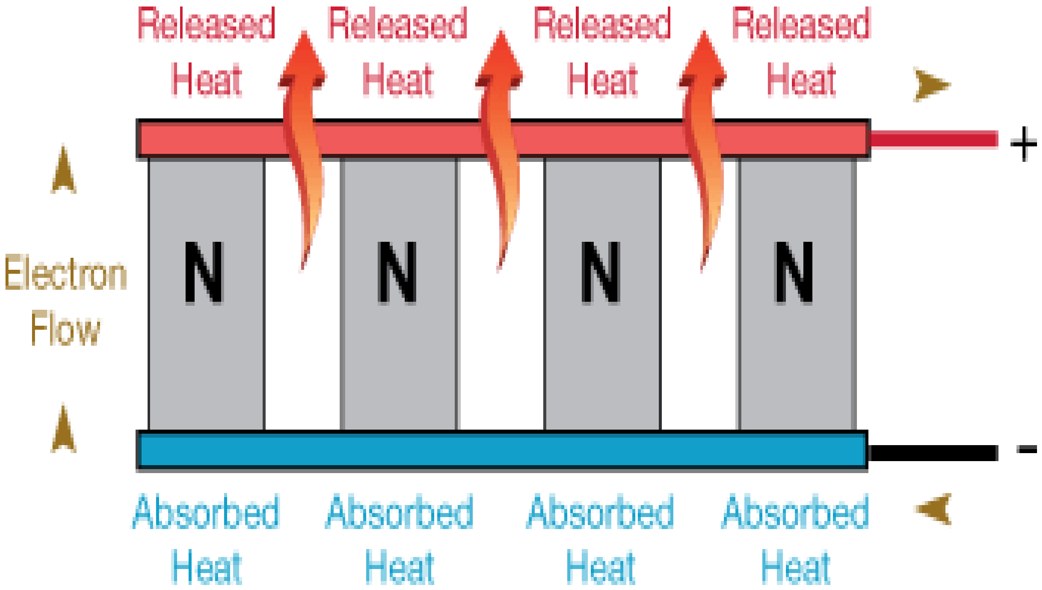


# Method of Heat Transport:

- Electrons can travel freely in the copper conductors but not so freely in the semiconductor.
- As the electrons leave the copper and enter the hot-side of the p-type, they must fill a "hole" in order to move through the p-type. When the electrons fill a hole, they drop down to a lower energy level and release heat in the process.
- Then, as the electrons move from the p-type into the copper conductor on the cold side, the electrons are bumped back to a higher energy level and absorb heat in the process.
- Next, the electrons move freely through the copper until they reach the cold side of the n-type semiconductor. When the electrons move into the n-type, they must bump up an energy level in order to move through the semiconductor. Heat is absorbed when this occurs.
- Finally, when the electrons leave the hot-side of the n-type, they can move freely in the copper. They drop down to a lower energy level and release heat in the process.

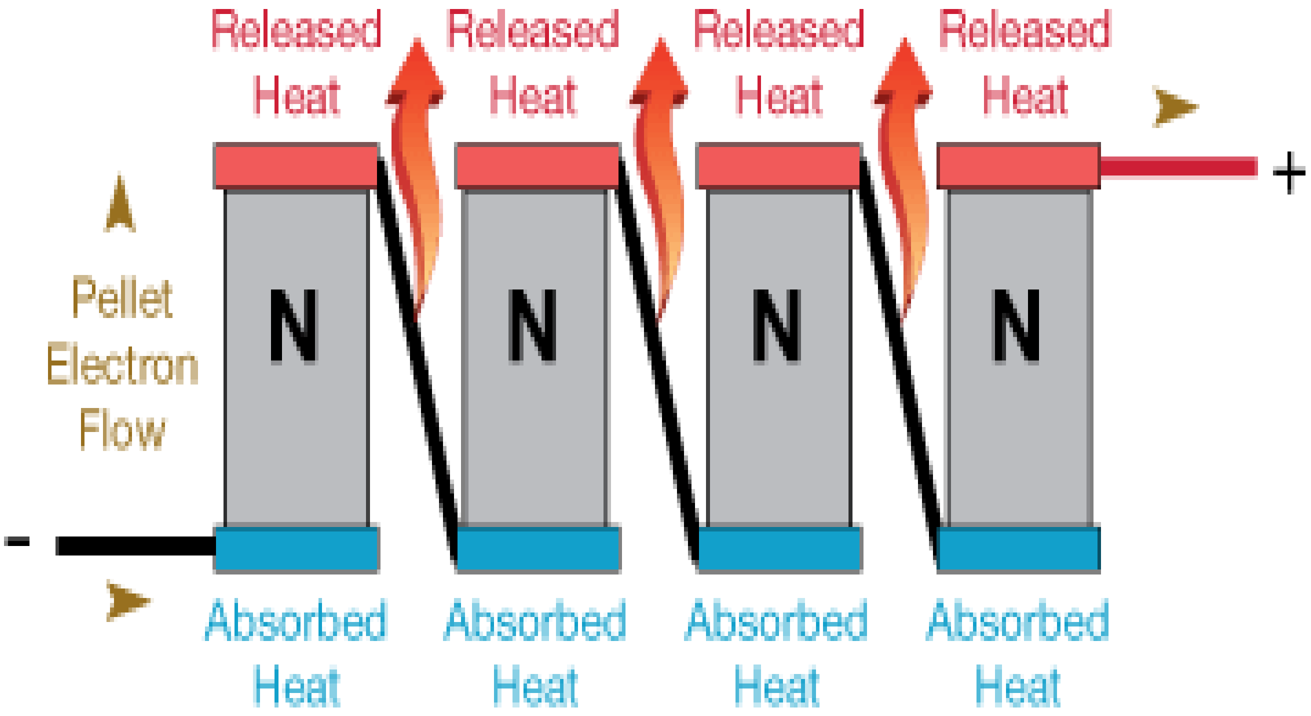
# ELECTRICALLY AND THERMALLY PARALLEL MULTIPLE PELLETS

- To increase heat transport, several p type or n type thermoelectric(TE) components can be hooked up in parallel.
- However, the device requires low voltage and therefore, a large current which is too great to be commercially practical.

