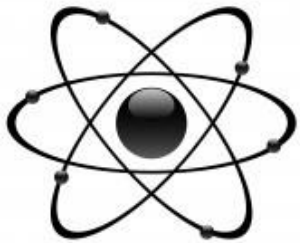


INDUCTION HEATING METHODOLOGY



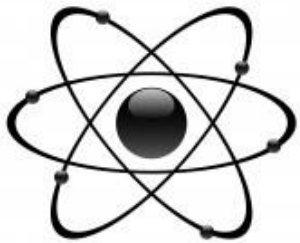
Kushagra Nigam
Bits Pilani K.K. Birla Goa Campus



INTRODUCTION

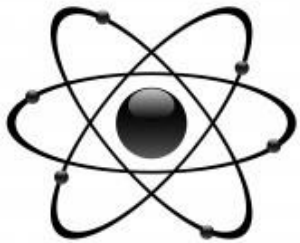
- Electromagnetic induction is a heating technique for electrical conductive materials.
- Applications:-
 - Melting
 - Spherodizing
 - Sintering
 - Heat Treating of Light Metals





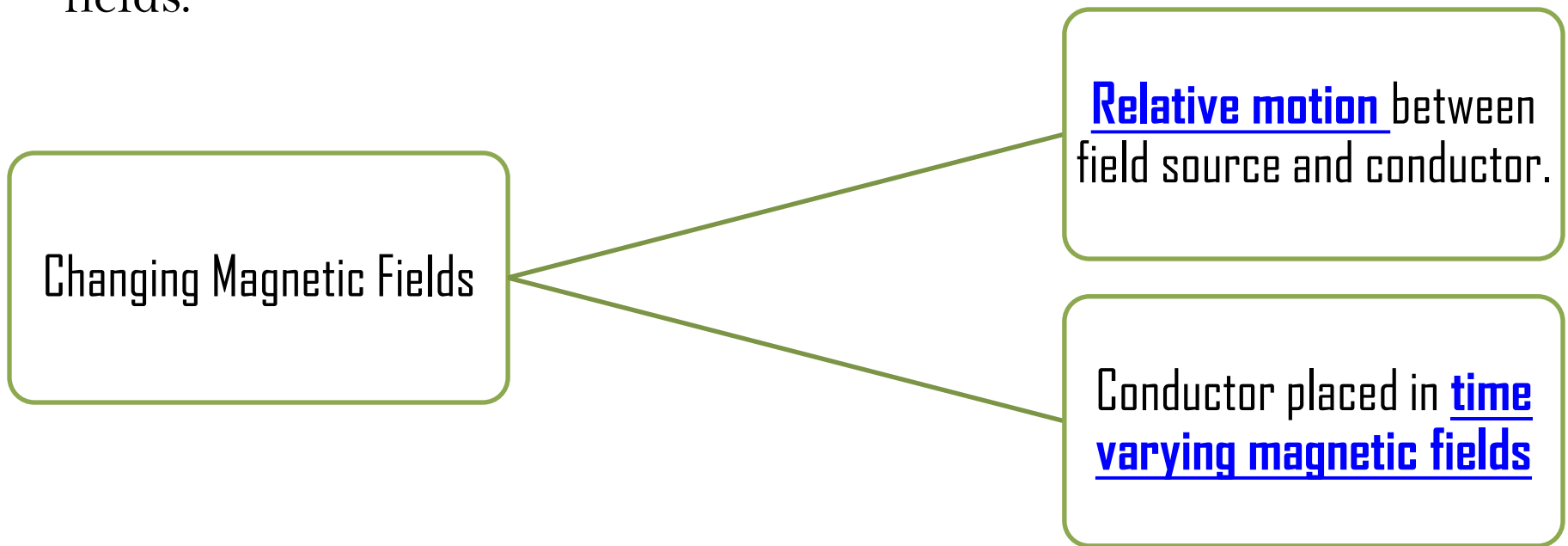
Advantages And Disadvantages

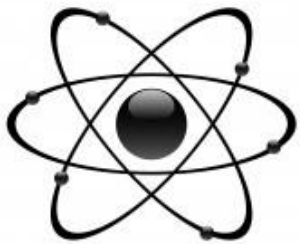
<i>Advantages</i>	<i>Disadvantages</i>
➤ Heat is produced in the material to be heated.	➤ Noise Produced during operation.
➤ Quick Response	➤ Hefty Price Tag
➤ Localized Heating	➤ Complex Power System Design
➤ High Power Density	➤ Poor Efficiency
➤ Eco Friendly	➤ Suitable for components having specific shapes



Basics of Induction Heating

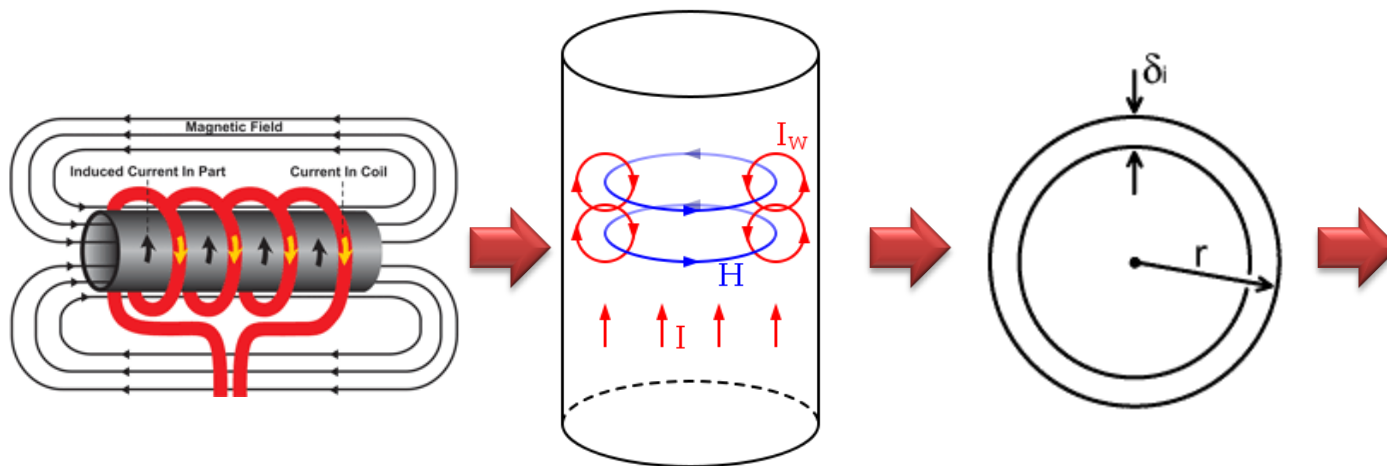
- Governing Phenomenon:- Eddy Currents
- Eddy Currents(Foucault currents):- Currents induced in a conducting material when it is exposed to a changing magnetic fields.

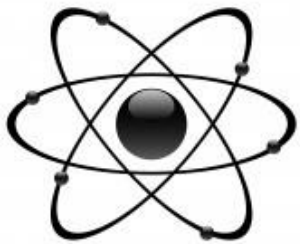




Basics of Induction Heating

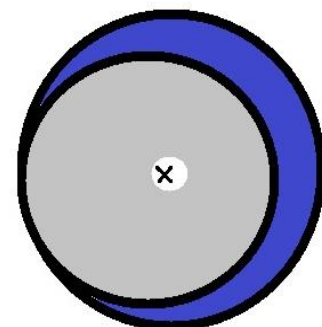
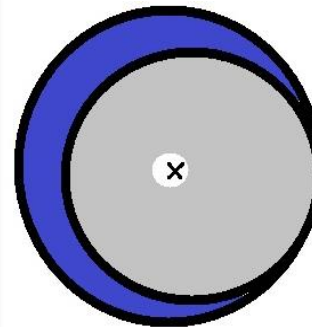
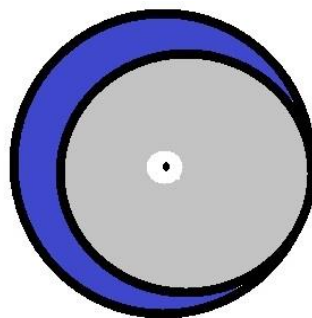
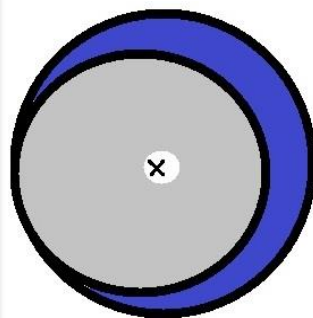
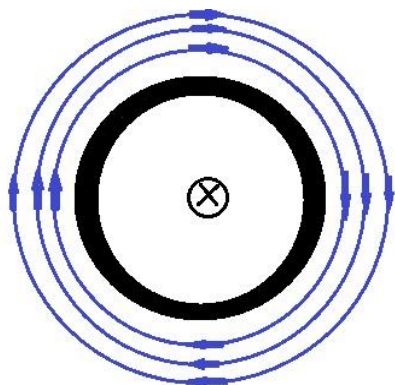
- **Skin Effect Phenomenon:**-Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor.

