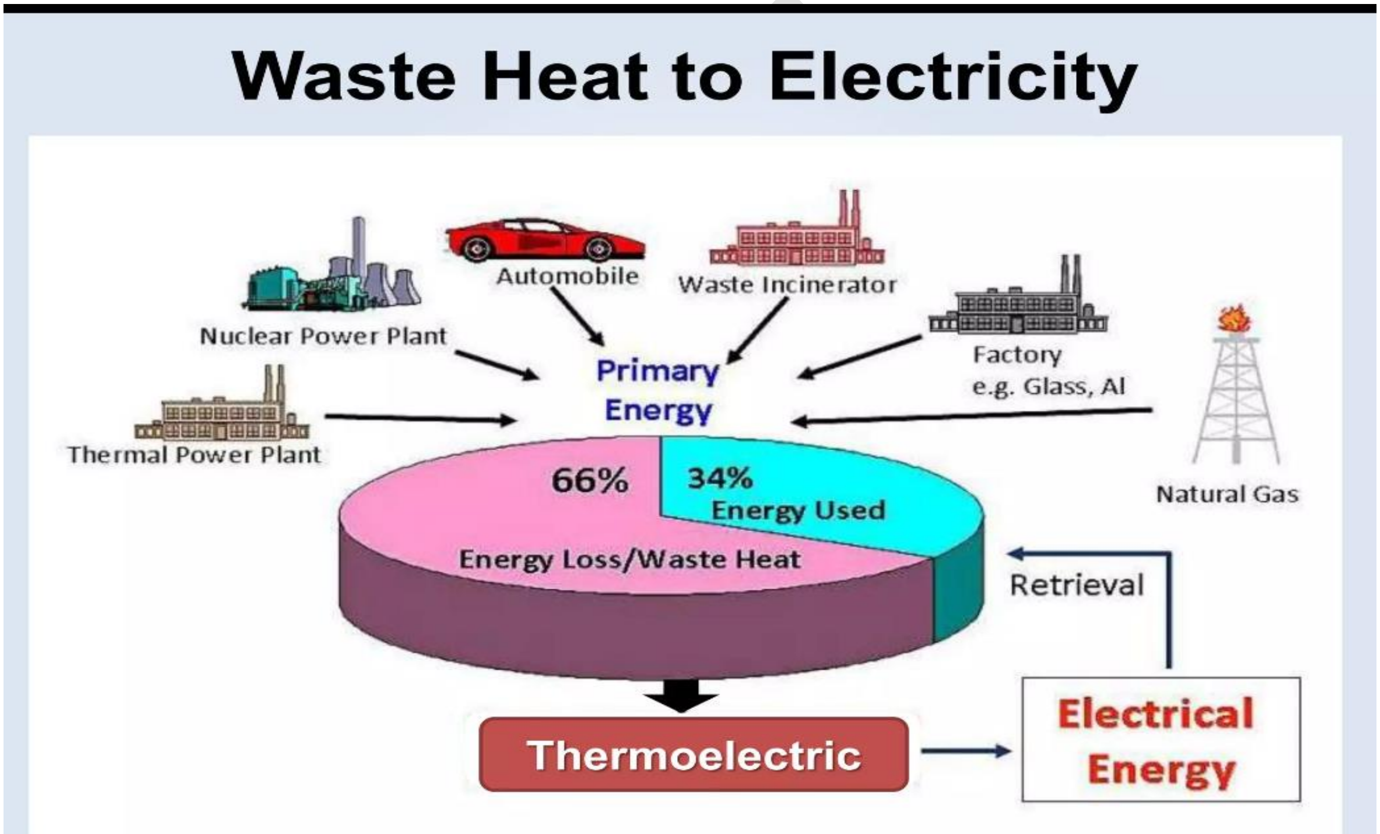
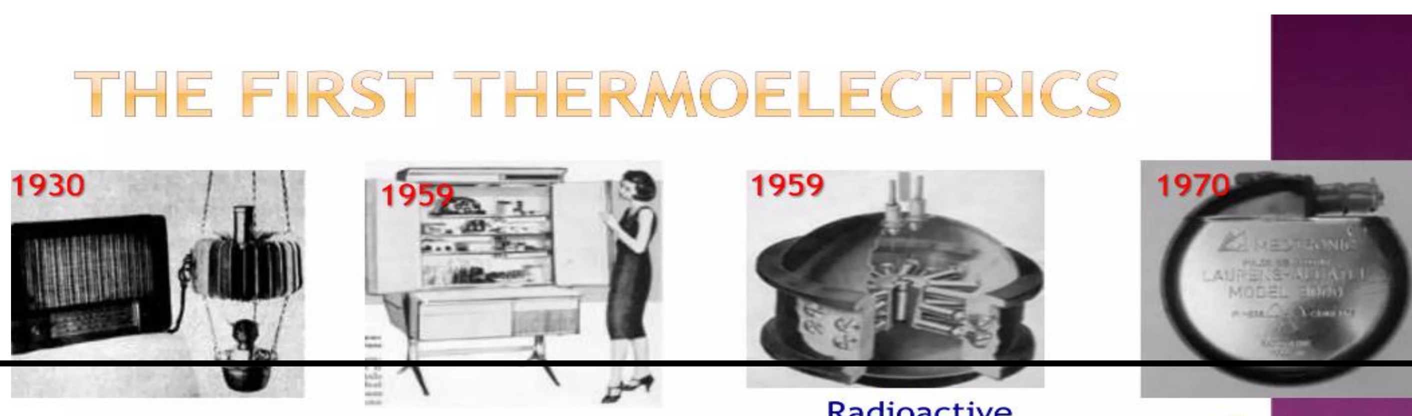
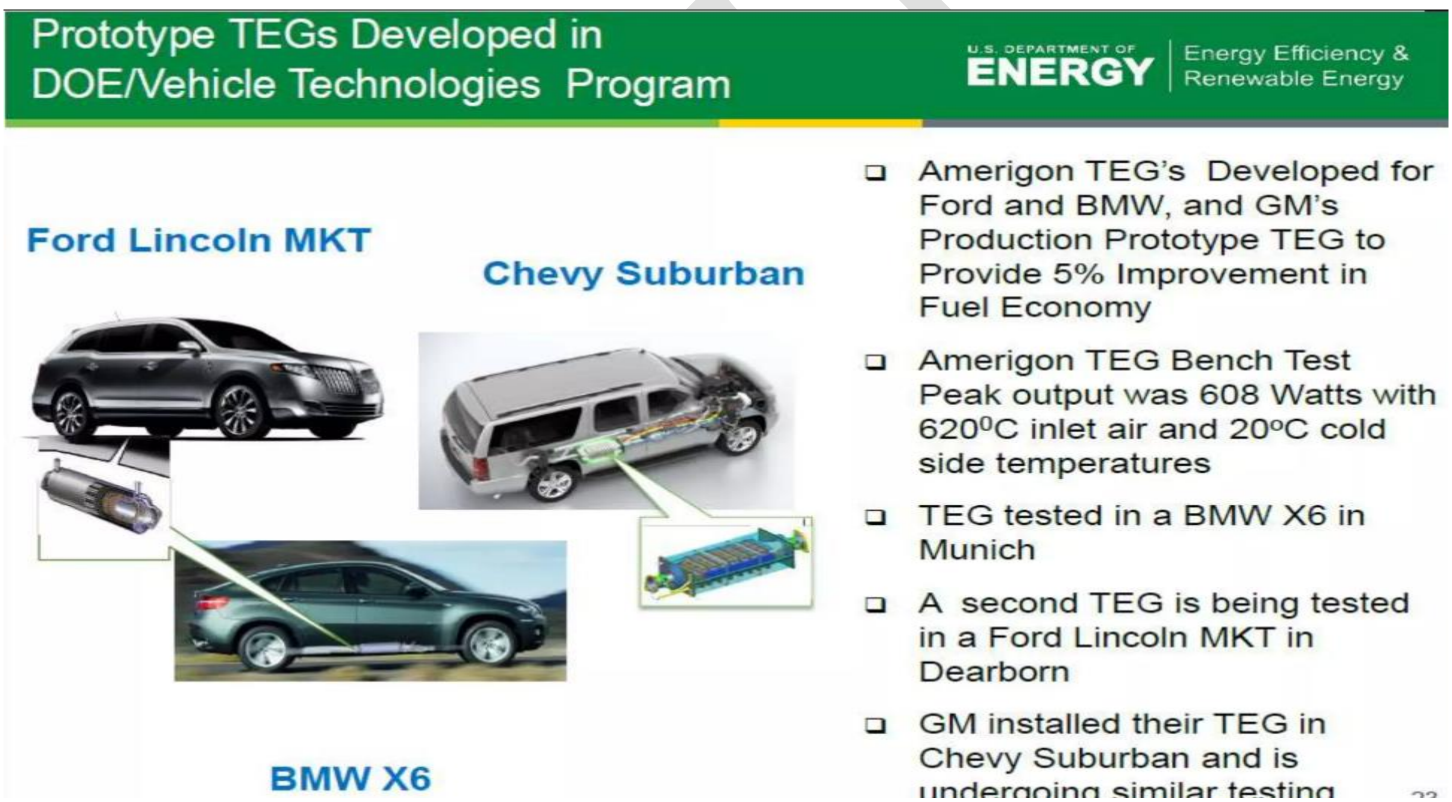
# Module-3