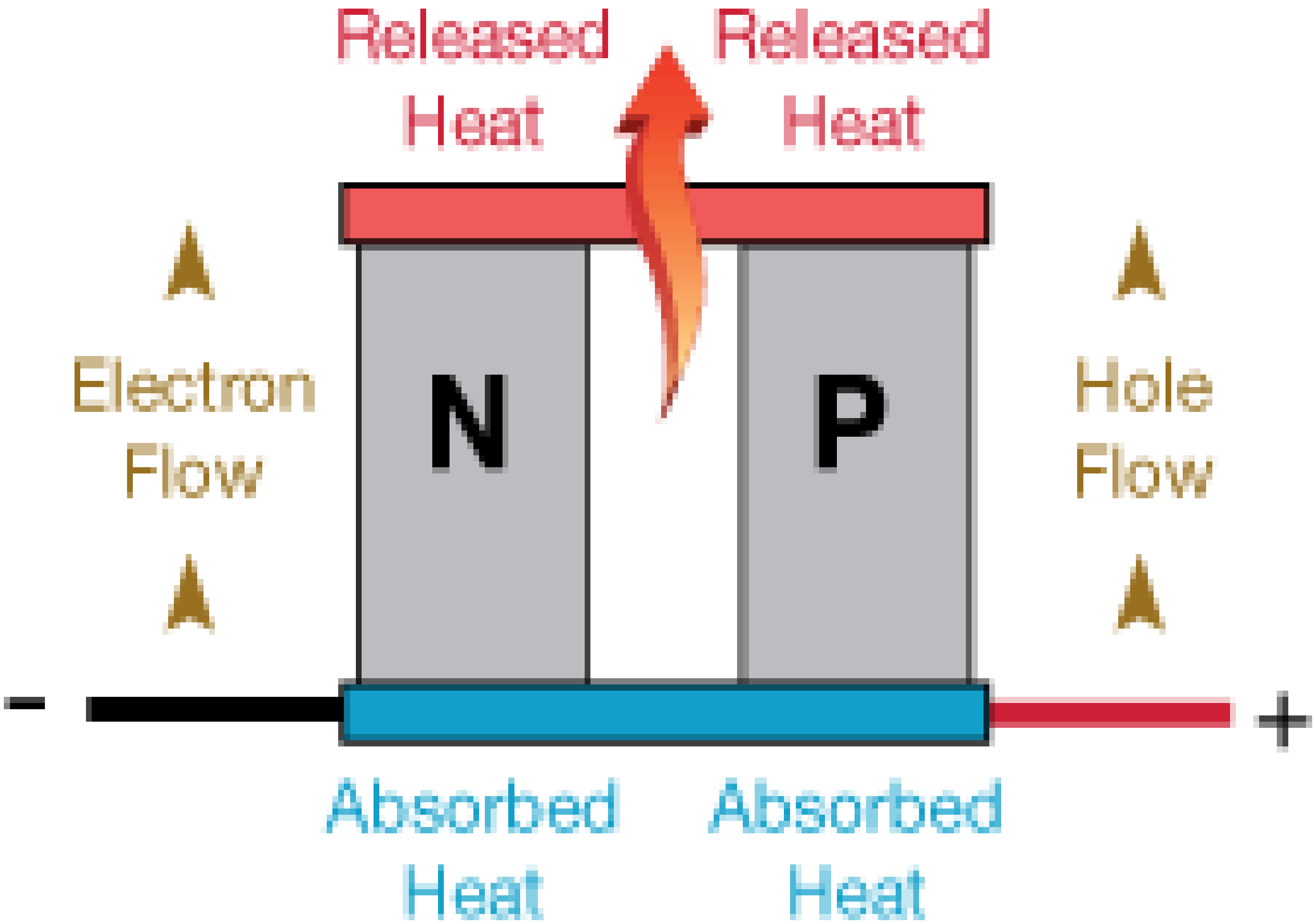


# THERMALLY PARALLEL AND ELECTRICALLT IN SERIES MULTIPLE PELLETS

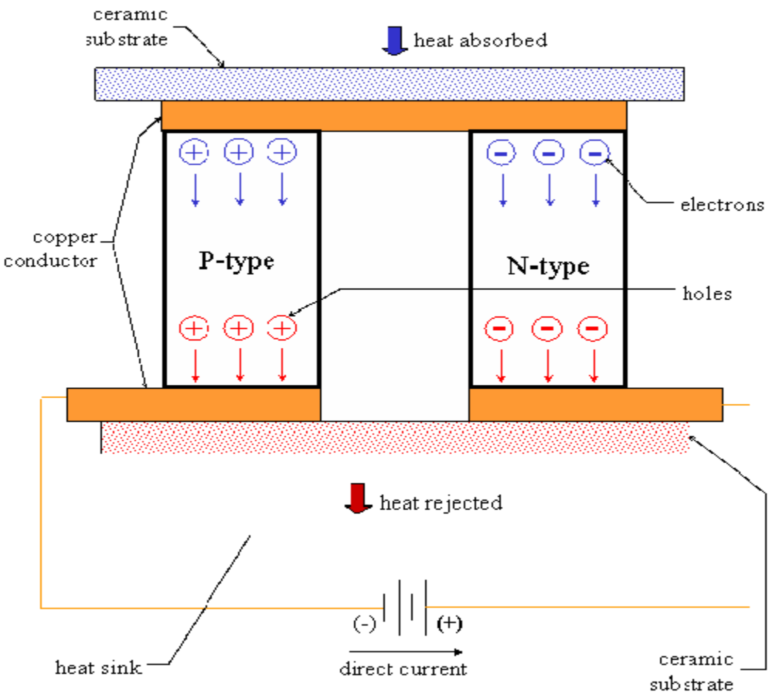
- The TE components can be put in series but the heat transport abilities are diminished because the interconnectings between the semiconductor creates thermal shorting.



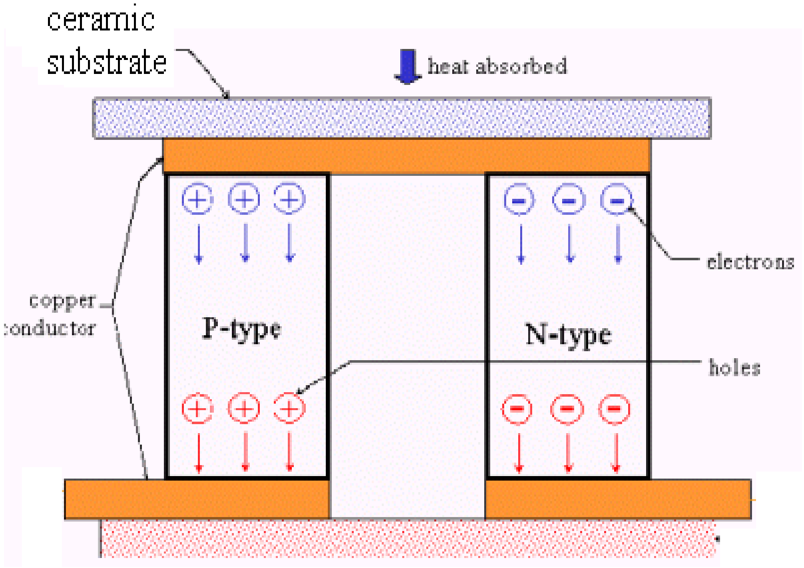
# N AND P-TYPE PELLETS



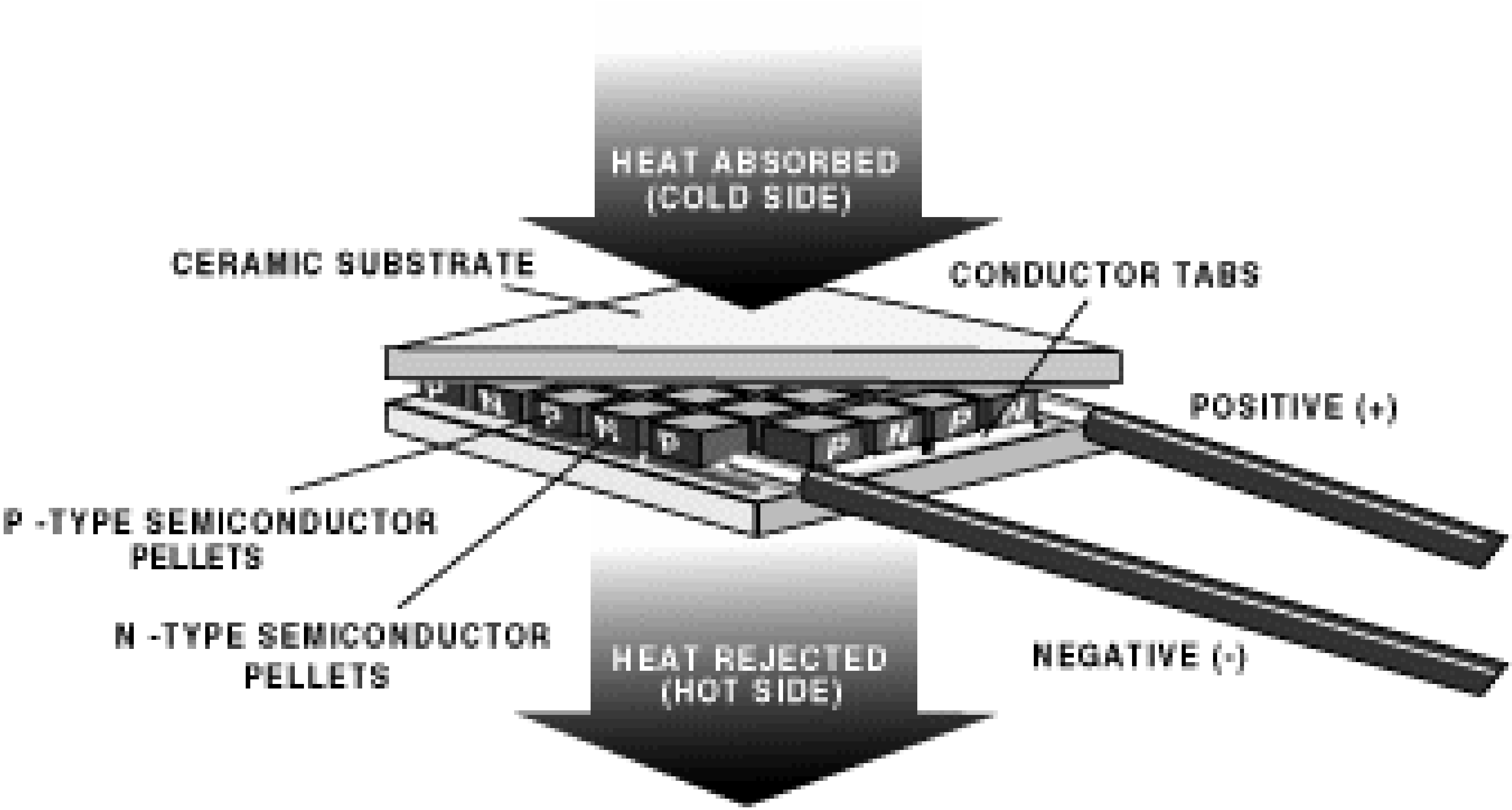
- The most efficient configuration is where a p and n TE component is put electrically in series but thermally in parallel . The device to the right is called a couple.
- One side is attached to a heat source and the other a heat sink that convects the heat away.
- The side facing the heat source is considered the cold side and the side facing the heat sink the hot side.