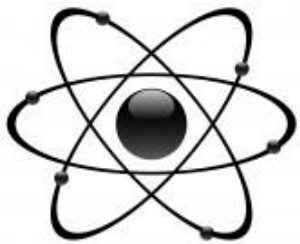




Basics of Induction Heating

- Proximity Effect Phenomenon:- Unlike skin effect that does not take into account the nearby conductors, proximity effect accounts the interfering magnetic fields due to the conductors in close proximity. These interfering magnetic fields result in the distortion of the current and power density of distributions of the original conductor.

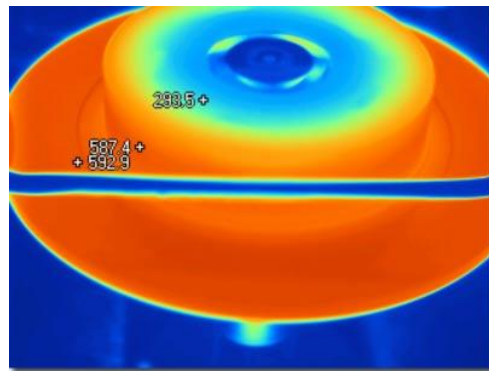
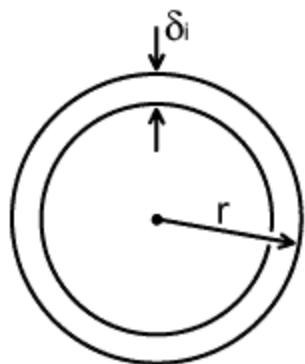


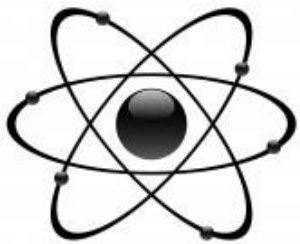


Basics of Induction Heating

➤ **Joule Effect:-** Joule's first law, also known as the *Joule Effect*, is a physical law expressing the relationship between the heat generated by the current flowing through a conductor.

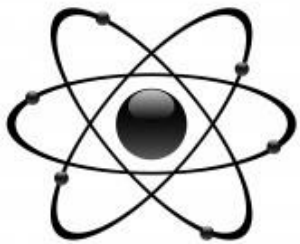
$$Q = I^2 \cdot R \cdot t$$





Governing Equations

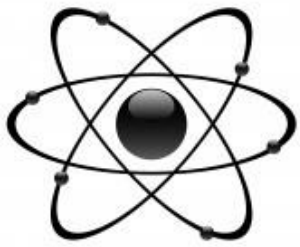
<i>Name</i>	<i>Equation</i>
1) Specific Heat equation	$Q = mC_p(T_2 - T_1)$
2) Law of conservation of energy	$R_{in} + R_{gen} = R_{out} + R_{stor}$
3) Heat transfer equation for cylindrical case	$\alpha \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right] + \frac{q'''}{\rho c_p} = \left[\frac{\partial T}{\partial t} + V_r \frac{\partial T}{\partial r} + \frac{V_\theta}{r} \frac{\partial T}{\partial \theta} + V_z \frac{\partial T}{\partial z} \right]$
4) Fourier's law	$\dot{q} = -kA \frac{\partial t}{\partial n} \hat{n}$
5) Newton's law of cooling	$\dot{q} = hA\Delta T$
6) Stefan's Boltzmann's law	$W = \epsilon\sigma T^4$



Existing Induction Heating System at SOFI

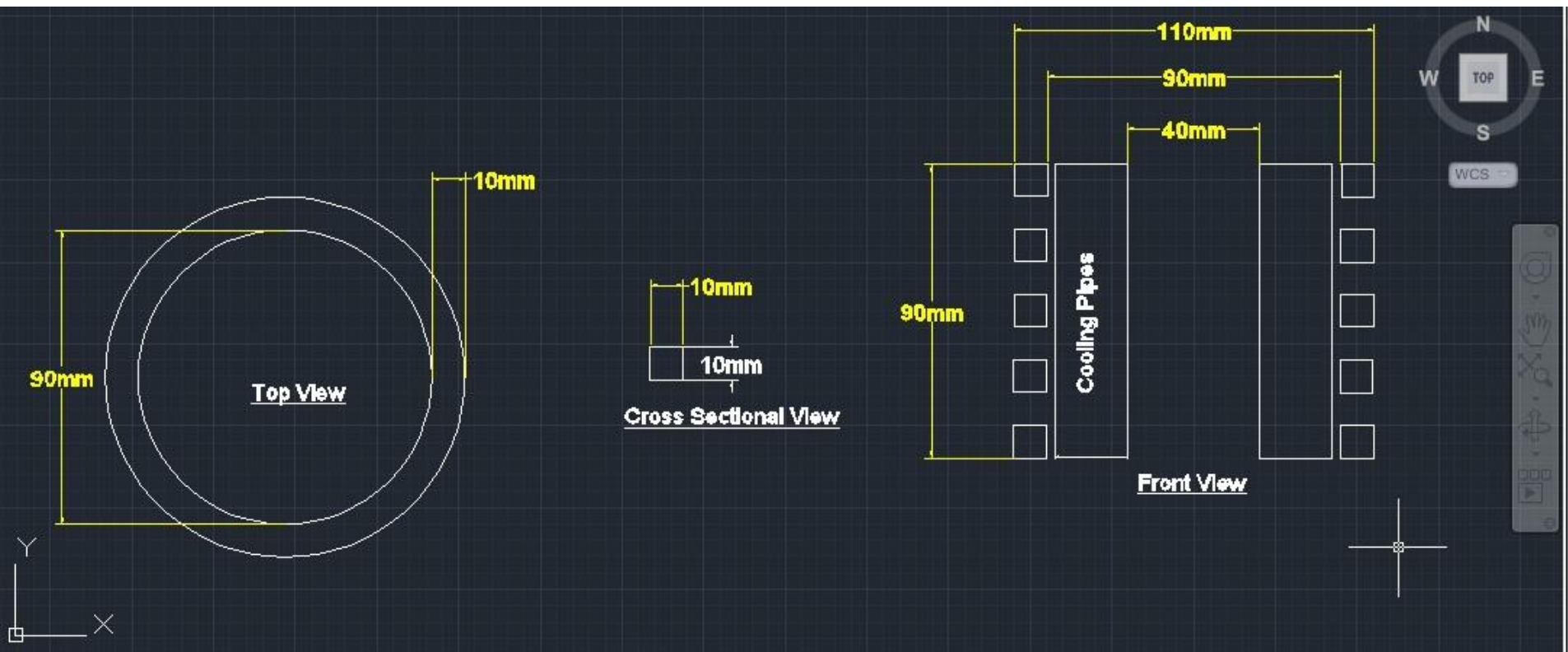
➤ Technical Specifications:- Type: VEL/MF/50 VEL Induction Heater

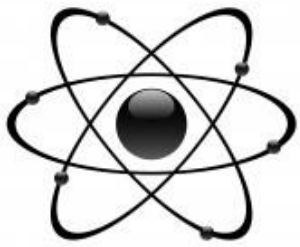
<i>Components</i>	<i>Specifications</i>
Inverter Type	Series Resonant Swept Frequency Inverter
Incoming Voltage	415V/3Ph/50Hz/ 4 Wire
Input Feeder Rating	100 A
Output Power	50 kW
Output Frequency	0-5 kHz
Output Voltage	0-400 V
Output Current	100 A
Type of Cooling	Water Cooled



Existing Induction Heating System at SOFI

➤ Coil Specifications:-

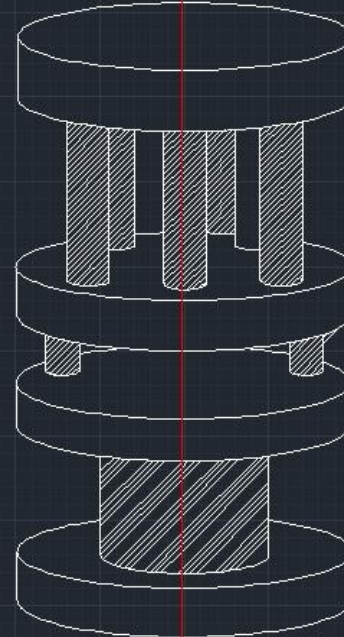
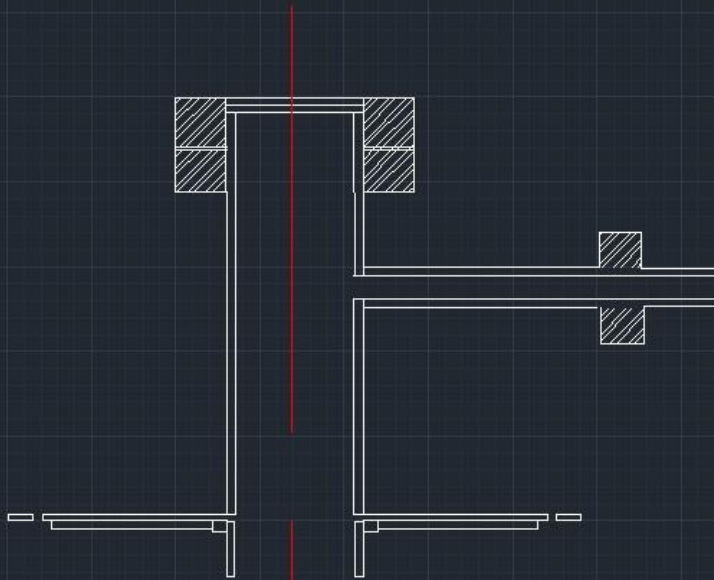