## Thermoelectric materials and devices:

**Syllabus:** Thermo emf and thermo current, Seeback effect, Peltier effect, Seeback and Peltier coefficients, figure of merit (Mention Expression), laws of thermoelectricity. Expression for thermo emf in terms of T1 and T2, Thermo couples, thermopile, Construction and Working of Thermoelectric generators (TEG) and Thermoelectric coolers (TEC), low, mid and high temperature thermoelectric materials, Applications: Exhaust of Automobiles, Refrigerator, Space Program (RTG), Numerical Problems



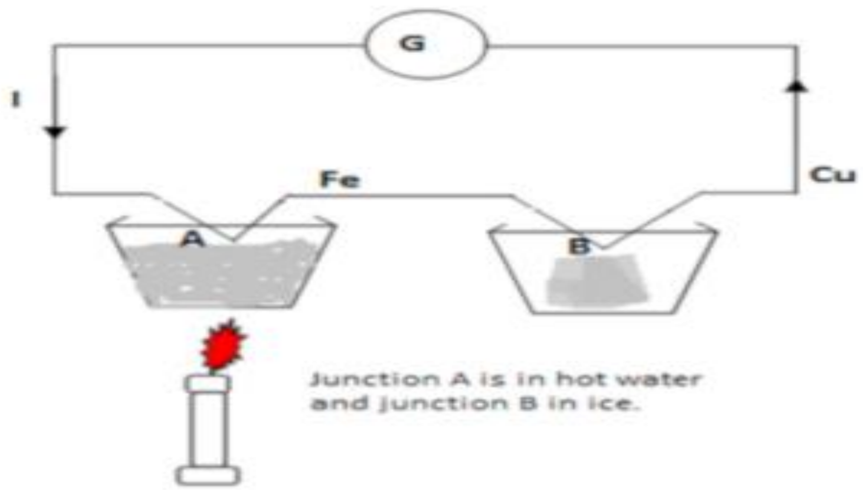






**Thermo EMF and Thermo Current:**

When two dissimilar metals are joined at their ends to form two junctions and if these two junctions are maintained at two different temperatures a current is found to flow in the closed circuit and hence emf is produced.

