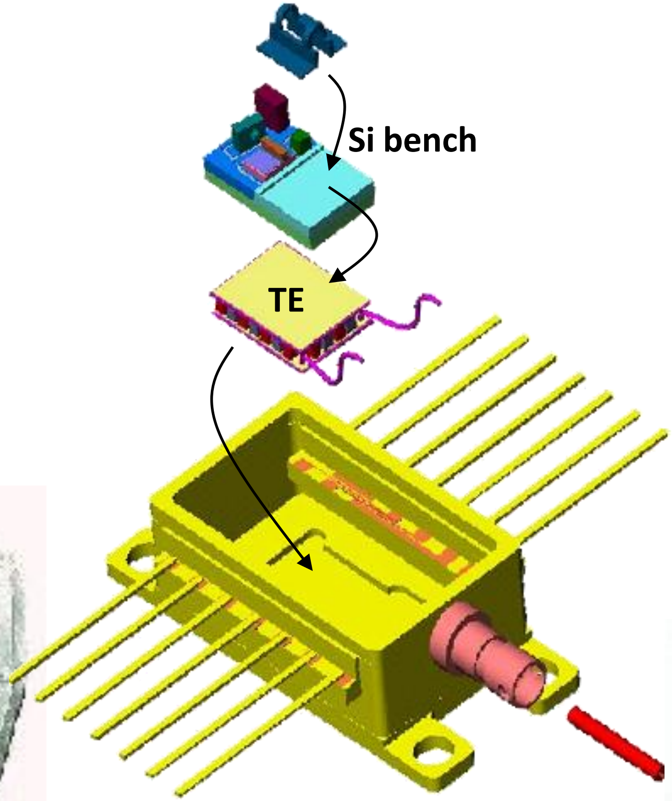
Outline

- Thermoelectric Effects
- Thermoelectric Refrigeration
- Figure of Merit (Z)
- Direct Thermal to Electric Power Generation

Applications

Water/Beer Cooler

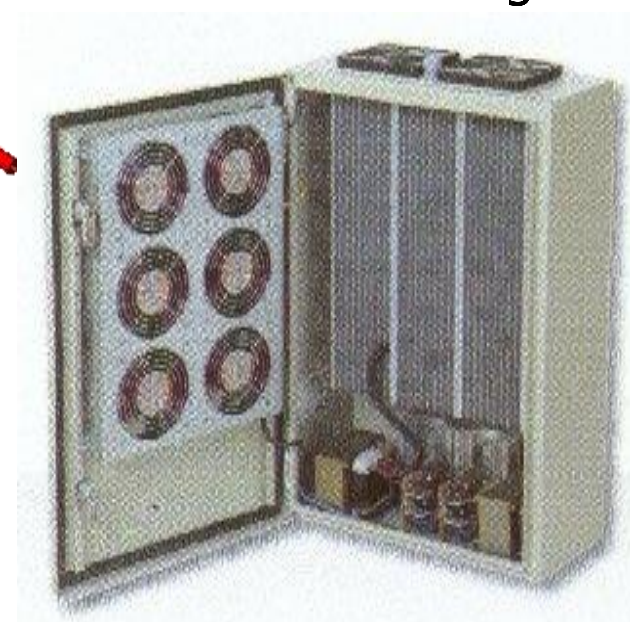
Cryogenic IR Night Vision



Laser/OE Cooling

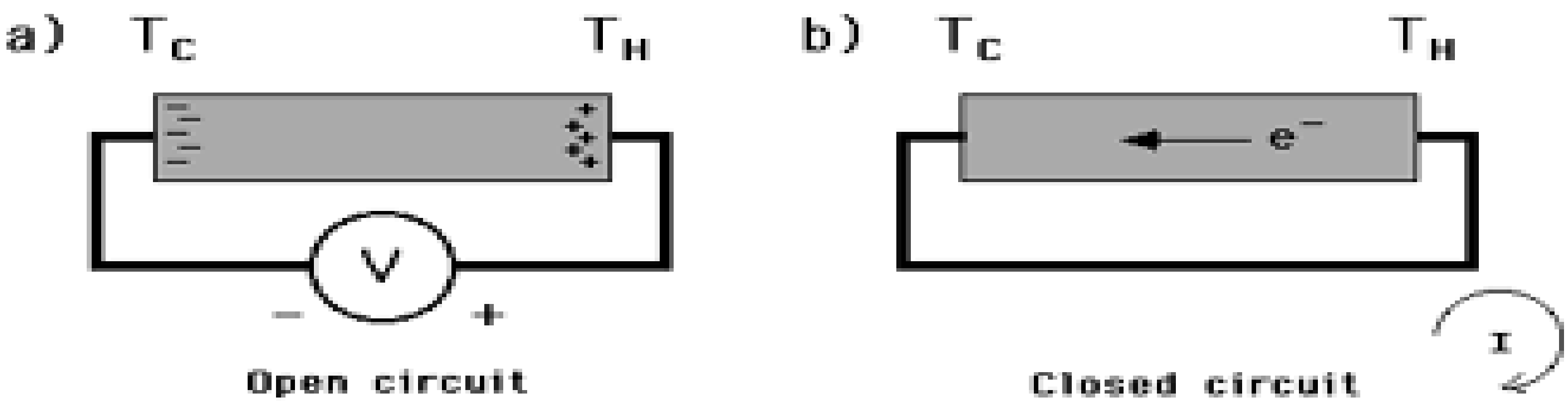
Cooled
Car Seat

Electronic Cooling



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.