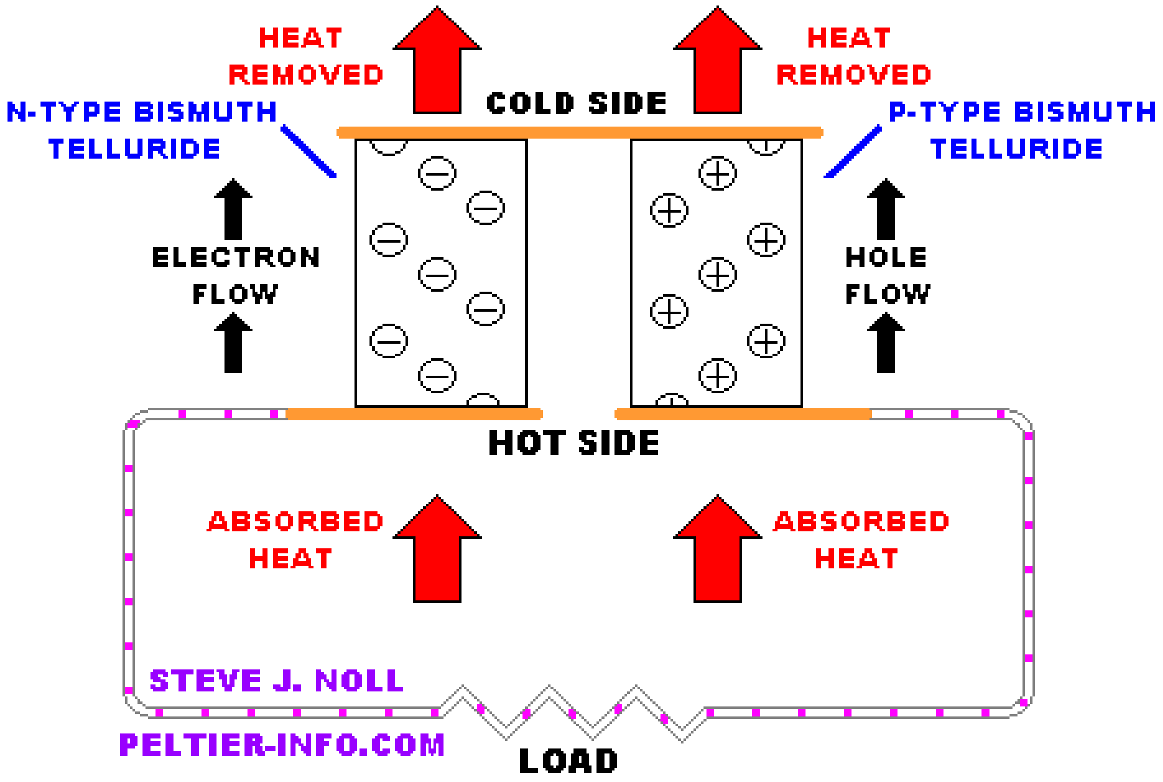
- Between the heat generating device and the conductor must be an electrical insulator to prevent an electrical short circuit between the module and the heat source.
- The electrical insulator must also have a high thermal conductivity so that the temperature gradient between the source and the conductor is small.
- Ceramics like alumina are generally used for this purpose.



# An entire assembly



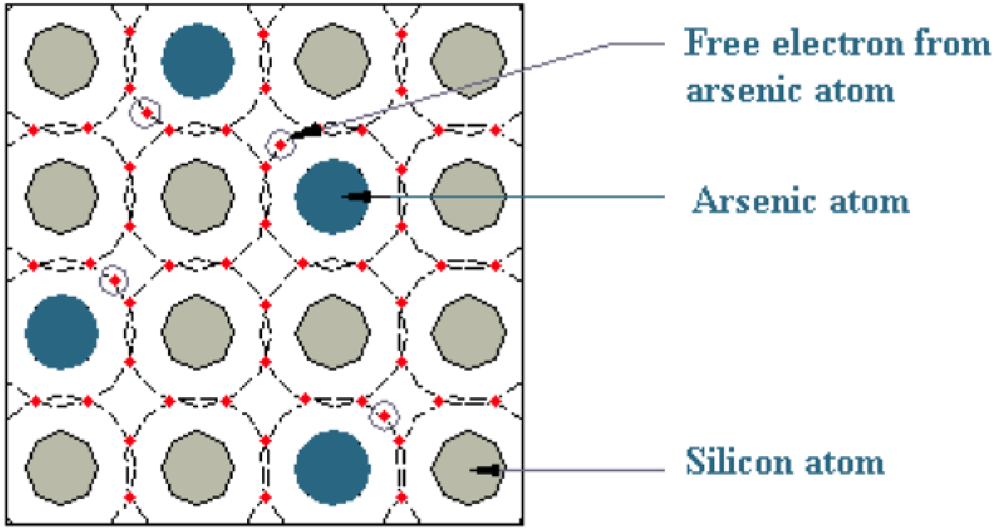
ONE SEEBECK DEVICE "COUPLE" CONSISTS OF ONE N-TYPE AND ONE P-TYPE SEMICONDUCTOR PELLET



THERE MUST BE A TEMPERATURE DIFFERENCE BETWEEN THE HOT AND COLD SIDES FOR POWER TO BE GENERATED

# Semiconductor Doping: N Type

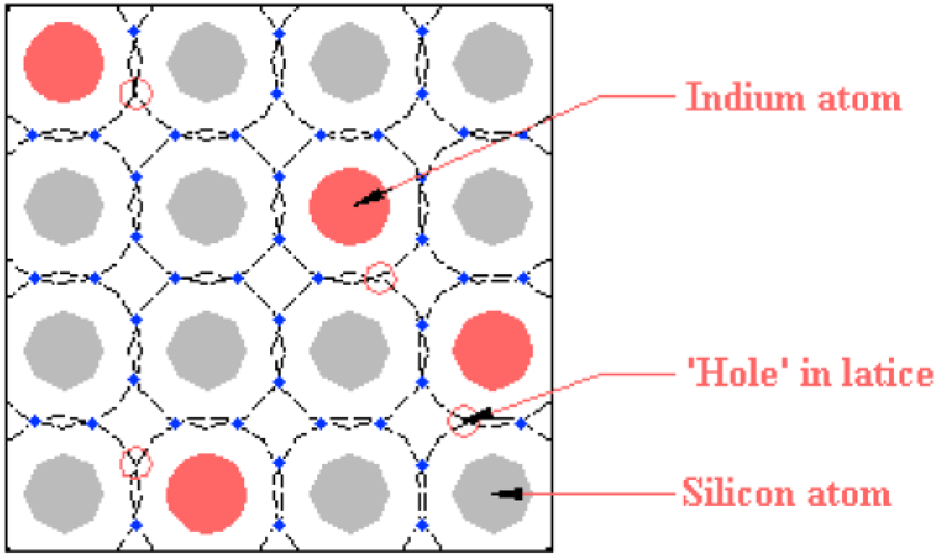
N doped semiconductors have an abundant number of extra electrons to use as charge carriers. Normally, a group IV material (like Si) with 4 covalent bonds (4 valence electrons) is bonded with 4 other Si. To produce an N type semiconductor, Si material is doped with a Group V metal (P or As) having 5 valence electrons, so that an additional electron on the Group V metal is free to move and are the charge carriers



Arsenic dopant adds free electrons to the crystalline lattice, making it more electrically conductive, creating 'N' material.