The emf is called as Thermo Emf and current is known as Thermo Current. Thermo emf is generated due to the thermal gradient.

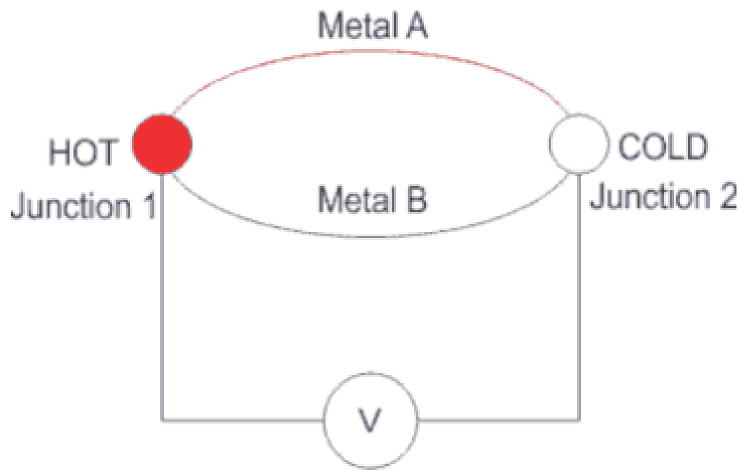



Consider two junctions formed between two metals Fe and Cu as in the figure. One junction is kept in hot water and the other in ice. Thus, Thermo current flows through the circuit indicated by the deflection in the galvanometer. The flow of Thermo current indicates the existence of Thermo Emf. The pair of metals forming the circuit is called a Thermocouple.

**Seebeck Effect and Seebeck Coefficient**

Seebeck Effect Seebeck Effect was discovered in the year 1821 by a German Physicist Thomas Johann Seebeck.

The Seebeck effect is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances (Fig)The voltage (Thermo electric emf) created is of the order of several micro volts per kelvin difference. If the circuit forms a closed loop, then Thermo-current flows through the circuit.




The Thermo EMF developed is directly proportional to the difference in the temperatures of cold and hot junctions.

$$\boldsymbol{V = \alpha\,(T_2 - T_1)}$$

$$\boldsymbol{\alpha = \alpha_B - \alpha_A}$$

here $\alpha_A$ and $\alpha_B$ are Seebeck Coefficients of Metal A and Metal B and $T_1$ and $T_2$ are the temperatures of cold and hot Junctions.

The magnitude and direction of thermometric current depends on the types of metals used and the temperature between the hot and cold ends.

**Seebeck Coefficient:** The Seebeck coefficient is a property that measures the magnitude of voltage generated per unit temperature difference for a given material. It is defined as the ratio of open circuit potential difference generated ($\Delta V$) to the difference in temperature between the junctions ($\Delta T$).

$$\boldsymbol{\alpha = -\frac{\Delta V}{\Delta T}}$$

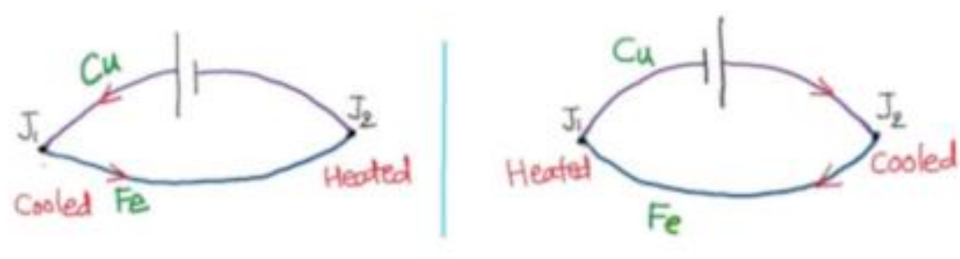
$\alpha$ defines the efficiency of thermometric material.

**Peltier Effect:**

It was discovered by Jean-Charles-Athanase Peltier in the year 1834 Peltier. If electric current passed in a circuit consisting of two dissimilar metals, heat is evolved at one junction and absorbed at the other junction. This is known as Peltier effect.

It is the inverse of the Seebeck effect. There is heat absorption or generation at the junctions depending on the direction of current flow.

The Peltier effect depicts the transformation of electrical energy into heat energy. The heating and cooling effect depends on the direction of flow of current and is as shown in the figure



Peltier effect

The Peltier coefficient is defined as the amount of heat energy absorbed or evolved at the junction of two dissimilar metals when one ampere of current flows through it for one second. It is denoted by $\pi$ and expressed in volts. It is a property that depends on both the materials of the junction

Heat absorbed in one second = $\pi_{ab}\ I$

Heat absorbed in 't' Seconds = $H = \pi_{ab}\ It = \pi_{ab}q$

The junction emf $\pi ab$, is known as Peltier coefficient and is given by

$$\boldsymbol{\pi_{ab} = \frac{H}{It}}$$

**Thermo-electric power:**

The rate of change of emf with temperature is called Thermo-electric power and is denoted by P.

$$P = de/dT$$

Relation between Peltier coefficient and Thermo-electric power is given by $\pi = TP$ , here T is the temperature of the junction and P is the thermometric power at that temperature.