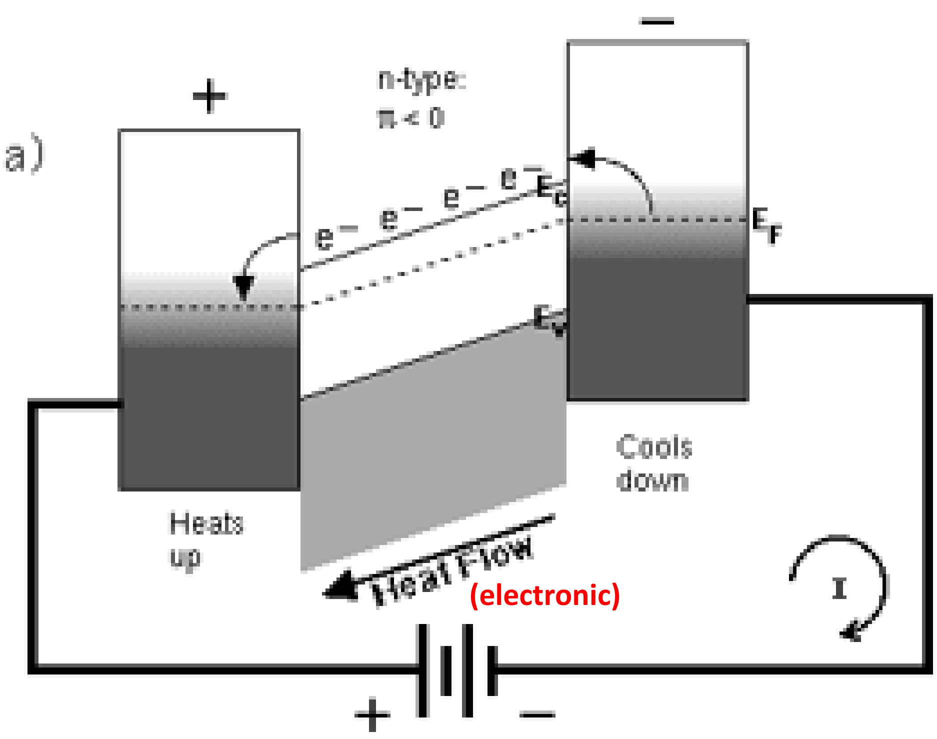
S= dV / dT;

S is the Seebeck Coefficient with units of Volts per Kelvin

S is positive when the direction of electric current is same as the direction of thermal current

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.

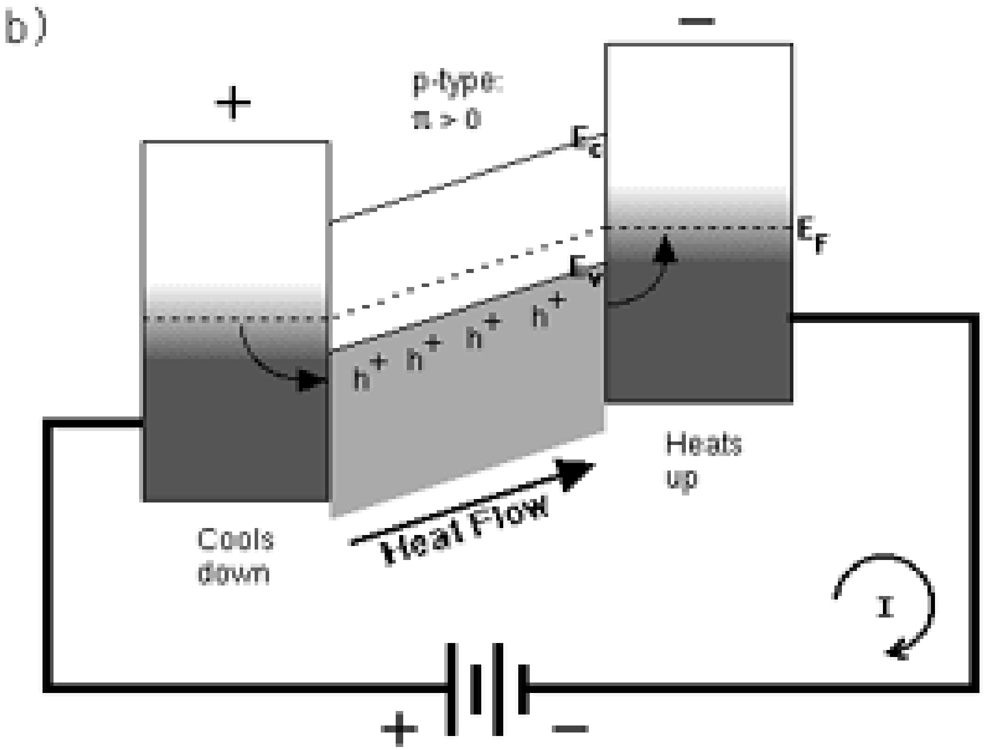


$\Pi < 0$; Negative Peltier coefficient

High energy electrons move from right to left.

Thermal current and electric current flow in opposite directions.

Peltier Cooling



$\Pi > 0$; Positive Peltier coefficient

High energy holes move from left to right.

Thermal current and electric current flow in same direction.

$q = \Pi * j$, where q is thermal current density and j is electrical current density.

$\Pi = S*T$ (Volts) S ~ 2.5 k_B/e for typical TE materials

T is the Absolute Temperature

Thomson Effect

- Discovered by William Thomson (Lord Kelvin)
- When an electric current flows through a conductor, the ends of which are maintained at different temperatures, heat is evolved at a rate approximately proportional to the product of the current and the temperature gradient.

$$\frac{dQ}{dx} = \tau I \frac{dT}{dx}$$

τ is the Thomson coefficient in Volts/Kelvin

→ Seebeck coeff. S is temperature dependent

Relation given by Kelvin: $\tau = T \frac{dS}{dT}$

Kelvin Relations

$$\bar{J} = \sigma(\bar{E} - S\nabla T)$$

$$\bar{J}_q = -k\nabla T + ST\bar{J} = \sigma ST\bar{E} - (\sigma S^2 T + k)\nabla T$$

$$\left.\begin{aligned} \nabla \bullet \bar{J} &= 0 \\ \nabla \bullet \bar{J}_q &= \bar{J} \bullet \bar{E} \end{aligned}\right\}$$

$$-\nabla \bullet (k\nabla T) + T\bar{J} \bullet \nabla S - \frac{|\bar{J}|^2}{\sigma} = 0$$