# Semiconductor Doping: P Type

For P type semiconductors, the dopants are Group III (In, B) which have 3 valence electrons, these materials need an extra electron for bonding which creates “holes”. P doped semiconductors are positive charge carriers. There’s an appearance that a hole is moving when there is a current applied because an electron moves to fill a hole, creating a new hole where the electron was originally. Holes and electrons move in opposite directions.



## Figure of Merit:

The figure of merit represents the quality of performance of a thermoelectric material, sometimes it is multiplied by temperature. It is defined as:

$$Z = \frac{\alpha}{\rho k}$$

Where ρ is the electrical resistivity, k is the thermal conductivity, and α is the Seebeck Coefficient.

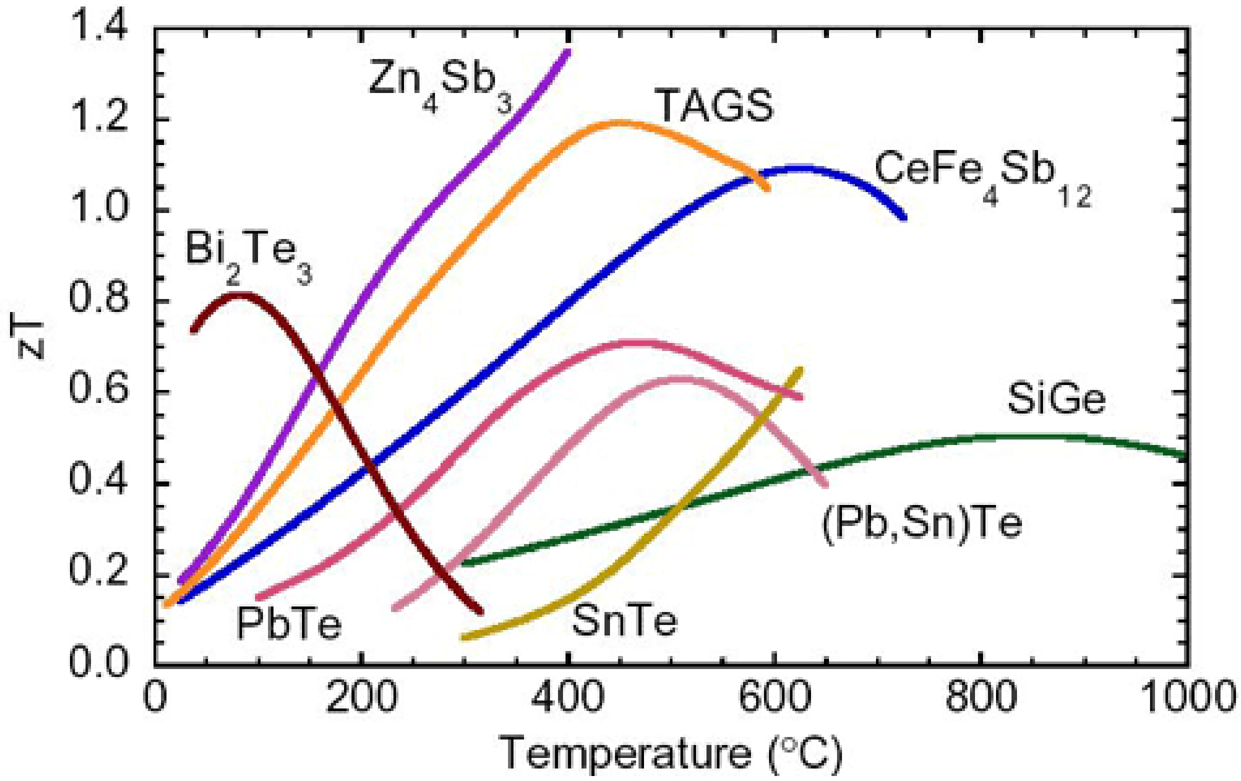
Note: low electrical resistivity and thermal conductivity are required for high figure of merit. These values are temperature dependent therefore, the figure of merit is temperature dependent. P and N type material have different figures of merit and are averaged to determine a materials overall quality.

# Thermoelectric Materials

- Semiconductors are the optimum choice of material to sandwich between two metal conductors because of the ability to control the semiconductors' charge carriers, as well as, increase the heat pumping ability.
- The most commonly used semiconductor for electronics cooling applications is $Bi_2Te_3$ because of its relatively high figure of merit. However, the performance of this material is still relatively low and alternate materials are being investigated with possibly better performance. Alternative materials include:
  - Alternating thin film layers of $Sb_2Te_3$ and $Bi_2Te_3$.
  - Lead telluride and its alloys
  - SiGe
  - Materials based on nanotechnology

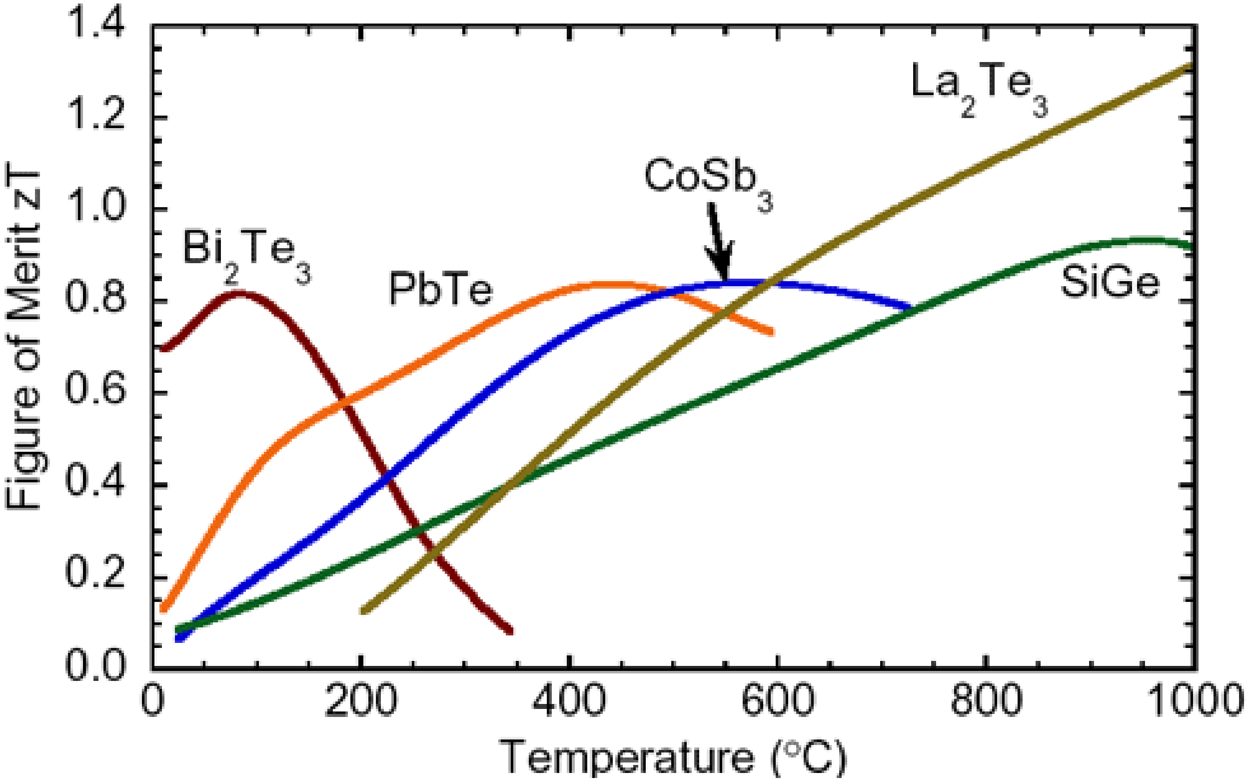
# Thermoelectric Materials

- A plot of various p-type semiconductor figures of merit times temperature vs. temperature are shown. Within the temperature ranges concerned in electronics cooling (0-200°C) $Bi_2Te_3$ performs the best.