**Figure of Merit**:

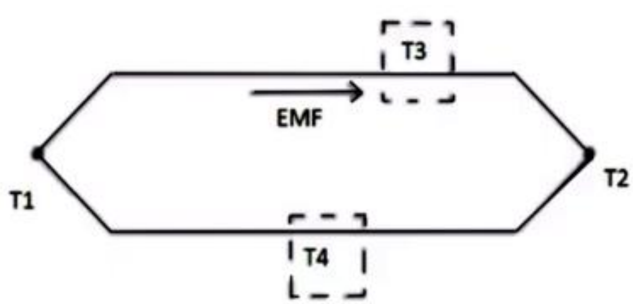
The usefulness of a material in Thermo-electric systems is determined by the device efficiency. This is determined by the material's electrical conductivity ($\sigma$), thermal conductivity ($\kappa$), and Seebeck coefficient ($\alpha$), which change with temperature ($T$). The maximum efficiency of the energy conversion process (for both power generation and cooling) at a given temperature point in the material is determined by the figure of merit $zT$ of Thermo-electric materials.

$$zT = \frac{\alpha^2 \sigma}{\kappa} T$$

**Laws of Thermo-electricity:**

**1.Law of homogeneous circuits Statement:**

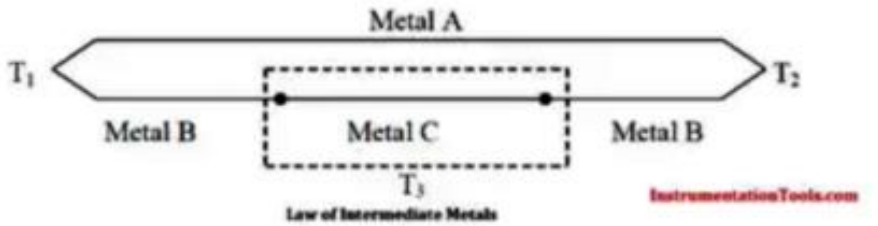
A Thermo-electric current cannot be sustained in a circuit of single homogeneous material by the application of heat alone. The thermal emf produced by two thermocouples at $T_1$ and $T_2$ is independent of and unaffected by any temperature variation down the wires.



**Practical significance:** Two different materials are required for any thermocouple circuit to produce thermo emf.

**2.Law of intermediate metals Statement:**

A third metal may be inserted into a thermocouple system without effecting the emf generated, if and only if, the junctions with the third metal are kept at the same temperature.

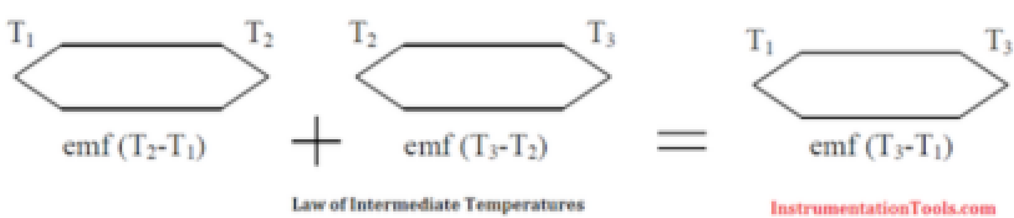



**Practical Significance**:

It allows the use of extension wires of metal for measuring instruments and soldering different from the metal used to form Thermocouple.

**Law of intermediate temperature Statement:**

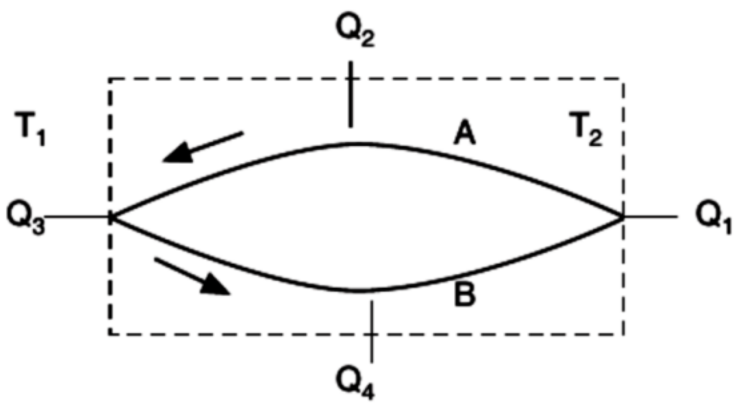
The sum of the EMFs developed by a thermo couple with its junctions at temperatures $T_1$ and $T_2$, and with its junctions at temperatures $T_2$ and $T_3$, will be the same as the EMF developed if the thermocouple junctions are at temperatures $T_1$ and $T_3$.



**Practical significance:** Referring to the figure, this law is useful in practice because it helps in giving a suitable correction in case of a reference junction temperature other than 0 °C is employed.

## Expression for Thermo EMF in terms of Temperature of Cold ($T_1$) and Hot ($T2$) Junctions

Consider circuit of two dissimilar metals $A$ and $B$ with two junctions. Let $T_1K$ and $T_2K$ be the temperatures of cold and hot junctions. The electric current flows in the circuit due to Seebeck effect. Due to the flow of electric current through hot and cold junctions the Peltier effect will be in action which results in the absorption of heat by Hot junction and loss of heat at the cold junction. Let $\pi_1$ and $\pi_2$ be the Peltier coefficients at cold and hot junctions.