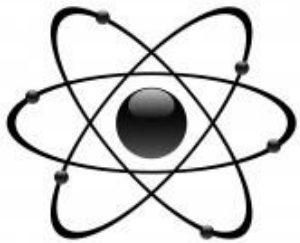


Existing Induction Heating System at SOFI

➤ Crucible Designs:-

[-] [Top] [2D Wireframe]

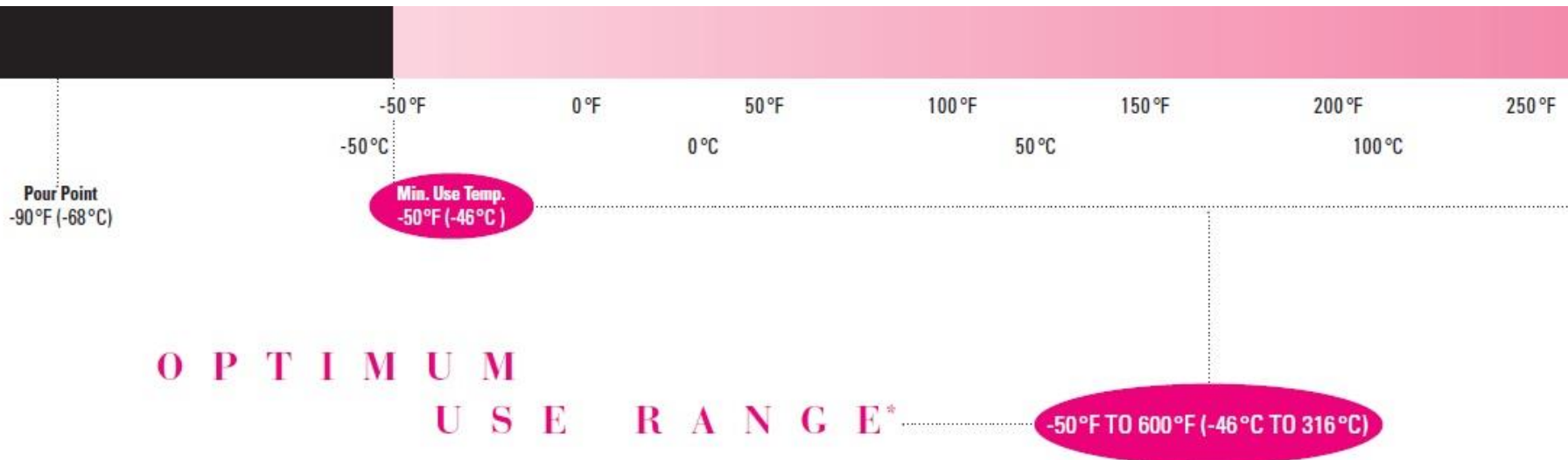


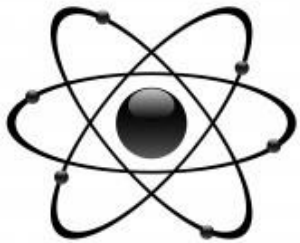


Existing Induction Heating System at SOFI

➤ Coolant used:- Therminol-59

Therminol® 59 is a synthetic, liquid phase heat transfer fluid with excellent low-temperature pumping characteristics (pumpable at -56°F), yet thermally stable to allow 600°F bulk temperature use. Therminol 59 is ideally suited for both heating and cooling applications between -50°F and 600°F .

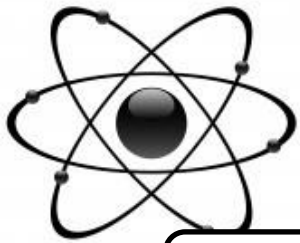




Why to use Cylindrical Geometry??

➤ Advantages:-

- 1) Low surface area to volume ratio relative to other geometries - Reduced Heat Losses
- 2) Simplified calculations as it matches the geometry of inductor coil hence facilitates extensive theoretical work.
- 3) Easy Fabrication.



Safety Measures

Leak Tight Steel Enclosure for crucible and coil.

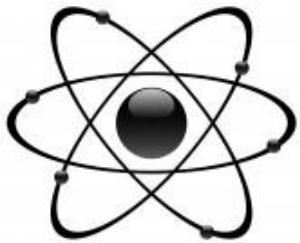
Draining System for collecting oil in sump during accident

Inert Gas is circulated in crucible to prevent fire during leakage and filtered through [HEPA](#) before being sent to exhaust.

Separate enclosure for piping process to avoid oil spillage in vicinity .

Thermocouple and smoke detectors are provided at critical locations to monitor temp. and feedback purposes

Fire extinguishers are installed for quick mitigation.



Calculations and Derivations

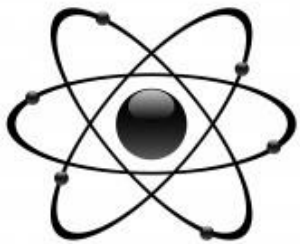
INDEX

1) [*Skin Depth Formula Derivation*](#)

2) [*Efficiency Derivation*](#)

3) [*Heat Absorbed By Cooling System*](#)

[*BACK*](#)

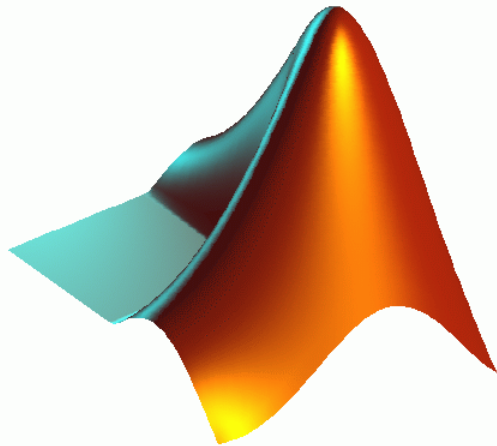


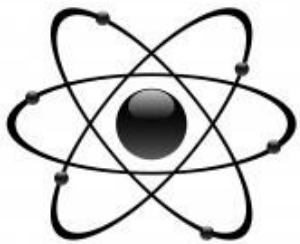
Development of Simple Program

➤ Software Specifications:-

Platforms Used: Python 2.7.2, Matlab

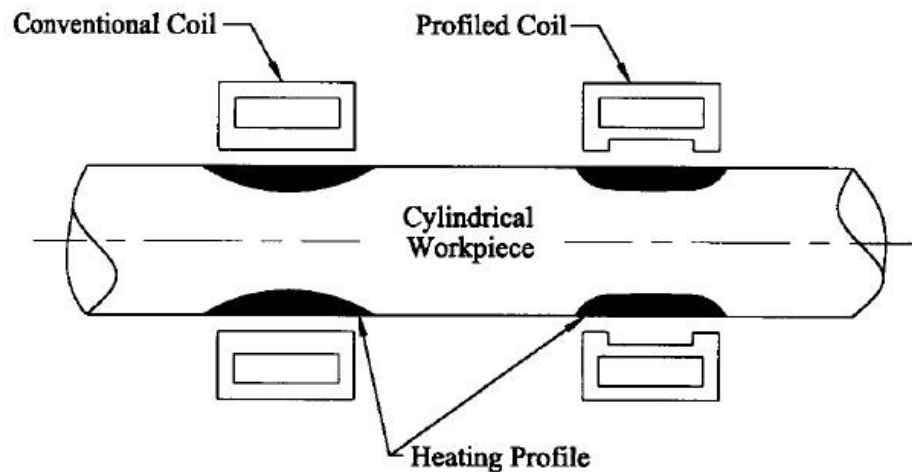
Supporting Python Libraries: Matplotlib, Py2exe, Pygame, Vpython, Numpy