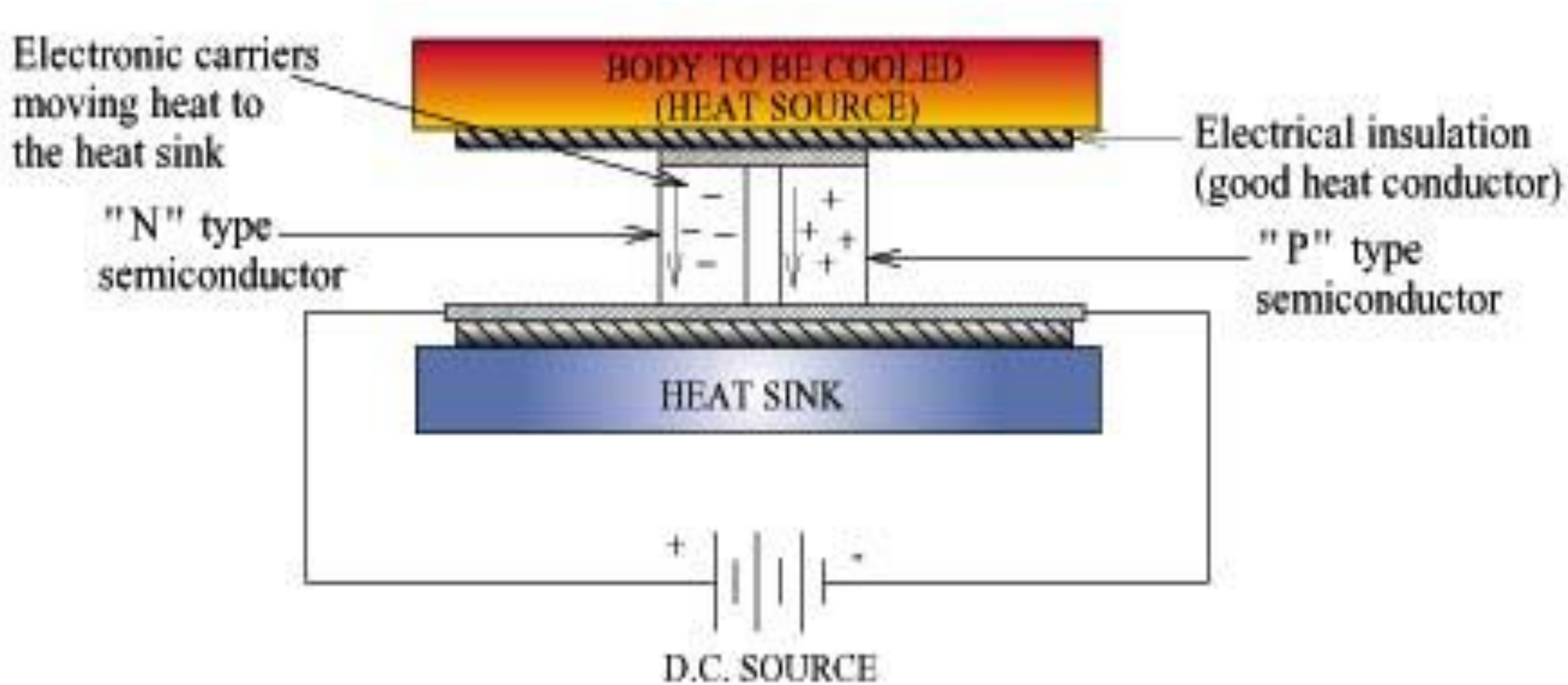
TE Heat Conduction

$$\sigma = \int_{-\infty}^{\infty} dE\left(-\frac{\partial f}{\partial E}\right)(e^2 N \tau v^2)$$

$$S = \frac{1}{eT} \cdot \frac{\int_{-\infty}^{\infty} dE\left(-\frac{\partial f}{\partial E}\right)(E-\mu)(e^2 N \tau v^2)}{\sigma} \approx \frac{(3k_B T)}{eT} = 3\left(\frac{k_B}{e}\right)$$

for Bi chalcogenides

Thermoelectric Refrigeration



The rate of heat flow from one of the legs (i=1 or 2) :

$$q_i\Big|_{x=0} = S_i I T - k_i A_i \frac{dT}{dx}\Big|_{x=0} \qquad (1)$$

The rate of heat generation per unit length due to Joule heating is given by:

$$\frac{I^2}{\sigma_i A_i} = -k_i A_i \frac{d^2T}{dx^2} \qquad (2)$$

Eqn 2 is solved using the boundary conditions T= T_c at x=0 and T= T_h at x= l. Thus it is found that:

$$-k_i A_i \frac{dT}{dx} = \frac{I^2[x - l/2]}{\sigma_i A_i} - \frac{k_i A_i (T_h - T_c)}{l} \qquad (3)$$

The total heat removed from source will be sum of q_1 and q_2

$$q_c = (q_1 + q_2)|_{x=0} \qquad (4)$$

Eqs. 1, 3, 4→

$$q_c = (S_2 - S_1) I T_c - K \Delta T - 0.5 I^2 R$$

K: Thermal conductance of the two legs

R: Electrical Resistance of the two legs

The electrical power is given by:

$$w = (S_2 - S_1)I\Delta T + I^2 R$$

COP is given by heat removed per unit power consumed

$$\Phi = \frac{q_c}{w} = \frac{(S_2 - S_1)IT_c - K\Delta T - 0.5I^2 R}{I[(S_2 - S_1)\Delta T + IR]}$$

Differentiating w.r. to I we get max. value of COP

$$\phi_{\max} = \left(\frac{T_c}{T_h - T_c}\right)\left(\frac{\sqrt{1 + ZT_m} - T_h / T_c}{\sqrt{1 + ZT_m} + 1}\right)$$

can be reduced to unity by multistaging

where $Z = \frac{(S_2 - S_1)^2}{KR}$ $\quad T_m = \frac{(T_h + T_c)}{2}$

A similar approach can be used to obtain the maximum degree of cooling and maximum cooling power.