Thus $Q=\pi_1 q$ is the heat evolved at cold junction $Q' = \pi_2 q$ is the heat absorbed at hot junction. The total energy (PD) used in driving the current through the circuit is given by $(\pi_2 - \pi_1)q$. Since the Peltier coefficient represents voltage the Thermo EMF is given by

$e = \pi_2 - \pi_1$

Considering the process as similar to the Carnot's engine, hot junction representing the source and cold junction representing the sink and by the definition of Peltier coefficients we can write

$$\frac{\pi_1 q}{T_1} = \frac{\pi_2 q}{T_2}$$

$$\frac{\pi_1}{T_1} = \frac{\pi_2}{T_2}$$

$$\frac{\pi_1}{\pi_2} = \frac{T_1}{T_2}$$

$$\frac{\pi_2}{\pi_1} = \frac{T_2}{T_1}$$

$$\frac{\pi_2}{\pi_1} - 1 = \frac{T_2}{T_1} - 1$$

$$\frac{\pi_2 - \pi_1}{\pi_1} = \frac{T_2 - T_1}{T_1}$$

$$\pi_2 - \pi_1 = \frac{\pi_1}{T_1}(T_2 - T_1)$$

Thus the expression for Thermo EMF in terms of $T_1$ and $T_2$ is given by

$$e = \frac{\pi_1}{T_1}(T_2 - T_1)$$

If the temperature of the cold junction $T_1$ is constant then the Peltier coefficient $\pi_1$ is also constant and hence

$$e \propto (T_2 - T_1)$$

**Thermo-couple and Thermopile**

**Thermocouple:**

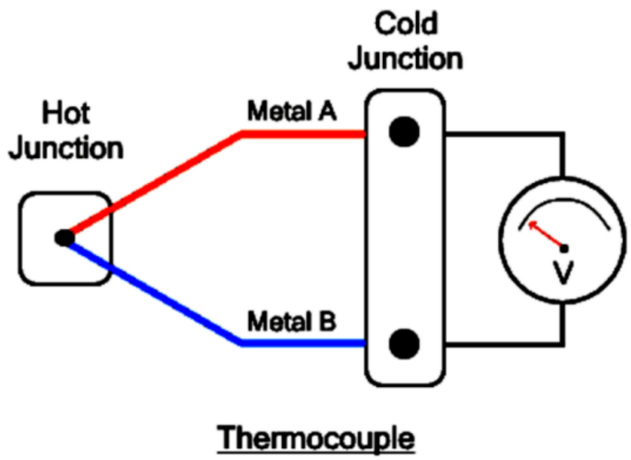
**Principle:** It is based on the principle of Seebeck effect.

A thermocouple is a transducer that converts thermal energy into electrical energy. It is used to measure unknown temperature.

**Construction:**

Thermo-couple is constructed by joining wires made from dissimilar metals to form a junction.

Voltage is produced when the temperature at the junction changes. And is used to measure Thermo EMF




https://youtu.be/mNoI62URtAk

**Working** - Measurement of Temperature :

First the thermocouple is calibrated by studying the variation of Thermo EMF as a function of the temperature of HOT junction keeping the temperature of cold junction constant, say 0°C.

A graph of Thermo EMF Vs Temperature of Hot junction is plotted This graph is known as the calibration graph.

Next, the hot junction is placed in a bath of unknown temperature and the EMF developed in the thermocouple is noted.

The temperature corresponding to this EMF is read from the calibration graph.

Advantages

1. It is an active transducer i.e., it operates without any external power source.
2. Measurement of wide ranges of temperature from - 200°C to 2800°C.
3. The response time is fast, which can measure fast changing temperatures.

4. The cost of thermocouples is low compared to thermistors.

**Disadvantages**

1. The output voltage produced is low.
2. The stray magnetic field can introduce errors in output voltage. Accuracy is low

**Thermo-pile**

Description: A thermopile is an electronic device that converts thermal energy into electrical energy.

It is composed of several thermocouples connected usually in series or less commonly in parallel.

The output voltage of a single Thermo electric cell is extremely small.

So a number of these cells is connected in series/parallel to get a larger signal output.

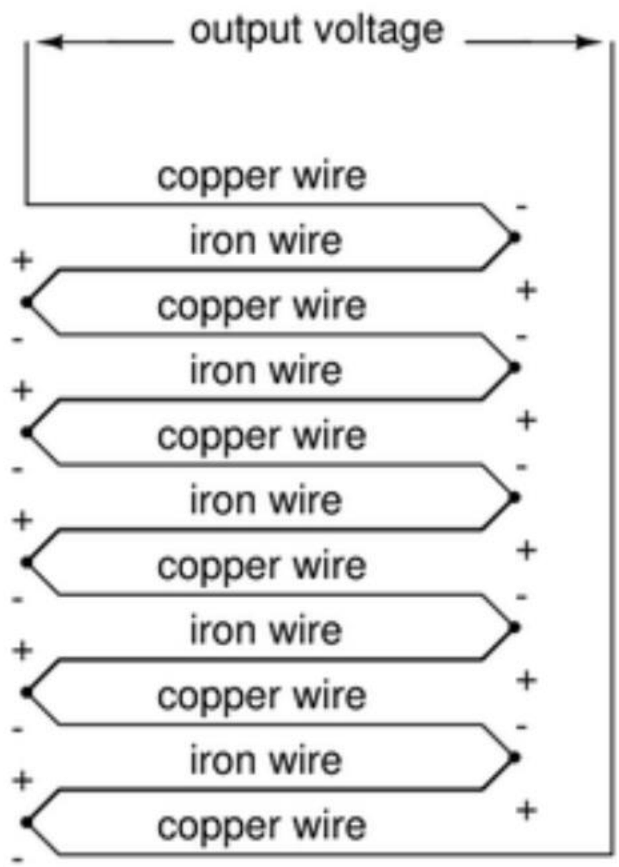
The arrangement of this thermocouple stack is called “thermopile”.