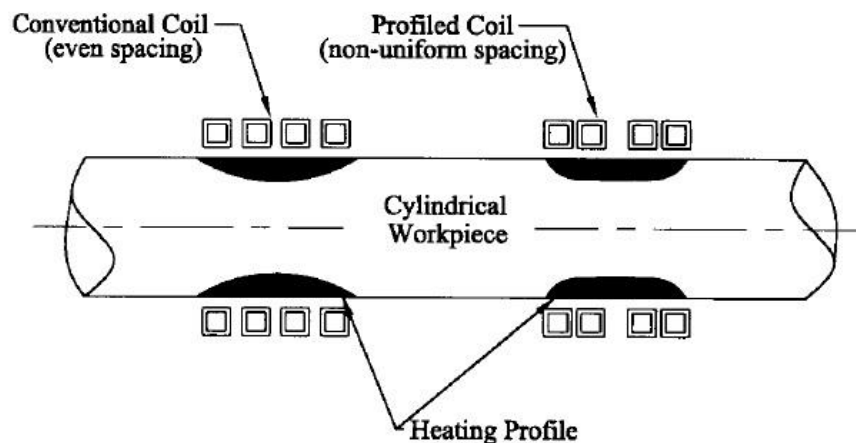


Suggested Improvements in the existing design

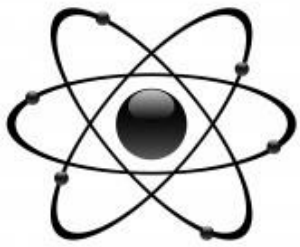
➤ Coil Design:-



Coil With Barrel Shape



Coil With Gaps

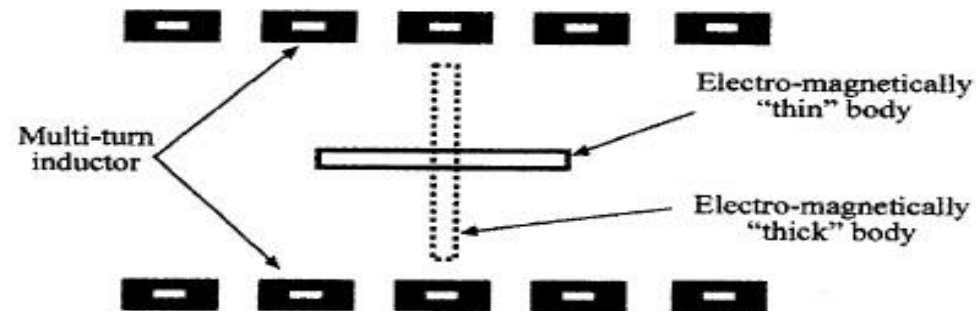
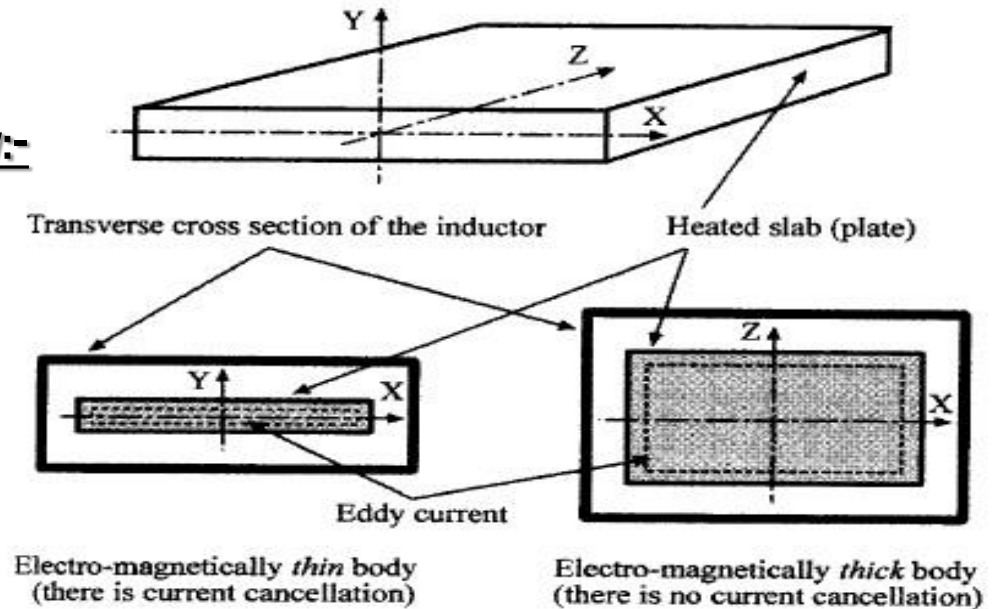


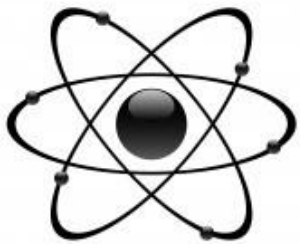
Suggested Improvements in the existing design

➤ Work Orientation:-

Advantages of electromagnetically "thick" body:-

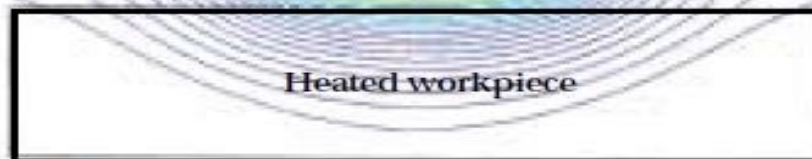
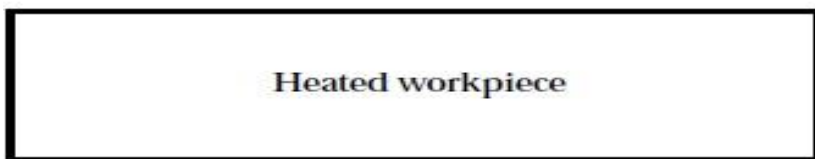
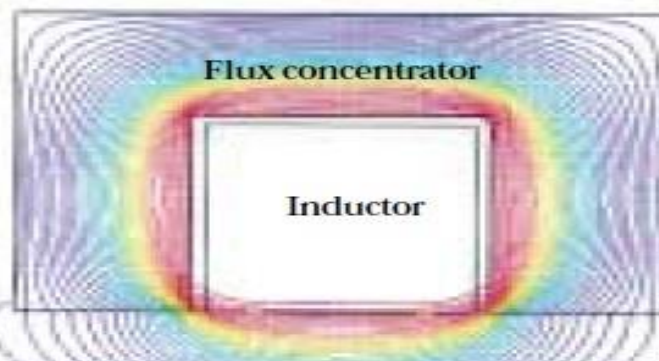
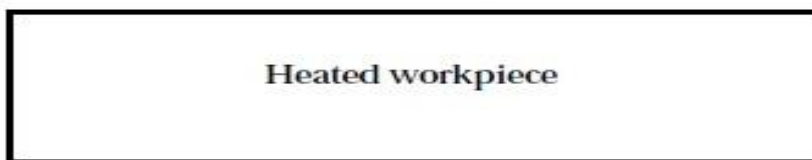
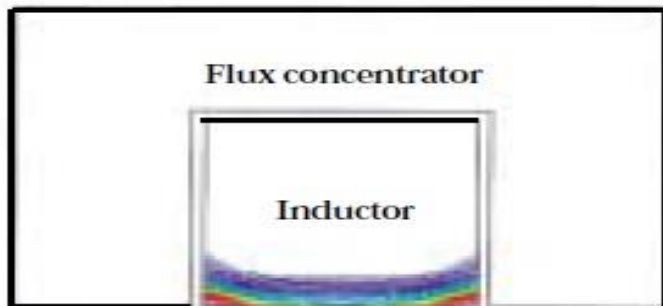
- 1) High flux linkage
- 2) Low heat losses
- 3) Reduced Edge Effects
- 4) Uniform heating profile.

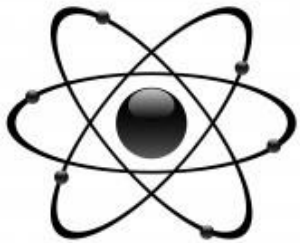




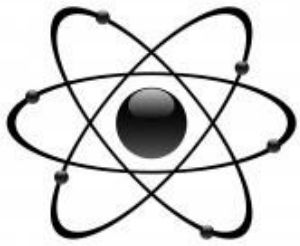
Suggested Improvements in the existing design