It is obvious that z will be maximum when RK will have minimum value. This occurs when:

$$\frac{A_1 / l_1}{A_2 / l_2} = \sqrt{\frac{\sigma_2 k_2}{\sigma_1 k_1}}$$

When this condition is satisfied z becomes:

$$Z = \frac{(S_2 - S_1)^2}{[(k_1 / \sigma_1)^{1/2} + (k_2 / \sigma_2)^{1/2}]^2}$$

Further, if $S_2 = -S_1 = S$, $k_1 = k_2 = K$, $\sigma_1 = \sigma_2 = \sigma$

$$Z = \frac{S^2 \sigma}{k}$$

power factor ($S^2 \sigma$)

ZT_m vs. COP

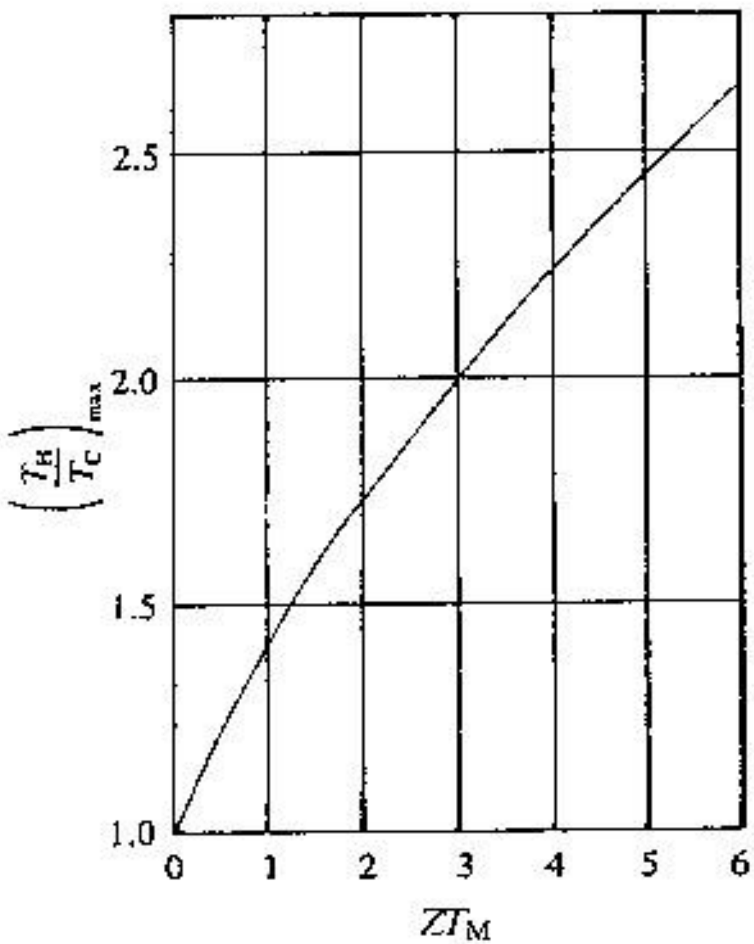


Fig. 1.6. Maximum ratio of hot to cold junction temperature as a function of the dimensionless figure of merit

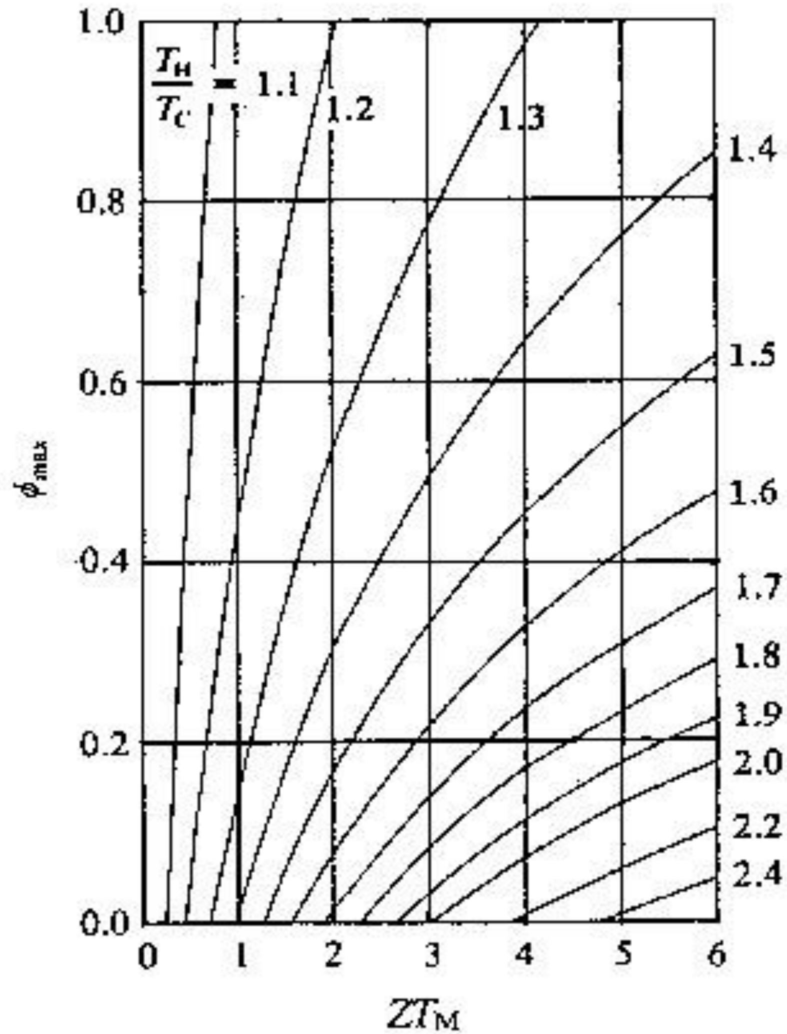


Fig. 1.7. Maximum coefficient of performance as a function of the dimensionless figure of merit for different ratios of hot to cold junction temperature