# Thermoelectric Materials

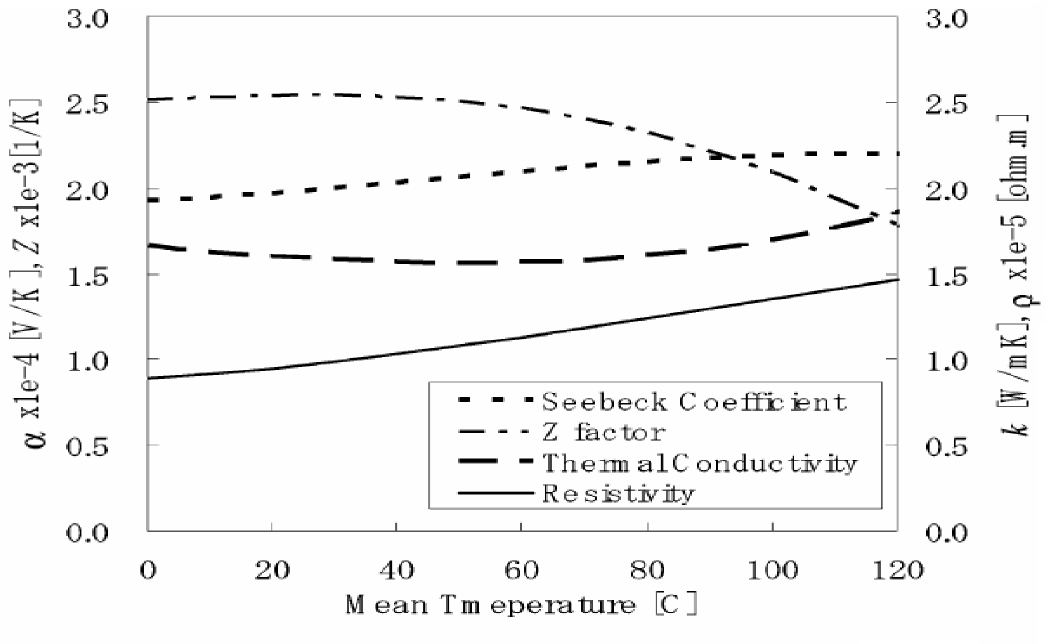
Similar results are shown for n-type semiconductors



***zT* for n-type thermoelectric materials**

# $Bi_2Te_3$ Properties:

Below is a plot of the figure of merit (Z), Seebeck coefficient, electrical resistivity, and thermal conductivity, as a function of temperature for $Bi_2Te_3$. Carrier concentration will alter the values below.



Temperature variation of $Bi_2Te_3$ material properties

# $Bi_2Te_3$ Properties:

$Bi_2Te_3$ figure of merit as a function of tellurium concentration.

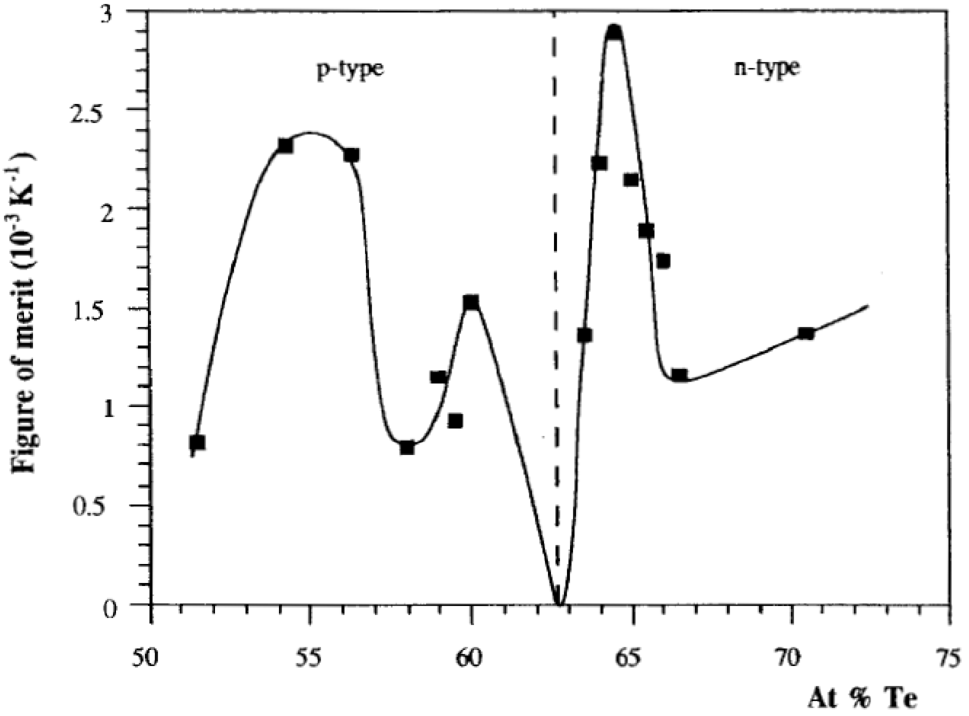


Figure-of-merit as the liquidus composition for both n- and p-type $Bi_2Te_3$.

# Thermoelectric Materials

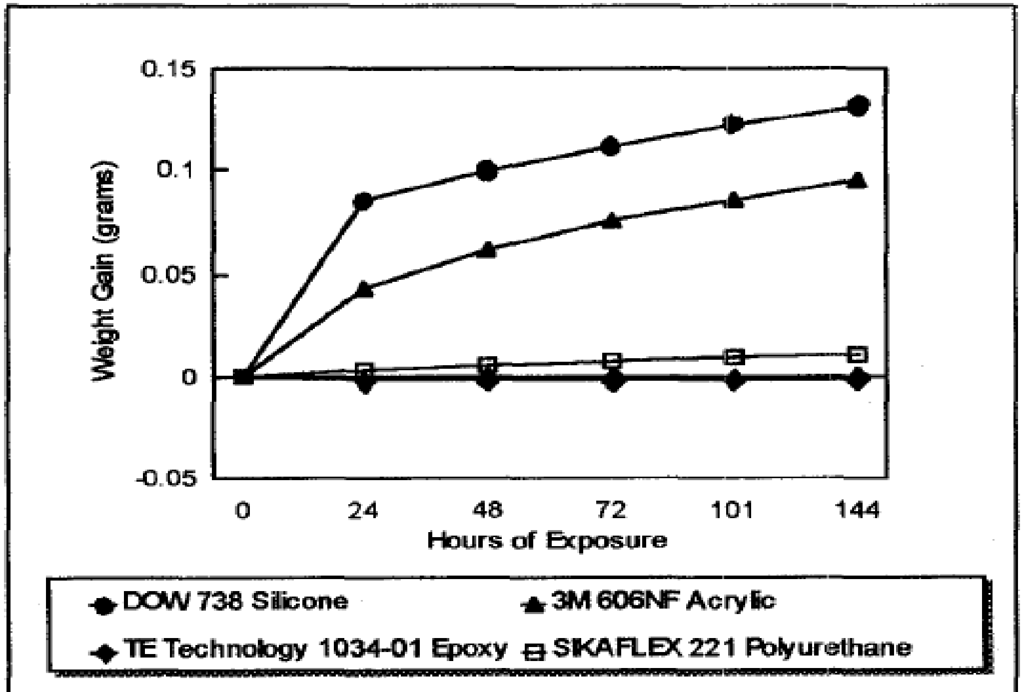
- Metals are used to sandwich the semiconductor. Because the TE performance is also dependent on these materials, an optimal material must be chosen, usually copper.