➤ Use of Flux Concentrators:-

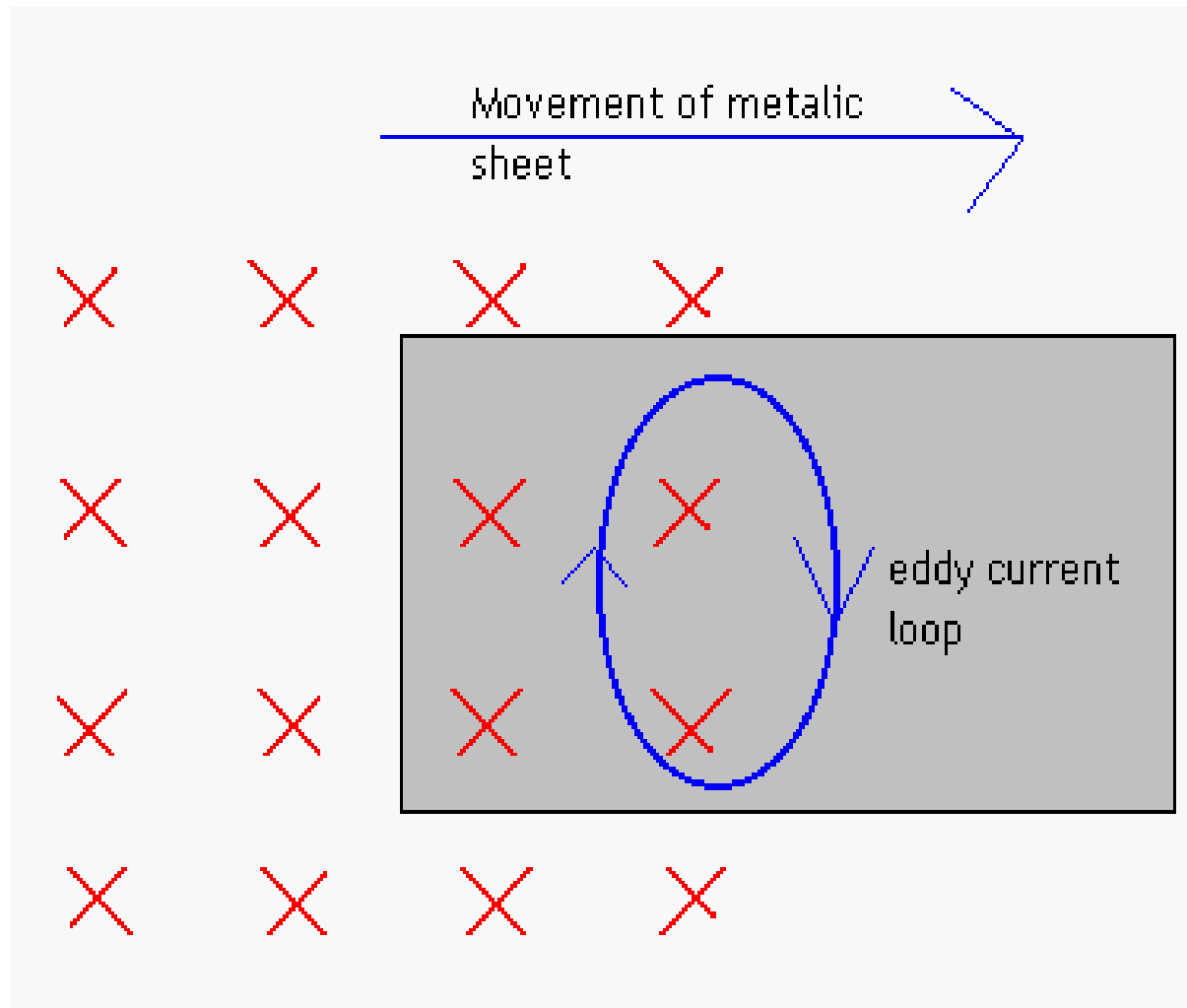
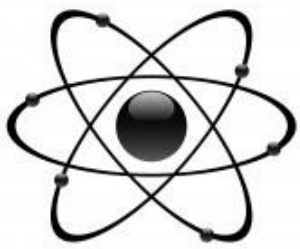




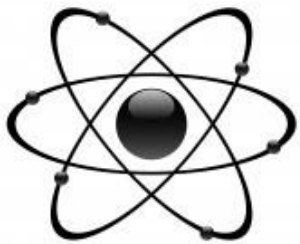
Thank You



Backup slides

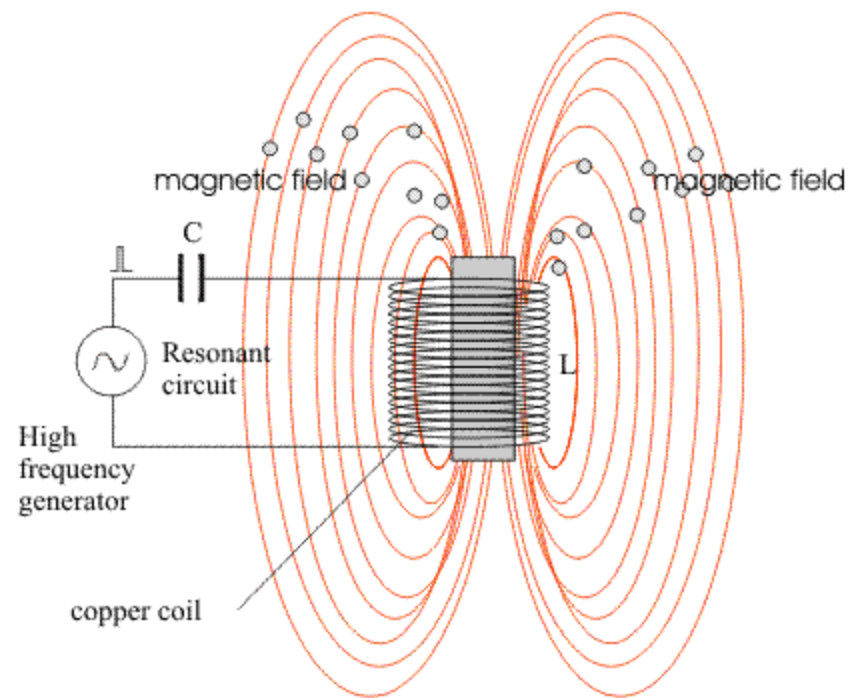


[BACK](#)

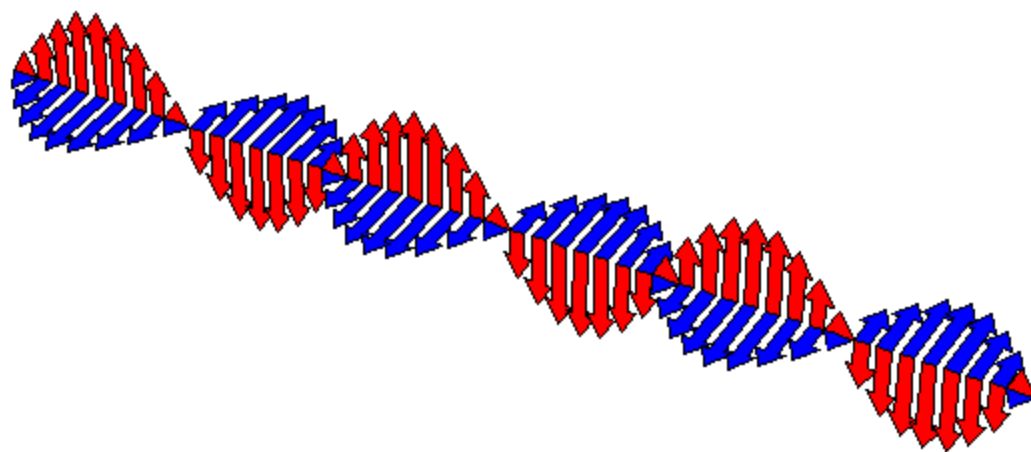
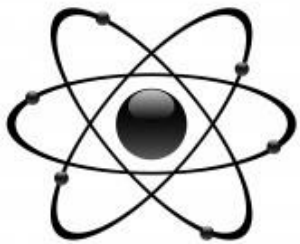


Induction Heating

Metallic bar placed in the copper coil is rapidly heated to high temperatures by induced currents from the highly concentrated magnetic field.



[BACK](#)



BACK

Derivation of Skin Depth Formula:-

Say a medium has:

- 1) Conductivity : σ
- 2) Permittivity : ϵ
- 3) Permeability : μ

And an electromagnetic field exists such that

$$\vec{B} = C e^{j\omega t} \quad - (1)$$

$$\vec{E} = D e^{j\omega t} \quad - (2)$$

Using Maxwell's equations

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad - (3)$$

$$\nabla \times \vec{H} = [J + \frac{\partial \vec{D}}{\partial t}] \quad - (4)$$

We Have,

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} \quad - (5)$$

$$\nabla \times \vec{H} = (\sigma + j\epsilon\omega)\vec{E} \quad - (6)$$

Now

$$\nabla \times (\nabla \times \vec{E}) = -j\omega\mu(\nabla \times \vec{H}) \quad - (7)$$

Using,

$$\nabla \times (\nabla \times \vec{E}) = \nabla(\nabla \cdot \vec{E}) - \nabla^2 \vec{E} \quad - (8)$$

From (6)

$$\vec{E} = \frac{\nabla \times \vec{H}}{\sigma + j\epsilon\omega}$$

$$\Rightarrow \nabla \cdot \vec{E} = \frac{\nabla \cdot (\nabla \times \vec{H})}{\sigma + j\epsilon\omega}$$

Since, divergence of curl is 0

$$\Rightarrow \nabla \cdot \vec{E} = 0$$

Now we are left with laplacian of electric field in equation (8)

Hence, from equation (7) and (8)

Maxwell's Equation:

- 1) $\nabla \cdot D = \rho$
- 2) $\nabla \cdot B = 0$
- 3) $\nabla \times E = -\frac{\partial B}{\partial t}$
- 4) $\nabla \times B = \mu_0 [J + \frac{\partial D}{\partial t}]$

Where,

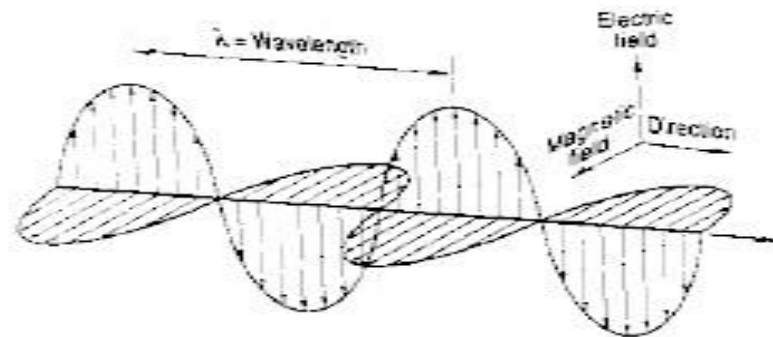
D= Electric Displacement field

B= Magnetic Field

E=Electric Field

J=Current Density

P=Charge Density



[BACK](#)

Hence, from equation (7) and (8)

$$\nabla^2 \vec{E} = j\omega\mu(\nabla \times \vec{H}) \quad - (9)$$

$$\Rightarrow \nabla^2 \vec{E} = j\omega\mu(\sigma + j\epsilon\omega)\vec{E} \quad - (10)$$

Say,

$$\gamma^2 = j\omega\mu[\sigma + j\epsilon\omega] \quad - (11)$$

$$\Rightarrow \nabla^2 \vec{E} = \gamma^2 \vec{E} \quad - (12)$$

Let's forget about the time part and concentrate on the space part i.e. amplitude,

Say, electric field is in z direction and is dependent only on x-coordinate

$$\Rightarrow \vec{E} = \vec{E}_z(x)\hat{k} \quad - (13)$$

$$\nabla^2 \vec{E} = \gamma^2 \vec{E}_z = \frac{\partial^2 E_z(x)}{\partial x^2} \hat{i}$$

On solving above equation we get,

$$\vec{E}_z(x) = \vec{A} e^{-\gamma x} + \vec{B} e^{\gamma x} \quad - (14)$$

Where A and B are arbitrary constants

Say,

$$\gamma = \alpha + j\beta \quad - (15)$$

$$\vec{A} = Ae^{j\theta}, \vec{B} = Be^{j\phi}$$

Hence,

$$\vec{E}_z(x) = Ae^{j\theta} e^{-\alpha x} e^{-j\beta x} + Be^{j\phi} e^{\alpha x} e^{j\beta x}$$

Considering time dependency,

$$E_z(x, t) = \text{Re}[\vec{E}_z(x)e^{j\omega t}] \quad - (16)$$

$$E_z(x, t) = \text{Re}[(Ae^{j\theta} e^{-\alpha x} e^{-j\beta x} + Be^{j\phi} e^{\alpha x} e^{j\beta x})e^{j\omega t}] \quad - (17)$$

$$E_z(x, t) = Ae^{-\alpha x} \cos[\omega t + \theta - \beta x] + Be^{\alpha x} \cos[\omega t + \theta + \beta x] \quad - (18)$$

Solving the 2nd order differential equation,

$$\gamma^2 X = \frac{\partial^2 X}{\partial x^2} \hat{i} \quad \text{Say, } \frac{\partial^2}{\partial x^2} = D$$

$$\Rightarrow D^2 X = \gamma^2 X$$

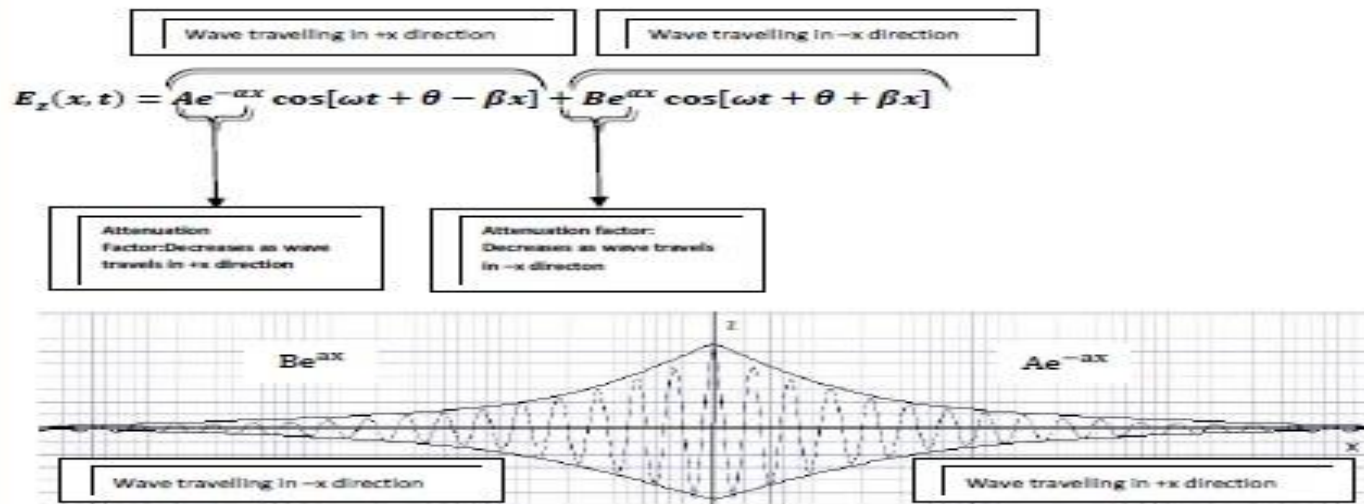
Factorizing, $(D-\gamma)(D+\gamma)X=0$

$$\text{Hence, } \frac{dX}{dx} = \gamma X \Rightarrow X = e^{\gamma x}$$

$$\text{And } \frac{dX}{dx} = -\gamma X \Rightarrow X = e^{-\gamma x}$$



[BACK](#)



ewave.jpg

Here,

$\alpha = \text{Attenuation constant } \left(\frac{\text{nepers}}{m}\right)$
 $\beta = \text{Phase constant}$
 $\gamma = \alpha + j\beta = \text{Propagation Constant}$

α and β Characterize the propagation of a wave

Now, let's say

$A = \vec{E}_z^+$ and $B = \vec{E}_z^-$

Hence, from (14)

$\vec{E}_z(x) = \vec{E}_z^+ e^{-\gamma x} + \vec{E}_z^- e^{\gamma x}$

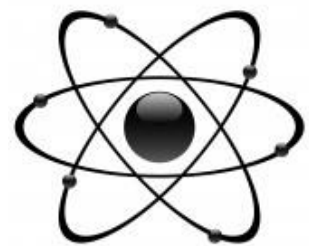
Now,

$\nabla \times \vec{E} = \nabla \times \vec{E}_z(x)$

$$= \frac{\partial \vec{E}_z^+(x)}{\partial x} [-j] + \frac{\partial \vec{E}_z^-(x)}{\partial y} [i]$$

$$= \vec{E}_z^+ \gamma e^{-\gamma x} - \vec{E}_z^- \gamma e^{\gamma x}$$

From (5)



[BACK](#)

$$\vec{H}_y(x) = \frac{Y}{j\omega\mu} [\vec{E}_z^+ e^{-\gamma x} - \vec{E}_z^- e^{\gamma x}]$$

$$\Rightarrow \vec{H}_y(x) = \frac{1}{\eta} [\vec{E}_z^+ e^{-\gamma x} - \vec{E}_z^- e^{\gamma x}]$$

Where,

$$\eta = \frac{j\omega\mu}{\gamma} = \frac{j\omega\mu}{\sqrt{j\omega\mu[\sigma + j\omega\epsilon]}} \quad \text{From (11)} \quad - (19)$$

$$\Rightarrow \eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \quad \left. \vphantom{\eta} \right\} \begin{array}{l} \text{Intrinsic Impedance of} \\ \text{medium.} \end{array}$$

As $\gamma = \alpha + j\beta = \sqrt{j\omega\mu[\sigma + j\omega\epsilon]}$ From (11) and (15)

Squaring and solving for α and β

We get,

$$\alpha^2 = \frac{\omega^2 \mu \epsilon}{2} \left[\pm \sqrt{1 + \frac{\sigma^2}{\omega^2 \epsilon^2}} - 1 \right]$$

Ignoring - sign,

$$\alpha = \sqrt{\frac{\omega^2 \mu \epsilon}{2} \left[\sqrt{1 + \frac{\sigma^2}{\omega^2 \epsilon^2}} - 1 \right]} \quad - (20)$$

And

$$\beta = \sqrt{\alpha^2 + \omega^2 \mu \epsilon}$$

$$\beta = \sqrt{\frac{\omega^2 \mu \epsilon}{2} \left[\sqrt{1 + \frac{\sigma^2}{\omega^2 \epsilon^2}} + 1 \right]} \quad - (21)$$



[BACK](#)

Let's take an example of a semi infinite plane slab of a material and plane wave is incident normally on it. Since the material is of infinite depth, it can sustain only those waves that are travelling in + x direction.