Thermoelectric Power Generation

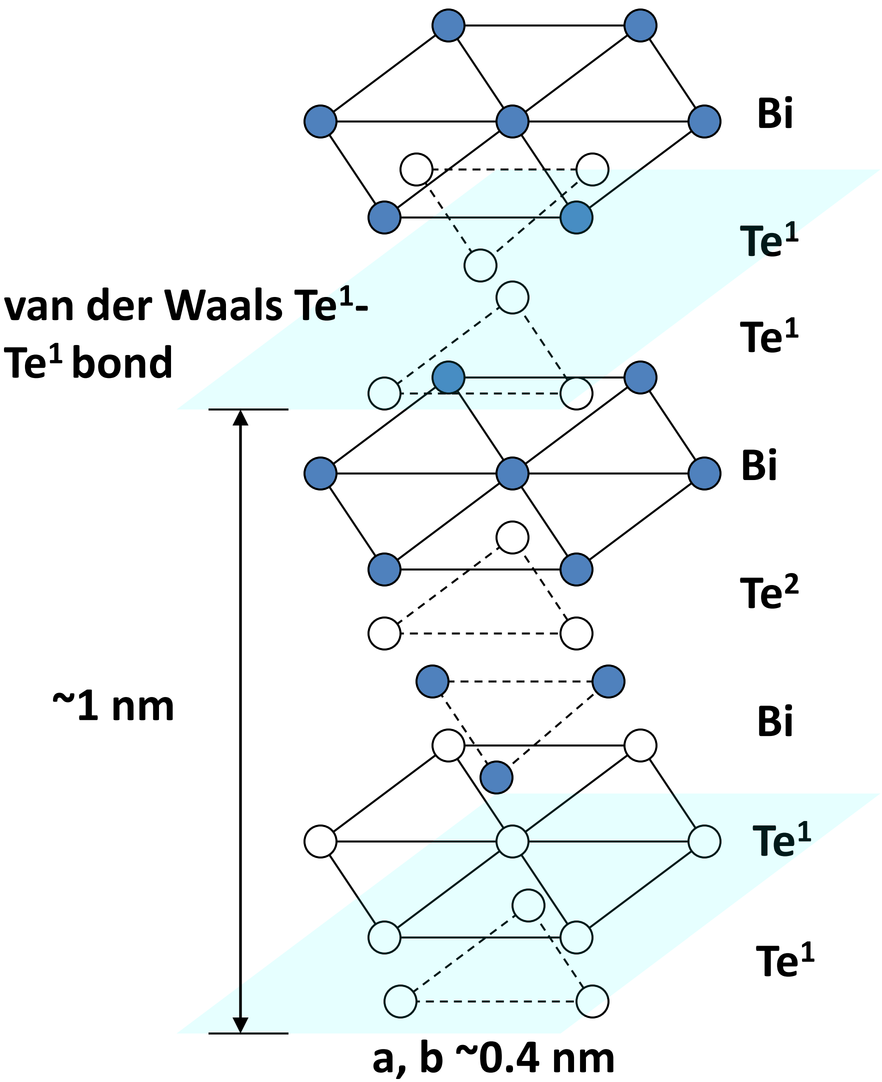
- **Used in Space shuttles and rockets for compact source of power.**
- **Energy recovery from automobile engines**
- **Diffusive heat flow and Peltier effect are additive i.e. both reduce the temperature gradient.**

$$\eta = \frac{w}{q_H} = \frac{I[(S_2 - S_1)\Delta T - IR]}{(S_2 - S_1)IT_c - k\Delta T - 0.5I^2R}$$

where: w is the power delivered to the external load and Q_H is the positive heat flow from source to sink

$$\phi_{\max} = \left(\frac{T_h - T_c}{T_h}\right)\left(\frac{\sqrt{1 + zT_m} - 1}{\sqrt{1 + zT_m} + T_c / T_h}\right)$$