A thermopile includes a series of thermocouples where each includes two special materials with large thermo electric power and reverse polarities which are interconnected in series.

**Working:** These thermocouples are arranged throughout the cold and hot areas and the hot junctions are isolated thermally from the cold junctions.

In reply to the temperature variation across the material, the output voltage of the thermopile is called a Seebeck coefficient or thermoelectric coefficient.

So, it is measured per kelvin (V/K) otherwise $mV/K$ in volts.




https://youtu.be/Fo8aSxLj6QM

**Advantages**

1. It doesn't need an external power supply.
2. It gives a stable response to radiation which is gone from temperature-measuring bodies.
3. It has stable response characteristics.
4. Thermopile is a non-contact temperature-detecting device that uses IR radiation to transfer heat.
5. These are available in small sizes. It is less costly.
6. It generates larger output voltage because of the usage of several thermocouple devices.

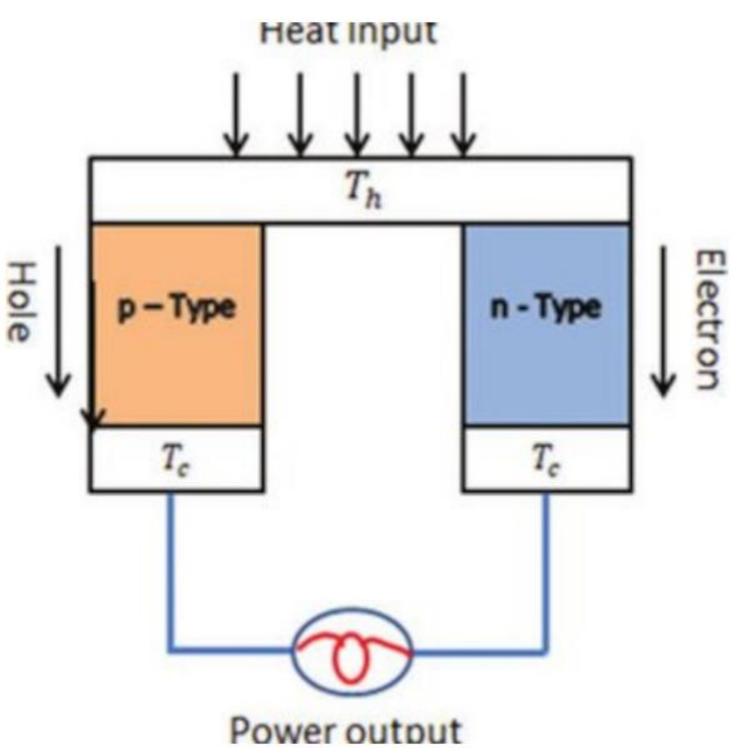
**Disadvantages.**

1. These can be damaged due to stress and reverse the polarity of the supply.
2. These should not be directly exposed to moisture or sunlight because this may harm or will have corrosion on the device's performance.
3. This device should not be operated with dirty or oily fingers because this dust will affect the device's performance.
4. For precise temperature measurement, an object should fill the field of view completely of the thermopile device

**Thermoelectric Generators (TEG)**

**Principle:** Thermoelectric generators are the devices that convert the temperature difference that is generated between the two sections into the electrical form of energy (DC Voltage). When a load is properly connected, electrical current flows.

**Construction:**




- The ... a thermocouple, comp... ected **electrically in series** and **thermally in parallel.**

- The P-type and N-type semiconductors are interconnected through a metal.
- Load is connected to free end of P and N type semiconductors.

**Thermoelectric Generator Working:**

- Heat is pumped into one side of the couple and rejected from the opposite side.
- The electrons present at the hot end would be at a high energy level as compared to electrons present at the cool end side.
- This means that when temperature gradient is produced hot electrons will tend to move towards the cool end and DC voltage is produced. An electrical current is produced, proportional to the temperature.
- An electrical current is produced, proportional to the temperature gradient between the hot and cold junctions.
- Some examples are semiconductors based on bismuth telluride, lead telluride and silicon-germanium alloys are found to be the best.

https://www.youtube.com/watch?v=0jOHce18AXM

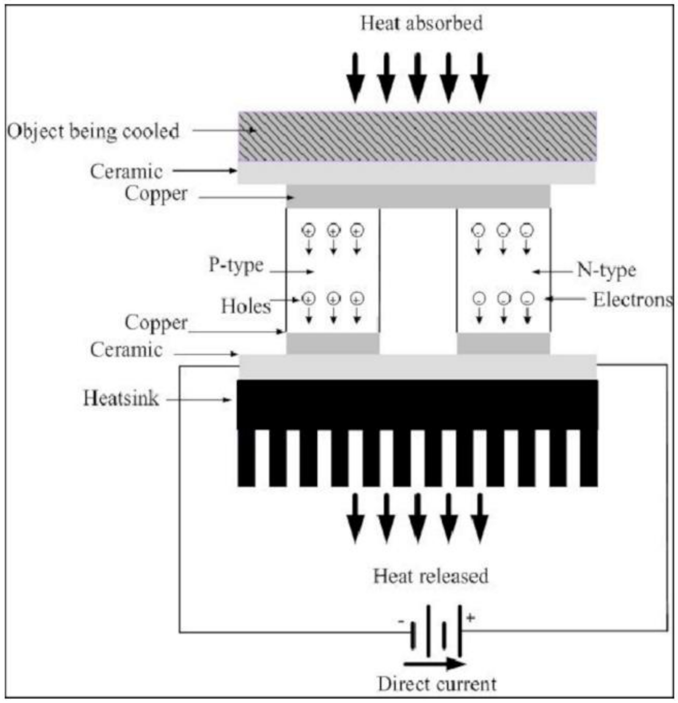
**Applications:**

1. TEGs enhance the fuel performance of cars by converting heat liberated into electricity.
2. Seebeck Power Generation is utilized to provide power for the spacecraft.
3. Thermoelectric generators to implemented provide power for the remote stations such as weather systems, relay networks, and others Typical applications for this technology include providing power for remote telecommunication, navigation, and petroleum installations.