Hence,

Fields inside the material can be given by

$$\vec{E}_z(x) = \vec{E}_z^+ e^{-\gamma x} = \vec{E}_z^+ e^{-(\alpha + j\beta)x}$$

$$\vec{H}_y(x) = \frac{\gamma}{j\omega\mu} [\vec{E}_z^+ e^{-\gamma x}]$$

Considering the fact that skin depth is the depth or distance from the surface where the magnitude of field is 1/e times its value on the surface,

we find,

$$|\vec{E}_z(x)| = |\vec{E}_z^+| |e^{-\alpha x}| |e^{-j\beta x}|$$

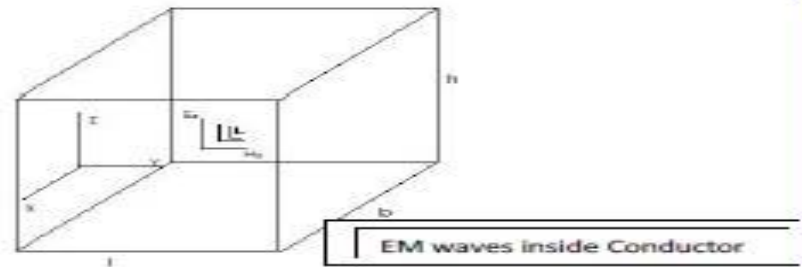
$$\frac{|\vec{E}_z^+|}{e} = |\vec{E}_z^+| e^{-\alpha\delta}$$

$$\Rightarrow \alpha\delta = 1$$

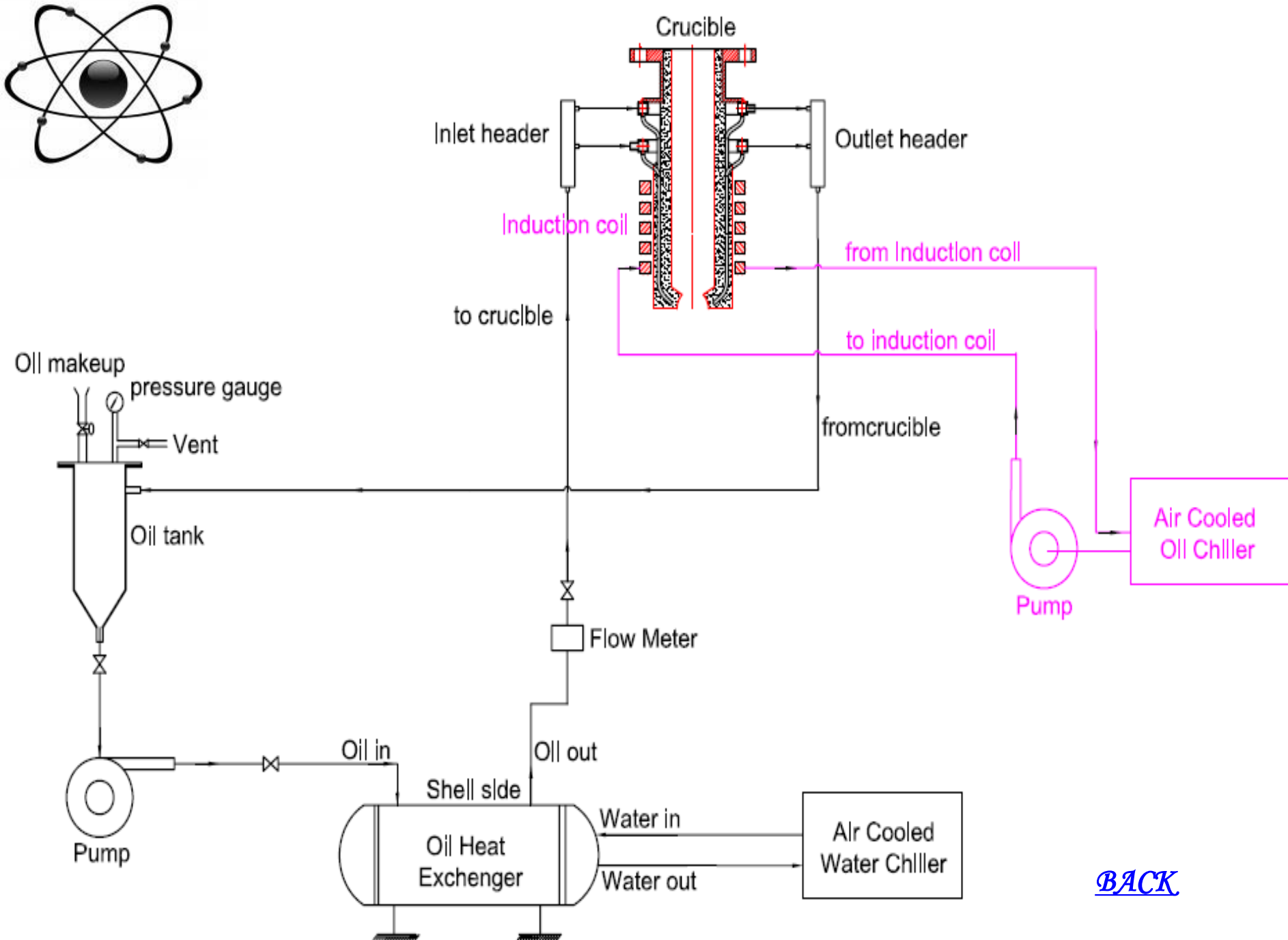
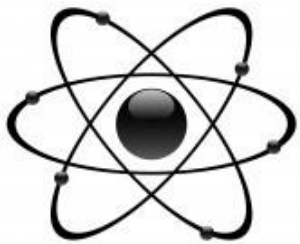
$$\delta = 1/\alpha = \frac{1}{\sqrt{\frac{\omega^2 \mu \epsilon}{2} [\sqrt{1 + \frac{\sigma^2}{\omega^2 \epsilon^2}} - 1]}}$$

Taking binomial approximation, we find

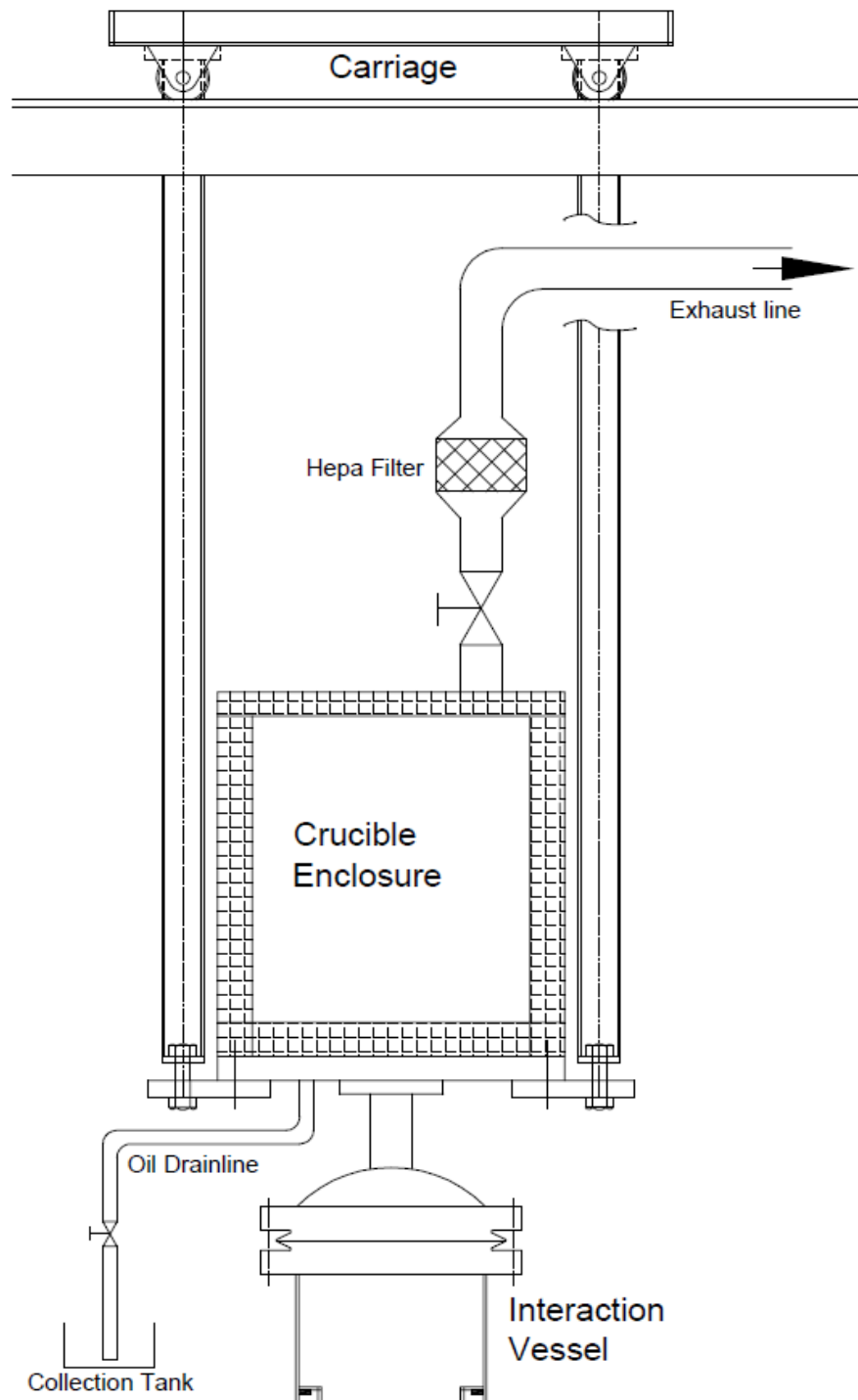
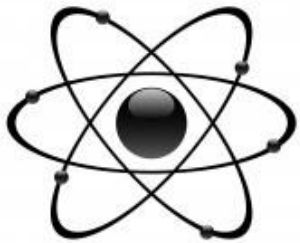
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \times \sqrt{\rho\omega\epsilon + \sqrt{1 + (\rho\omega\epsilon)^2}}$$