Bismuth Chalcogenides

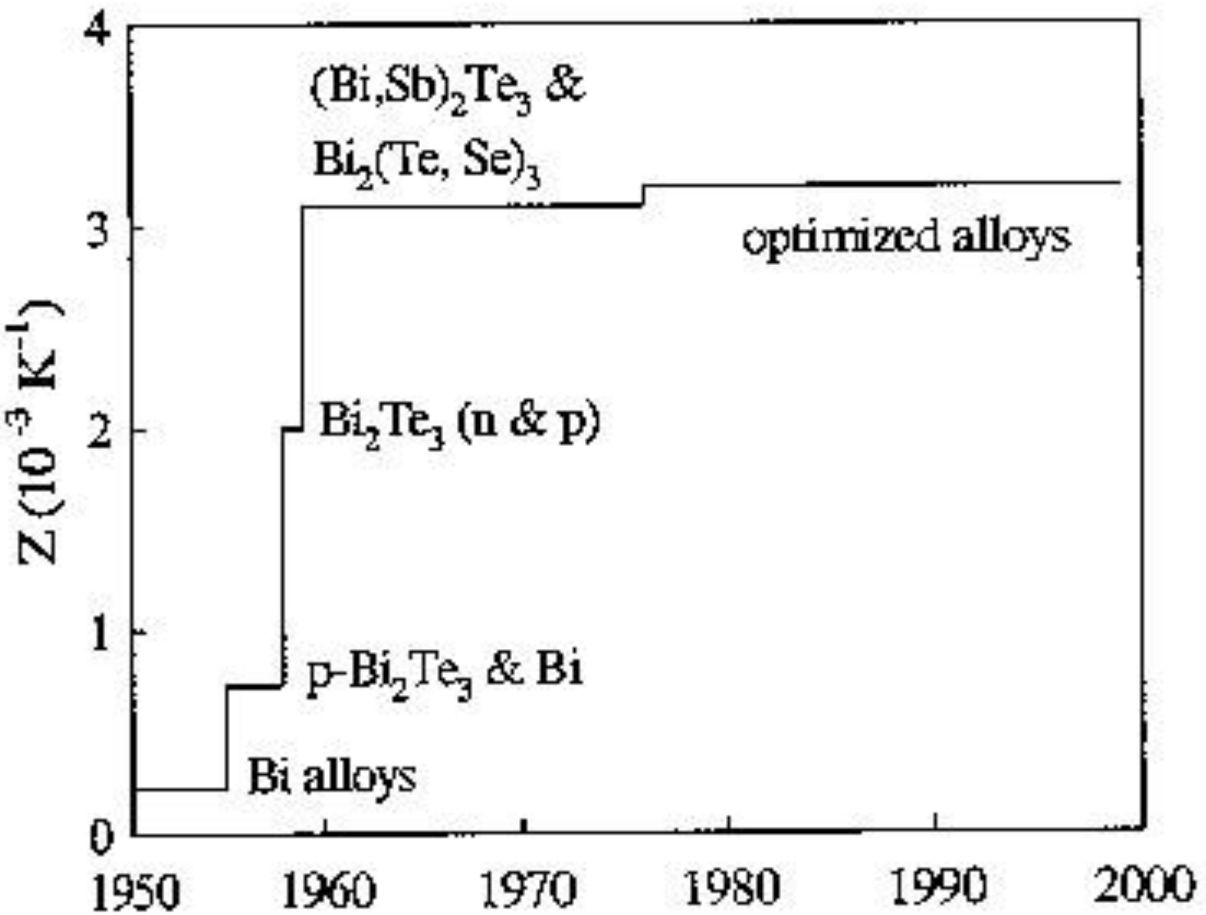


- Weak van der Waals bonds attenuate phonon conduction
- Sb substitutes Bi in Sb_2Te_3 and Se substitutes Te in Bi_2Se_3 structures, and results in greater mismatch in atomic masses
- Alloys such as $Bi_{0.5}Sb_{1.5}Te_3$ (p-type), $Bi_2Te_{2.8}Se_{0.2}$ (n-type) have $ZT_a = 0.8$
- Interface scattering in superlattices of Bi_2Te_3 and Sb_2Te_3 and ultra-thin films result in lower phonon thermal conductivities
- Phonon glass, electron crystal (PGEC)

Progress in *ZT*

Fundamental limitations:

k and σ, *S* and σ are coupled.



Miscellaneous

- Bismuth telluride is the best bulk TE material with *ZT*=1
- Trends in TE devices:
  - Superlattices and nanowires: Increase in *S*, reduction in *k*
  - Nonequilibrium effects: decoupling of electron and phonon transport
  - Bulk nanomaterial synthesis
- Trends in TE systems
  - Microrefrigeration based on thin film technologies
  - Automobile refrigeration
  - TE combined with fluidics for better heat exchangers
- To match a refrigerator, an effective *ZT*= 4 is needed
- To efficiently recover waste heat from car, *ZT* = 2 is needed

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Wind Power - Introduction

- Wind power is good renewable, clean and free source of energy for power production
- Reduce dependence on fossil fuels including imported oils
- Reduce emission of greenhouse gas and other pollutant
- One major concern is the noise – can be improved
- Intermittency and variability of the wind

Wind Energy in USA

Wind energy use is about 2% of the domestic energy consumption

Expected to increase to about 20% over next two decades.

Rates of wind turbine installation has been going up at a higher rate – highest in the world

- 8,500 MW in 2008
- 10,000 MW in 2009

Denmark is the world leader

- produces wind power over 20% of the country's power

Leading Manufacturers of Wind Turbine

1. Vestas (Denmark) - 35,000 MW
2. Enercon (Germany) - 19,000 MW
3. Gamesa (Spain) – 16,000 MW
4. General Electric (USA, Germany) – 15,000 MW
5. Siemens (Denmark, Germany) – 8,800 MW
6. Suzlon (India) – 6,000 MW
7. Nordex (Germany) – 5,400 MW
8. Acciona (spain) – 4,300 MW
9. Repower (Germany) – 3,000 MW
10. Goldwind (china) – 2,889

Source: Wikipedia

Typical Cost

1.0 – 2.5 million per MW for large scale

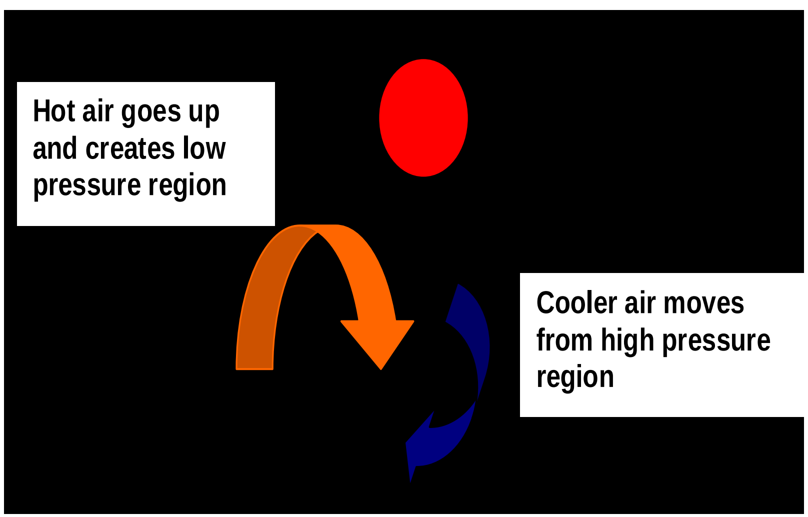
- Most commercial wind turbine are in the range of 2 MW

$3,000 – 5000 per kW in range less than 10kW

- $15,000 - $25,00 for residential home application

The Wind

- The wind is created by the movement of atmospheric air mass as a results of variation of atmospheric pressure, which results from the difference in solar heating of different parts of the earth surface.



Has different wind systems

Equator receives more solar radiation than higher latitude regions.

The curvature of the earth surface causes oblique interaction with incoming suns ray with increased altitude.

Wind Energy Conversion

- Wind power describes the process by which the wind is used to generate mechanical energy or electrical energy.

- Wind energy is the kinetic energy of the large mass of air over the earth surface.

- Wind turbines converts the kinetic energy of the wind into mechanical energy first and then into electricity if needed.

- The energy in the wind turns propeller like blades around a rotor shaft.

  - The rotor is connected to the main shaft, which spins a generator to create electricity.

- It is the design of the blades that is primarily responsible for converting the kinetic energy into mechanical energy.

- The rate of change of angular momentum of air at inlet and outlet of a blade gives rise to the mechanical torque.

  - As the air flows over the aerofoil-section of the blade, it induces a differential pressure distribution across the top and bottom surfaces of the blade.