**Thermo-electric Coolers**:

Thermoelectric coolers are solid state heat pump used in applications where temperature stabilization, temperature cycling, or cooling below ambient are required.

**Principle:** The principle used in this is Peltier effect. i.e: 'when electric current passed in a circuit consisting of two dissimilar metals, heat is evolved at one junction and absorbed at the other junction.'




**Construction:**

- It consists of a thermoelectric module, a heat sink and the object to be cooled.
- A typical thermoelectric module consists of an array of bismuth telluride semiconductor pellets that have been "doped" so that one type of charge carrier-either positive or negative carries the majority of current.
- The pairs of P/N pellets are configured so that they are connected electrically in series, but thermally in parallel.
- Metalized ceramic substrates provide the platform for the pellets and the small conductive tabs that connect them, they provide rigidity and the necessary electrical insulation.
- Thermoelectric modules can function singularly, in groups, or as stacked multi-stage modules.

**Working:**

- When DC voltage is applied to the module, the positive and negative charge carriers in the pellet array absorb heat energy from one substrate surface and release it to the substrate at the opposite side.
- The surface where heat energy is absorbed becomes cold the opposite surface where heat energy is released, becomes hot.
- These devices cannot only pump appreciable amount of heat, but with their series electrical connection, are suitable to be used as DC power supplies.

https://www.youtube.com/watch?v=FPFE7i7bz9Y

**Thermo-electric Materials Thermoelectric (TE) materials:**

They have the capability of converting heat into electricity, which can improve fuel efficiency as well as provide a robust alternative energy supply in multiple applications by collecting wasted heat, and therefore assist in finding new energy solutions.

**Classification:** The thermoelectric materials can be classified into the following three categories according to their operating temperature. They are low, mid and high temperature thermometric materials.

**Low and Near Room Temperature Thermoelectric Materials**

| Compound | Temperature range | Figure of merit | Applications |
|---|---|---|---|
| Iron Antimonide | <300K | 0.71 | Peltier cooling |

| | | | |
|---|---|---|---|
| **($FeSb_2$)** | | | applications |
| Bismuth telluride/Antimony Telluride **($Bi_2Te_3/Sb_2Te_3$)** | 300K to 500K | 1.1 to 1.8 | Thermoelectric applications b |

**Mid Temperature Thermoelectric Materials (500 to 800K)**

| Compound | Temperature range | Figure of merit |
|---|---|---|
| Tetrahedrites | Around 723 K | 1.0 |
| Skutterudites (Yb filled $CoSb_{12}$ BCC structre) | Around 800K | 1.1 to 1.35 |

**High Temperature Thermoelectric Materials (> 800K)**

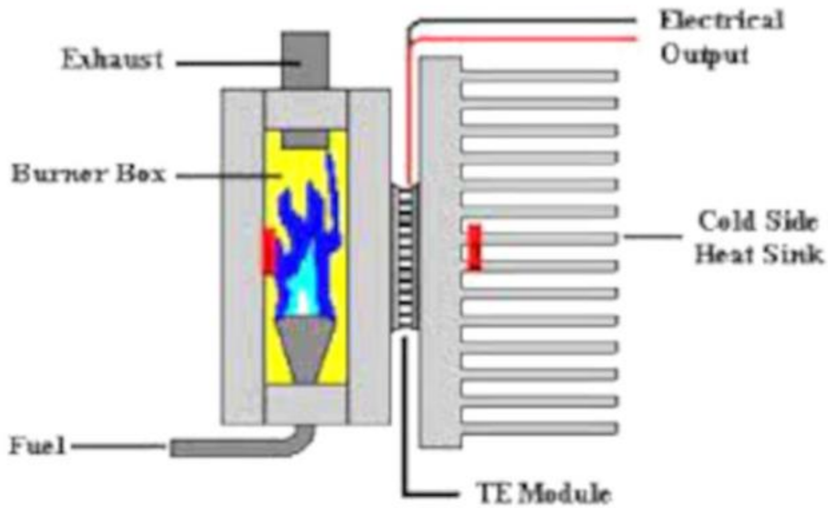


| Compound | Temperature range | Figure of merit | Applications |
|---|---|---|---|
| Lanthanum Telluride (Rare Earth Telluride) $La_{3-x}Te_4$ | 1275 K | 1.2 | TEGs application |
| SiGe alloy **($Si_{1-x}Ge_x$)** | 1200K | 0.7 to 1 | Thermoelectric applications |

**Applications:**

**ATEG:** Automotive Thermo Electric Generator.

Principle: An automotive thermoelectric generator (ATEG) is a device that converts some of the waste heat of an internal combustion engine (IC) into electricity using the Seebeck Effect.




**Construct**

- A typ
  1. A hot-side heat exchanger,
  2. A cold-side heat exchanger,
  3. Thermoelectric materials, and
  4. A compression assembly system.
- In ATEGs, thermoelectric materials made up of p-type and n-type semiconductors are packed between the hot-side and the cold-side heat exchangers.
- Heat exchangers are metal plates with high thermal conductivity.