# Condensation

- A common problem with TE cooling is that condensation may occur causing corrosion and eroding the TE’s inherent reliability.
- Condensation occurs when the dew point is reached. The dew point is the temperature to which air must be cooled at constant pressure for the water vapor to start to condense
- Condensation occurs because the air loses the ability to carry the water vapor that condenses. As the air’s temperature decreases its water vapor carrying capacity decreases.
- Since TE coolers can cool to low and even below ambient temperatures, condensation is a problem. The most common sealant employed is silicon rubber. Research has been performed to determine the most effective sealing agent used to protect the chip from water.

# Condensation

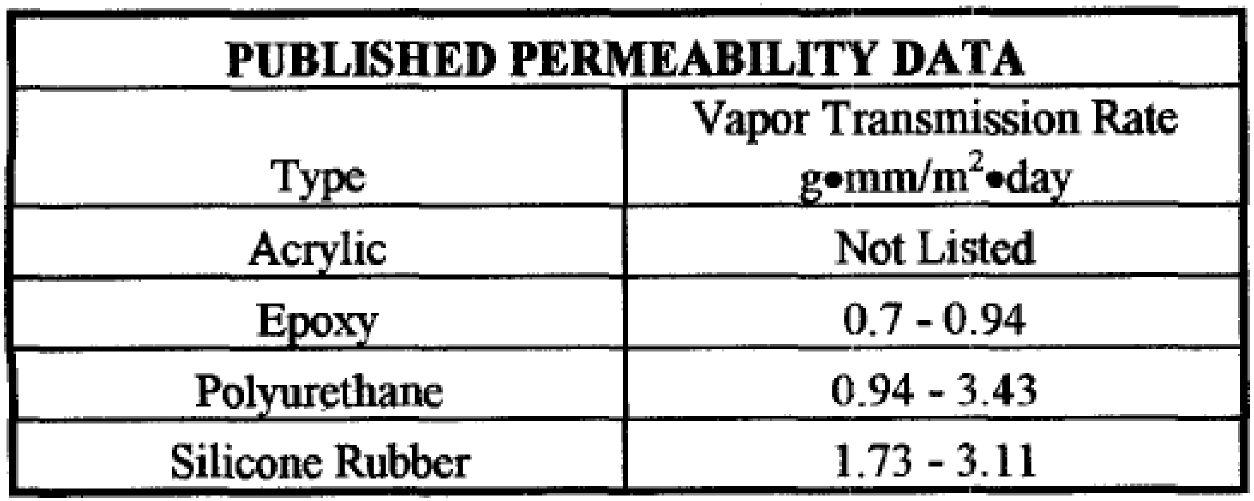
- Four sealants were used to seal a TE cooling device and the weight gain due to water entering the device measured. The best sealants should have the lowest weight gain. The epoxy has virtually no weight gain.



Weight Gain of Thermoelectric Modules

# Condensation

- According to the previous results, it seems that the epoxy is the best sealant. These results are verified by the published permeability data showing the epoxy having the lowest permeability (vapor transmission rate) of all the sealants.



**PUBLISHED PERMEABILITY DATA**

| Type | Vapor Transmission Rate g•mm/$m^2$•day |
|---|---|
| Acrylic | Not Listed |
| Epoxy | 0.7 - 0.94 |
| Polyurethane | 0.94 - 3.43 |
| Silicone Rubber | 1.73 - 3.11 |

# Thermoelectric Performance

TE performance depends on the following factors:

- The temperature of the cold and hot sides.
- Thermal and electrical conductivities of the device’s materials.
- Contact resistance between the TE device and heat source/heat sink.
- Thermal resistance of the heat sink.

# Thermoelectric Performance

- The current yielding the maximum COP is given by:

$$I_\phi = \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R[(1+ZT_m)^{1/2} - 1]}$$

- The maximum COP is:

$$\phi_{\max} = \frac{Q_c}{W_{in}} = \frac{T_1[(1+ZT_m)^{1/2} - T_2/T_1]}{(T_2 - T_1)[(1+ZT_m)^{1/2} + 1]}$$

Where Tm= (TH+TC)/2

# Thermoelectric Performance

- The COP corresponding to the maximum heat pumping capacity is:

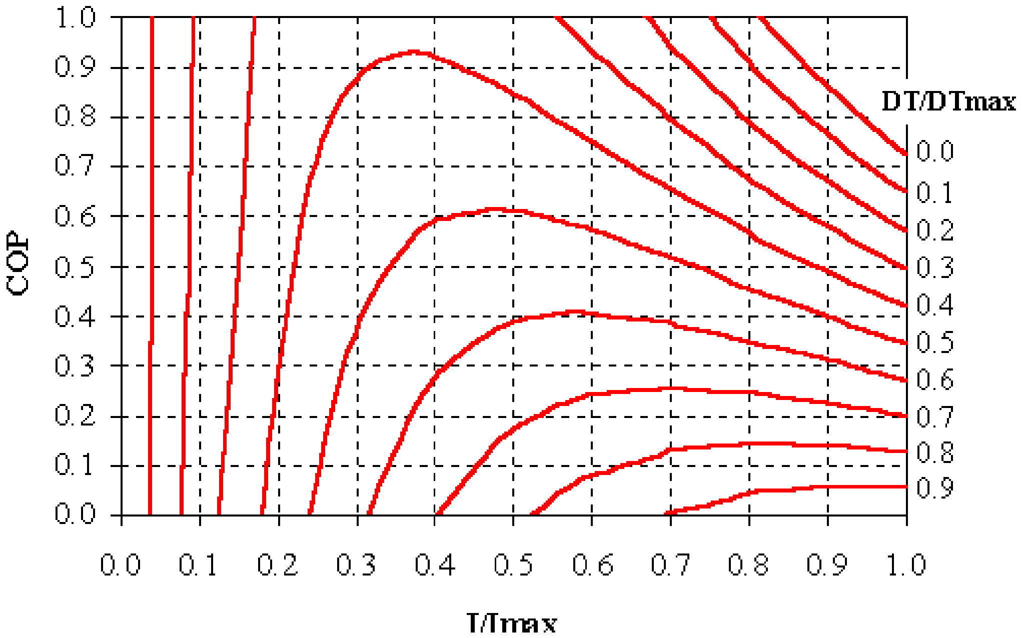
$$\phi_q = \frac{1/2ZT_c^{\,2} - (T_H - T_c)}{ZT_H T_c}$$

- The current corresponding to the maximum heat pumping capacity is:

$$I_q = \frac{(\alpha_p - \alpha_n)T_c}{R}$$

# Coefficient of Performance

- A typical AC unit has a COP of approximately 3. TE coolers usually have COP’s below 1; 0.4 to 0.7 is a typical range.
- Below are COP values plotted versus the ratio of input current to the module’s Imax specification. Each line corresponds with a constant DT/DTmax (the ratio of the required temperature difference to the module's max temperature difference specification).



# Thermoelectric Performance

- A simplified way of determining the voltage and the heat load are given by:

$$Qc = (\alpha_p - \alpha_n) IT_c - K(T_H - T_c) - 1/2I^2R$$

$$V = 2N\left[\alpha(T_h - T_c)\frac{IRL}{A}\right]$$

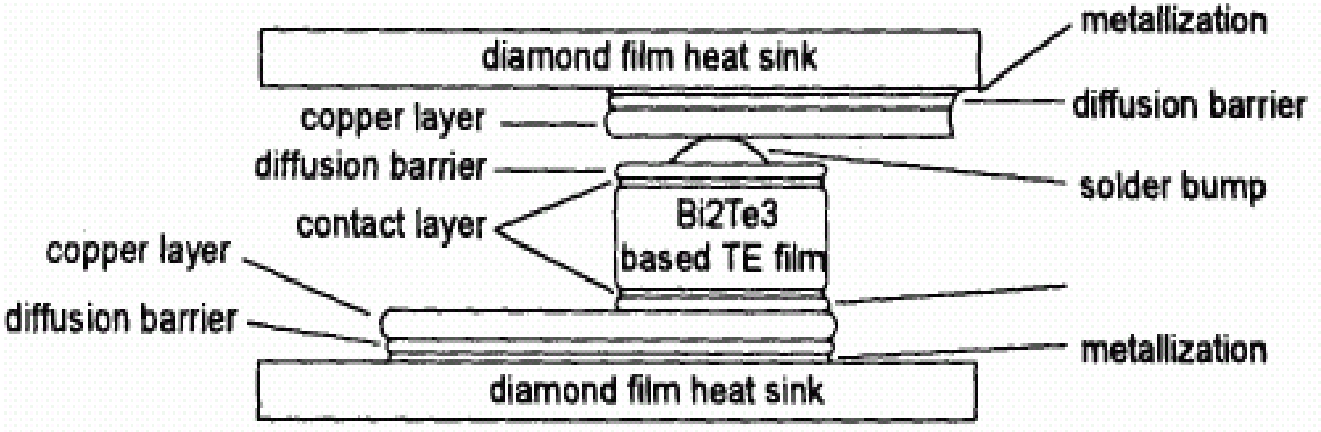
Where V is the voltage and $Q_c$ is the heat load, N is the number of couples, and L is the element height.