Available Wind Power

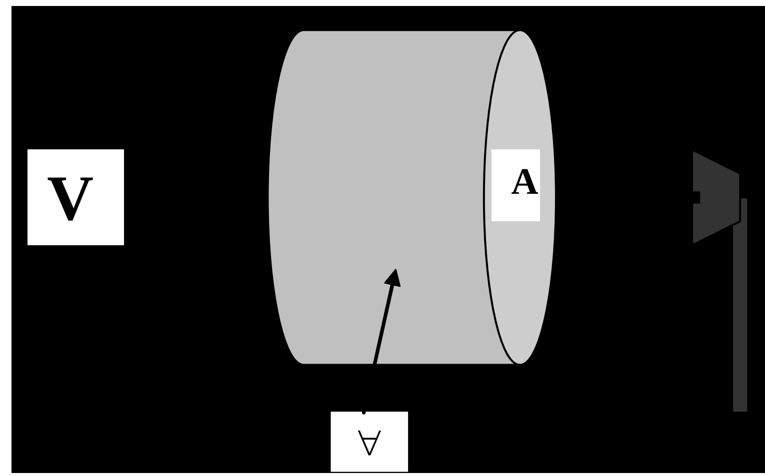
The kinetic energy of

a stream of air:

[redacted]

The kinetic energy of the air stream available for the turbine

[redacted]



[redacted] = Volume of air parcel available to the rotor

The ***air parcel interacting with the rotor per unit time*** has a cross-sectional area equal to that of the rotor ([redacted]) and thickness equal to the wind velocity (V).

Power is the ***energy per unit*** and expressed

[redacted]

- Major Factors: Air density, area of wind rotor and wind velocity

- The most important factor is ***Wind Speed***
(Power varies cubic power of velocity)

- As the velocity doubles, the power is increased by 8 times.

- The rotor area is reduced by a factor of 8.

- **The selection of site is very critical for the success of a wind power**

Wind Turbine Power and Efficiency

- A wind turbine converts a fraction of the wind energy into mechanical energy
  - A part is transferred to the rotor of the wind turbine (   ) [redacted]
  - Rest is carried away by passing air

- The efficiency is the ratio of actual power developed by wind turbine rotor to the available wind power
  - defined as power coefficient and expressed as

[redacted]

- The power coefficient or the power picked up by the wind turbine rotor is influenced by many factors:
  - profile of the rotor blade
  - number of blades
  - blade arrangement

Wind Turbine Torque

- The thrust force developed by the rotor is

[redacted]

- The rotor torque is

[redacted] ← Maximum Theoretical Torque

Where R is the radius of the rotor

Rotor Torque

- The torque developed by the rotor shaft is less than the maximum theoretical torque and given in terms of ***coefficient of torque***

as

[redacted]

Rotor Tip Relative Speed

- The rotor power at given wind speed depends on the relative speed between the rotor tip and the wind.

- Higher relative speed between the rotor tip and the wind leads to poor interaction the rotor and the wind.

  - For high speed wind approaching a slower moving rotor, a portion of the wind passes the rotor without transferring energy.

  - For low speed wind approaching a faster moving rotor, the wind deflects from the rotor and energy is lost due to turbulence and vortex shedding.

Relative speed is defined as velocity of rotor tip and wind speed as

[redacted]

N = Rotor rotational speed, rpm

[redacted] = Angular velocity

Also, it can be shown that power coefficient and torque coefficient is related by relative speed:

[redacted]

Types of Wind Turbine

- Horizontal axis
  - Primarily of the axial flow types
  - requires control mechanism to take account of variation in wind direction

- Vertical axis
  - Can handle winds from all directions

Betz’ Law

- States the theoretical limit for the conversion of wind energy in wind turbine
- According to this law maximum possible wind turbine efficiency is less than 59.3 %
- Derived assuming a thin rotor from a fluid at a speed

Major assumptions:

- Rotor without any hub
- Infinite number of blades with no drag
- axial flow in and out

Sizes of Wind Turbines

- Single small turbines , below 100 kW are for homes, water pumps, telecommunication dishes, stand alone system remote use, off grid location, hybrid applications, etc.

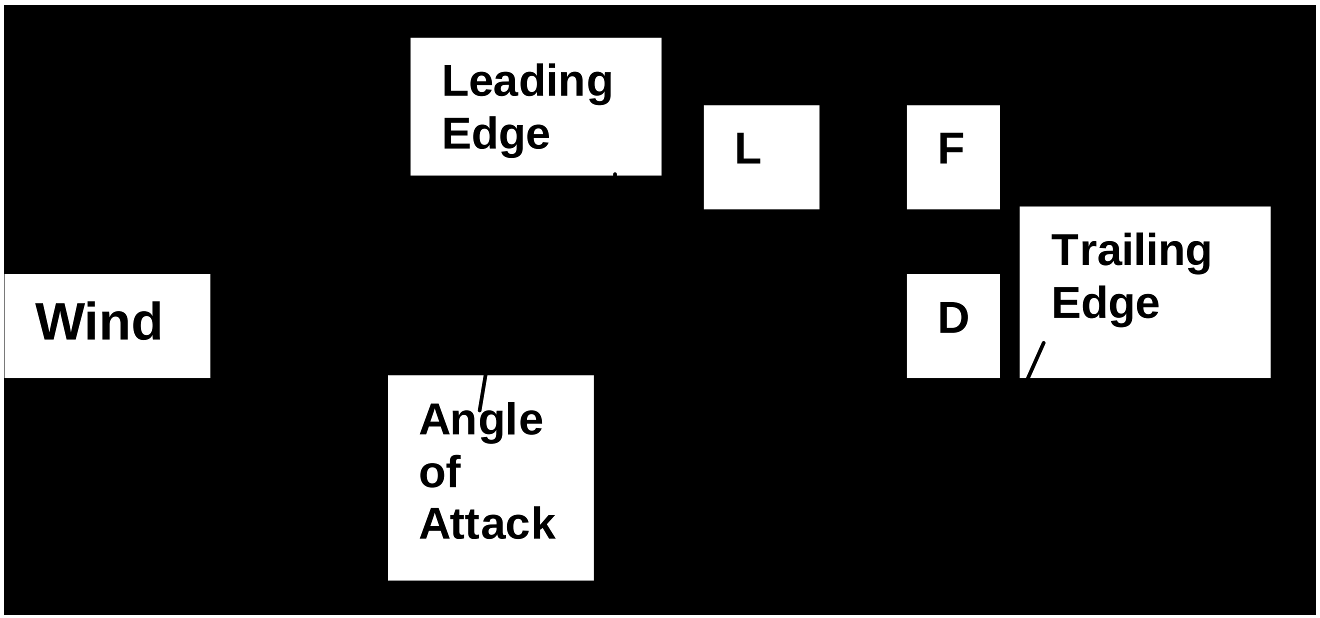
- Utility scale turbines range in sizes from 100 kW to MW.
  - Larger turbines are grouped together into a wind farms which provide bulk power to the electrical grid.