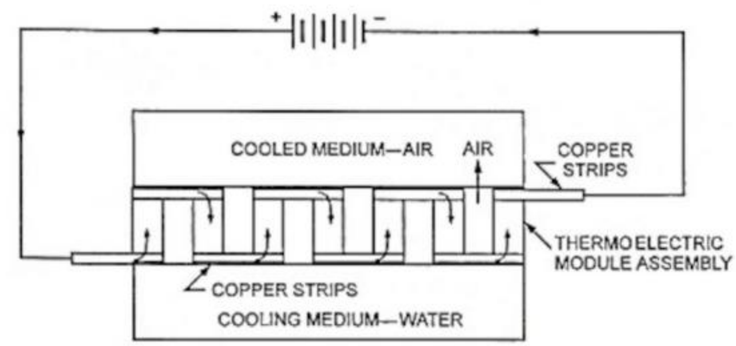
**Working:**

- When hot exhaust from the engine passes through an exhaust ATEG, the charge carriers of the semiconductors within the generator diffuse from the hot-side heat exchanger to the cold-side exchanger.
- The build-up of charge carriers results in a net charge, producing an electrostatic potential while the heat transfer drives a current.
- The temperature difference of several hundred degrees (700°C) is capable of generating 500 to 750W of electricity.

**Thermoelectric Refrigeration:**

**Principle:** Thermoelectric Refrigeration Thermoelectric Refrigeration System works on the principle of Peltier effect according to which heat energy is evolved at one junction and absorbed at the other one when direct current is passed through a junction of two dissimilar metals like antimony and bismuth.

It consists of a number of thermoelectric module assemblies in series joined by copper strips, as shown in figure




**Working:**

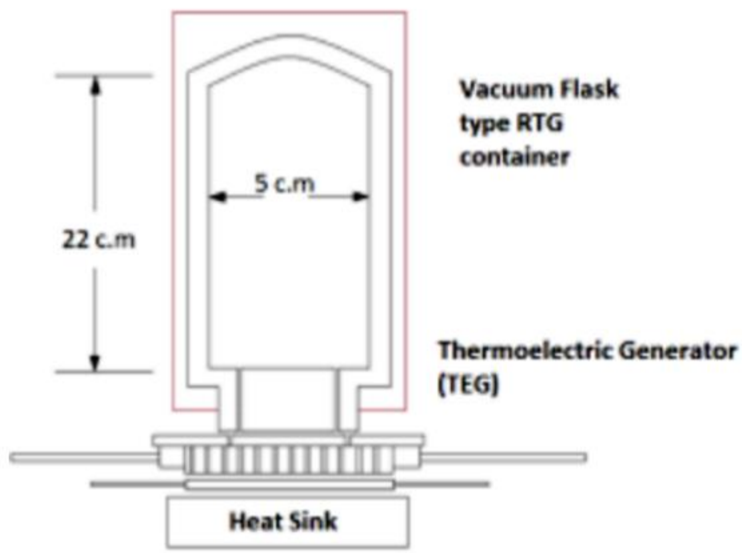
- When the direct current is passed through the thermoelectric module assemblies in the direction shown in figure, junctions at the top of the assembly are cooled and those at the bottom are heated up.
- Thus, top junctions abstract heat from the surroundings and produce refrigerating effect and bottom junctions require cooling by water.
- Module assembly, therefore, abstracts heat from the medium at top and rejects the same to the medium at bottom.

**Advantages:** The main advantages of this thermoelectric refrigeration system are absence of moving parts and ease of automatic control by controlling the magnitude of current.

**Disadvantages:** The only drawback of this system of refrigeration is its very high initial cost.

**Space Program- Radioisotope Thermoelectric Generator(RTG)**

Radioisotope Thermoelectric Generators (RTGs) are lightweight, compact spacecraft power systems that are extraordinarily reliable. RTGs provide electrical power using heat from the natural radioactive decay of plutonium-238, in the form of plutonium dioxide.




- The large difference in temperature between this hot fuel and the cold environment of space is applied across special solid-state metallic junctions called thermocouples, which generates an electrical current using no moving parts.
- The design of an RTG is simple by the standards of nuclear technology: the main component is a sturdy container of a radioactive material (the fuel).
- Thermocouples are placed in the walls of the container, with the outer end of each thermocouple connected to a heat sink.
- Radioactive decay of the fuel produces heat. It is the temperature difference between the fuel and the heat sink that allows the thermocouples to generate electricity

**Model Questions**

1. State and Explain Seebeck Effect and hence define Seebeck coefficient.
2. State and Explain Peltier Effect and hence define peltier coefficient.
3. Discuss the variation of Thermo EMF with respect to temperature.
4. Define neutral temperature and inversion temperature. and hence Deduce the relation between them.
5. Elucidate the laws of Thermo-electricity.
6. Derive an expression for Thermo EMF in terms of temperatures of hot and cold junctions.
7. Explain the principle, construction and working of thermocouple with a neat sketch.
8. Mention the advantages and disadvantages of thermocouples.
9. Mention the need for thermopile and hence describe its construction and working.
10. Enumerate the advantages and disadvantages of thermopile.
11. Discuss the principle construction and working of Thermo Electric Generator.
12. Explain the principle, construction, working and application of thermoelectric coolers.
13. Discuss Low temperature, Moderate temperature and High Temperatures with suitable examples and mention their ZT.
14. Describe the application of thermo electrics in Automobile Thermo Electric Generators.
15. Explain thermoelectric refrigeration.
16. Describe Radioisotope Thermometric Generator and its applications.