# Improving TE performance

- Various methods have been used to improve the performance of TE coolers which are its major drawback.
- Examples: thin film coolers or multistage (bulk) coolers.

# Thin Film Coolers

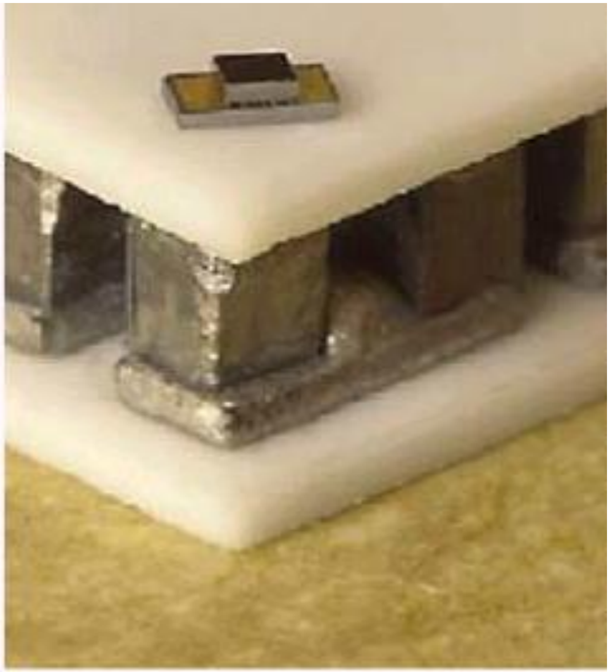
- Thin films are material layers of about 1 micrometer thickness. Alternating layers of $Sb_2Te_3$ and $Bi_2Te_3$ are used to produce thin film TE coolers. An example is shown below where the highest power components are mounted on a diamond substrate which would be the top or cold side substrate of a thin film TE cooler. Power densities were reported to be above $100W/cm^2$.



Structure for a thin film thermoelectric device
(adapted from Fleurial and Vandersande [9] ).

# Thin Film Coolers

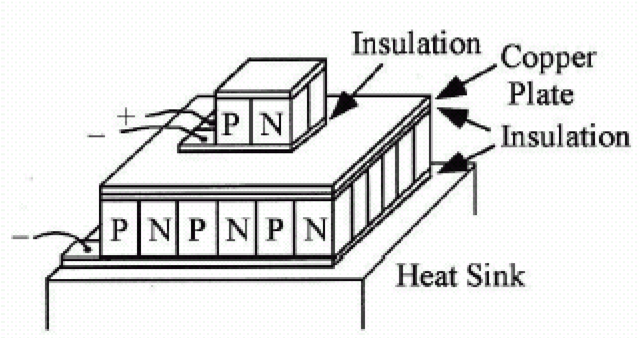
- Thin film coolers considerably reduce the size of TE devices. Because the cooling density of a Peltier cooler is inversely proportional to its length, scaling to smaller size is desirable. A comparison of sizes are shown below.

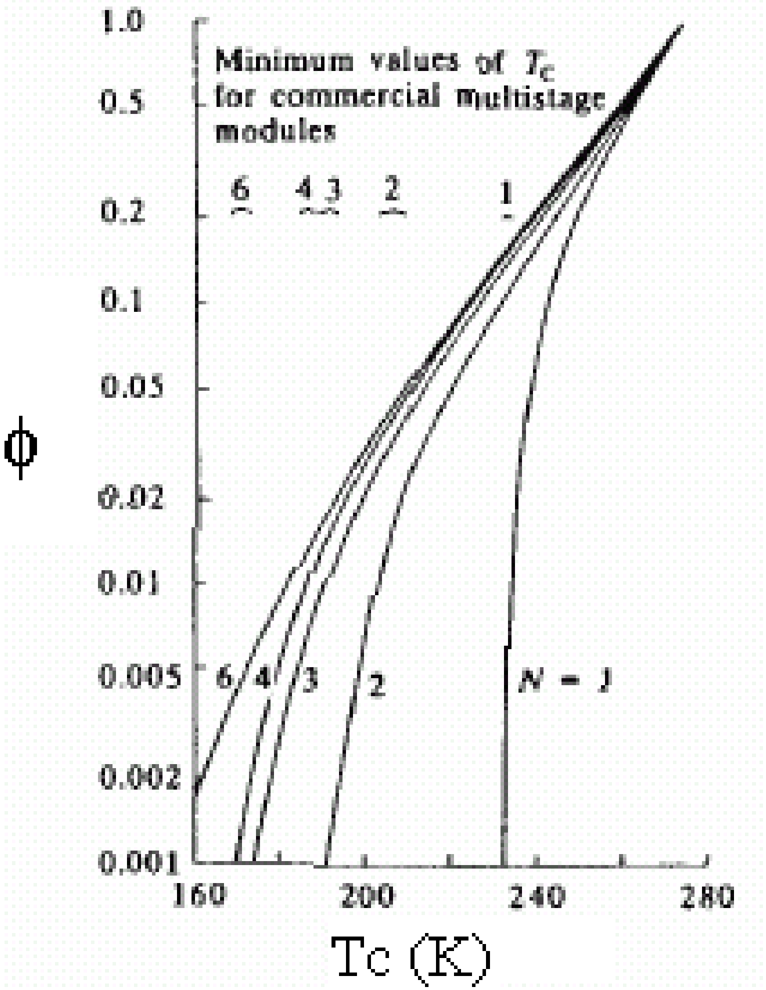


# Multistage Modules

- When the desired temperature differential between the cold and hot side cannot be obtained with a single stage module, or when the cold side temperature must be lower than a one stage cooler will allow, a multistage module may need to be applied.
- Multistage modules are essentially single stage modules stacked up in a vertical pyramid-shaped array (see next slide).
- As the number of stages increases, the minimum cold side temperature will decrease (Rowe, 1995) .
- Also, increasing the number of stages increases the coefficient of performance for a given cold side temperature

# Multistage Modules





Increasing the number of stages increases the coefficient of performance for a given cold side temperature, as seen in the figure on the right