Major Components

- Rotor
- Blades
- Low speed shaft
- Gear Box
- High speed shaft
- Generator
- Brakes
- Controller

Blades

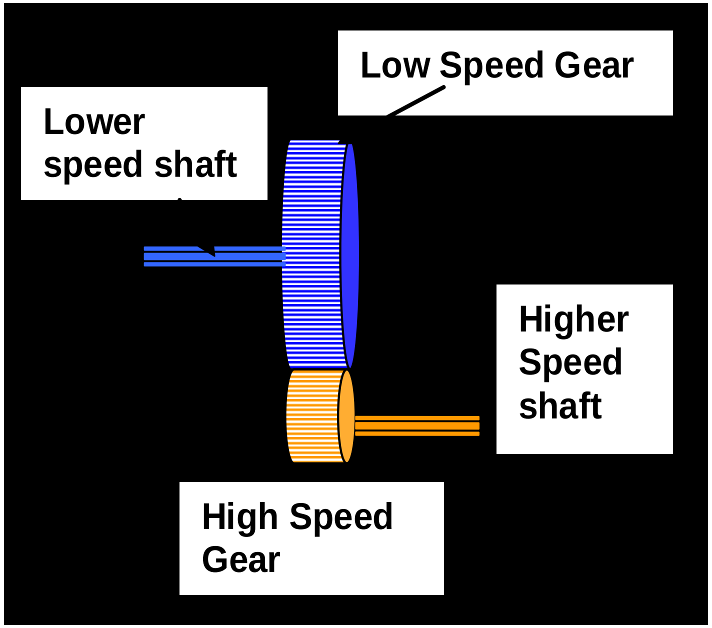
- Aerofoil design



- Air flow over the blade develops lift force and causes the blade to rotate

Gear Transmission

- Connects the low speed shaft of the rotor to the high sped shaft of the generator.



\- *Speed of a typical rotor* may be 30 rpm to 50 rpm.

\- *Generator speed* may be around 1000 rpm to 1500 rpm.

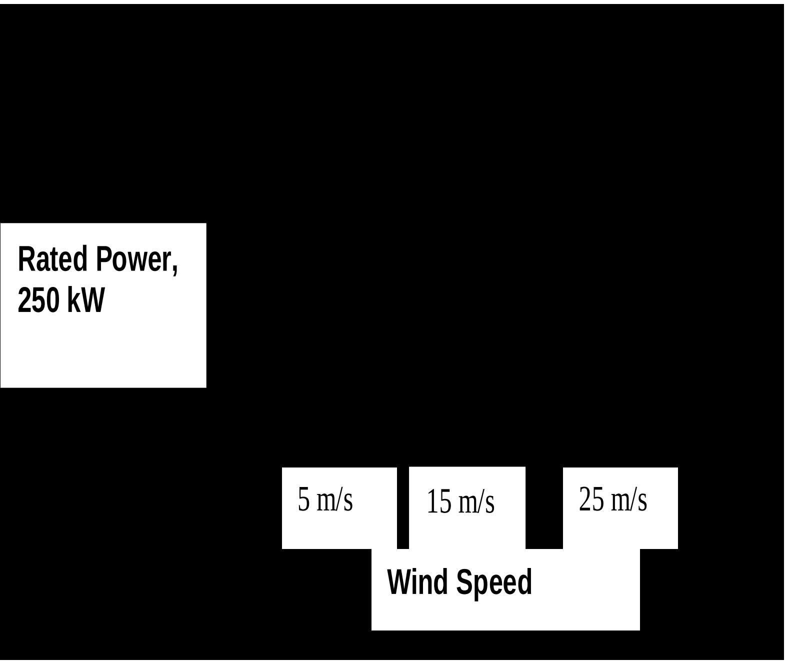
-Need gear trains in the transmission line to manipulate the speed according the requirements of the generator.

- May need multiple stages to achieve the speed ratio.

Additional Consideration for Gear System

- Heat dissipation, power losses and cooling
- Compact design
- Weight
- Bearing system

Power Regulation



- Turbine starts generating power at lower set wind speed.
- Power increases with increase in wind speed up to a rated wind speed and rated power.
- Power output remains constant at rated power between the rated wind speed and the cut-out speed
- Turbines stops operating speeds higher than the rated speed due to safety reason.

Turbine Power Control

- As the wind speed changes (15 m/s to 20 m/s for example over the rated power range, the rotor speed also changes (30 rpm to 50 rpm for example).
- Need to address the rapid acceleration.
- Turbine power is regulated.

Common Power Control Methods

- Pitch control
  - blade pitch and blade angle of attack is decreased with wind speed greater than rated speed.
  - Wind speed and power output and power out put are continuous monitored by sensors
  - Need sophisticated control mechanism
- Stall control
  - blades are designed in such a that with increase in wind speed, the angle of attack increases.
  - Pressure variation at the tp and bottom surface changes causing flow separation and vortex shedding
  - kills lift forces and leads to blades stalling
  - Need very sophisticated blade aerodynamic design

- Active stall-Controlled power regulation
  - The blades are pitched to to attain its best performance.
  - As the wind speed exceeds the rated velocity, the blades are turned in the opposite direction to increase the angle of attack and forces the blade to stall region.
- Yaw Control
  - The rotor is partly pushed away from the wind direction at higher wind speeds.
  - The rotor spin axis is pushed to an angle to the incoming wind direction