# Multistage Modules

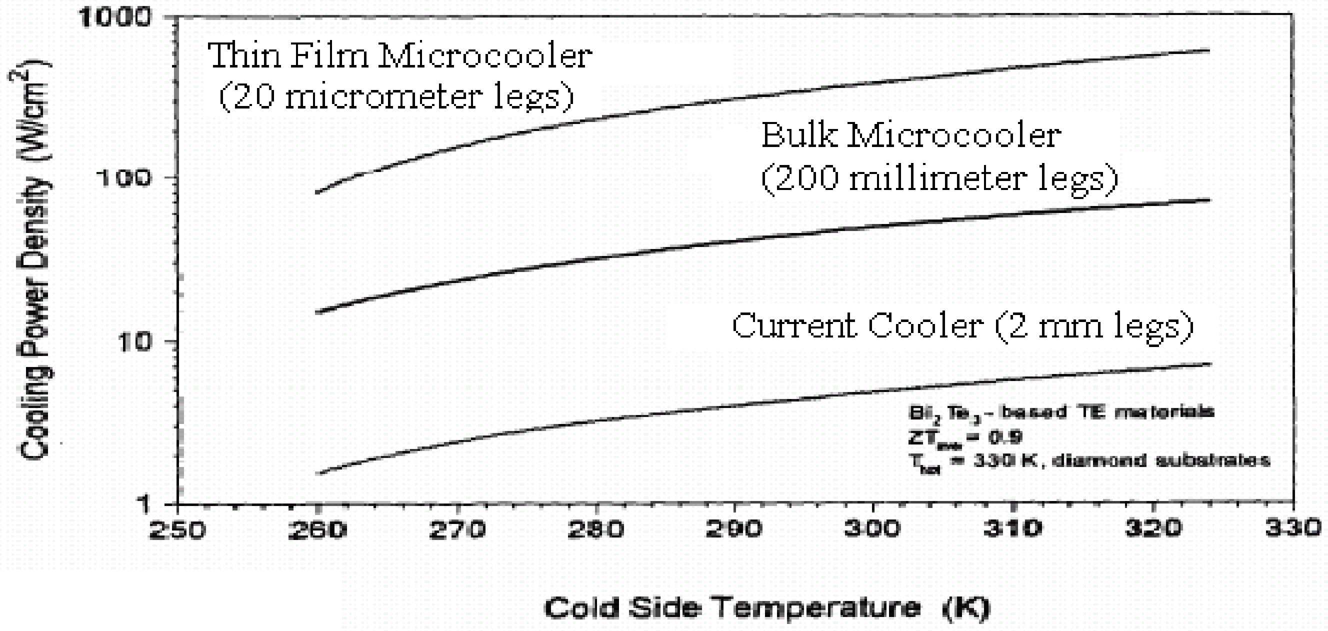
The coefficient of performance of a multistage module is given by:

$$\phi = \left[ \left( 1 + \frac{1}{\phi'} \right)^{N} - 1 \right]^{-1}$$

Where $\phi'$ is the coefficient of performance of one stage of the module and N is the number of stages.

# Comparison of Various TE Coolers

- The Figure below compares the three types of coolers bulk (multistage), thin film, and current.



Cooling power density for different T.E. cooler designs (adapted from Vandersande and Fleurial ).

# Improving Performance

More exotic TE devices are being researched that could result in better performance such as, superlattice structures, quantum wires and quantum wells, thin films using SiGe/Si, and thermionic cooling. However, research in these are preliminary and are not in widespread use.

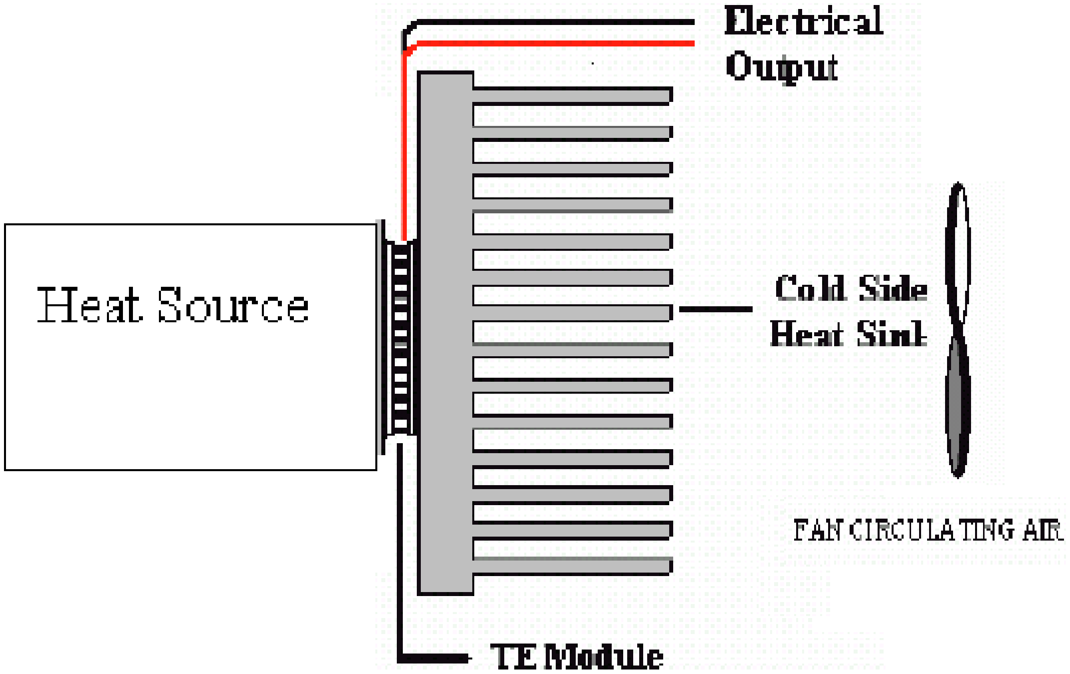
# Temperature stability

- TE cooling provides high degrees of temperature stability because the amount of cooling it provides is proportional to the applied current.
- The reported temperature stability of a TE device has been ±.0003 degrees Celsius but considerable effort had to be used for this level of stability.
- Several factors are involved in the temperature stability:
    - The controller and its resolution.
    - The response time of the specific cooling assembly
    - The response time of the object being cooled.

# TE Cooling of Electronics

- TE cooling devices are favorable in electronics cooling systems because of their high reliability, flexibility in packaging and integration, low weight and ability to maintain a low junction temperature, even below ambient temperature.
- Also, other cooling devices that can fit the tiny spaces required for electronics cooling, such as, a capillary loop heat or a miniature scale vapor compression refrigerator are not commercially available.
- Disadvantages of these devices are the limit to their cooling capacity limit and coefficient of performance which may be restrictive in the future when heat transfer demands become much larger.
- Typical TE cooling schemes have a TE device attached to a heat source (the cold side) that transports heat to a heat sink (the warm side).

- Without a heat sink it is difficult to get an adequate ΔT but with a good airflow the heat sink size can be reduced.
- A DC power supply is needed for the TE cooler.



# MAJOR APPLICATIONS OF THERMOELECTRIC COOLERS

- Include equipment used by military, medical, industrial, consumer, scientific/laboratory, and telecommunications organizations.
- Uses range from simple food and beverage coolers for an afternoon picnic to extremely sophisticated temperature control systems in missiles and space vehicles.

## Why are TE Coolers Used for Cooling?

- No moving parts make them very reliable; approximately $10^5$ hrs. of operation at 100 degrees Celsius, longer for lower temps.
- Ideal when precise temperature control is required.
- Ability to lower temperature below ambient.
- Heat transport controlled by current input.
- Able to operate in any orientation.
- Compact size make them useful for applications where size or weight is a constraint.
- Ability to alternate between heating and cooling.
- Excellent cooling alternative to vapor compression coolers for systems that are sensitive to mechanical vibration.

# ADVANTAGES OF THERMOELECTRIC COOLING:

- Small size and light weight.
- Compact and reliable.
- Steady-state operation.
- No moving parts and fluids.
- Durable and maintenance-free.
- Very long operation life.
- Effective in spot cooling.
- Environmentally friendly.
- No chlorofluorocarbons.
- Ability to heat and cool.
- Work in any orientation.
- Generate no electrical noise
- Can powered directly by PV cells.

# LIMITATIONS OF THERMOELECTRIC COOLING

- Able to dissipate limited amount of heat flux.
- Lower COP as compared to VC systems.
- Relegated to low heat flux applications.
- More total heat to remove than without a TEC.

# THERMOELECTRIC COOLING VERSUS TRADITIONAL REFRIGERATION

- **Solid state design**
  - No moving parts
  - Integrated chip design
  - No hazardous gases
  - Silent operation
- **Compact and lightweight**
  - Low profile
  - Sizes to match your component footprint
  - No bulky compressor units
- **Precise temperature stability**
  - Tolerances of better than +/- 0.1°C
  - Accurate and reproducible ramp and dwell times
- **Cooling/heating mode options**
  - Fully reversible with switch in polarity
- **Localized Cooling**
  - Spot cooling for components or medical applications
  - Perfect for temperature calibration in precision detection systems
- **Rapid response times**
  - Instantaneous temperature change
  - Reduced power consumption
- **Dehumidification**
  - Efficient condensation of atmospheric water vapor

Thank You!

# ANY QUESTION