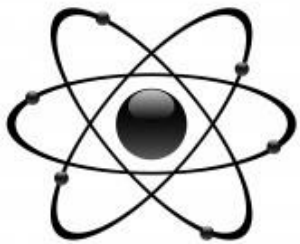
[BACK](#)



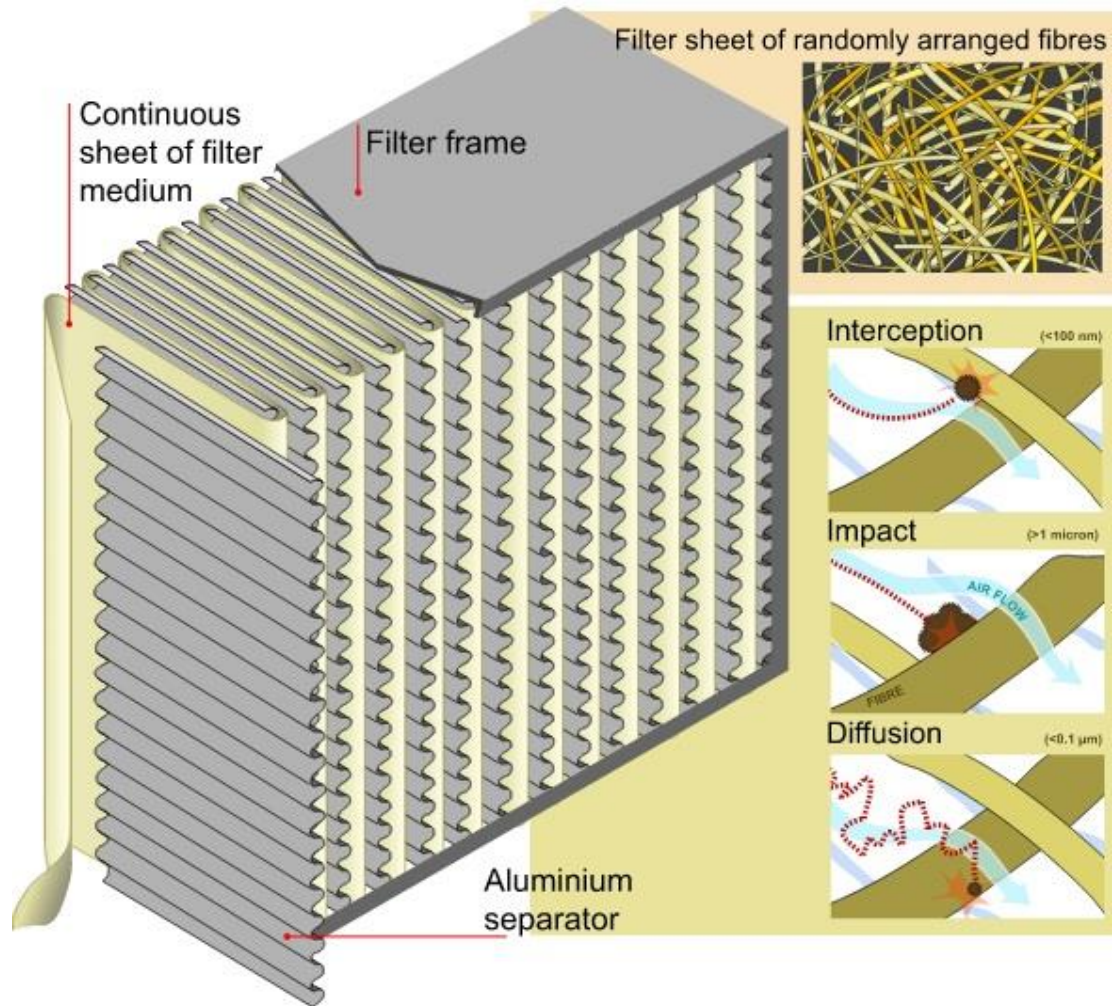
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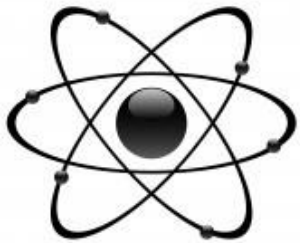
[*BACK*](#)



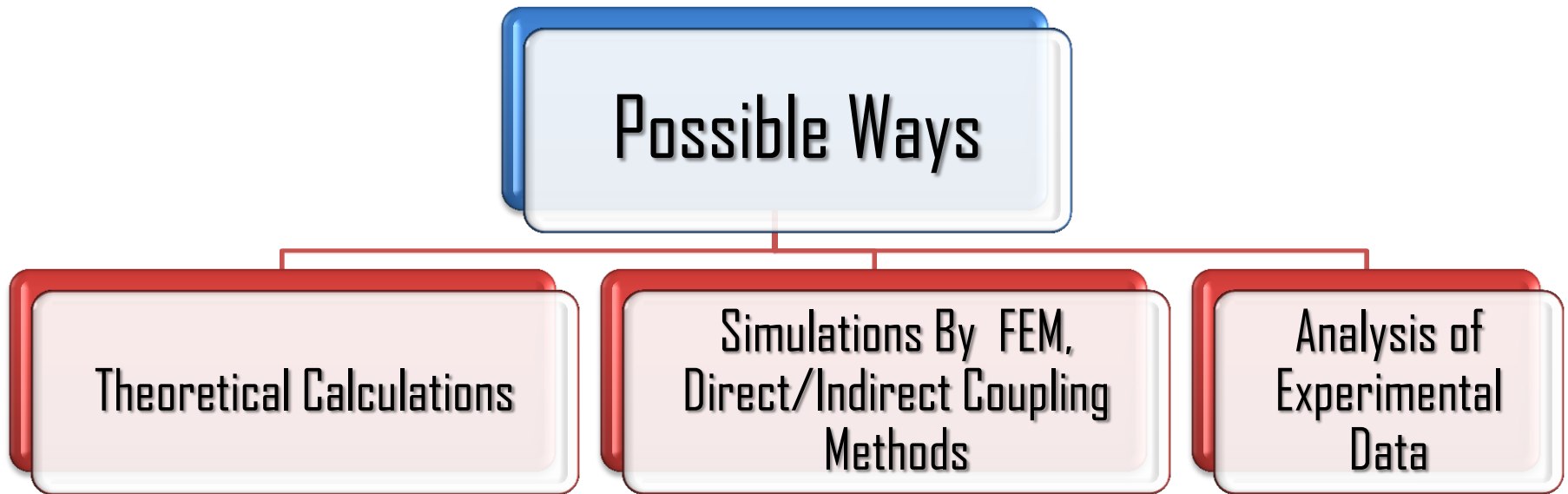
HEPA (High Efficiency Particulate Arresting)



[BACK](#)



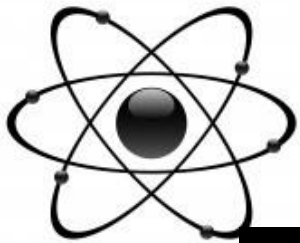
Efficiency Derivation



Method Selected:-Analysis of experimental data.

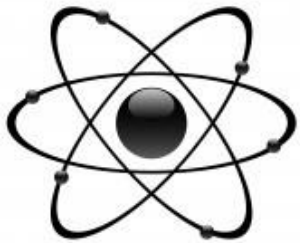
Advantage:- Less time consuming

Disadvantage:-Does not take coupling factor into consideration. Can produce errors if experimental conditions vary to greater extents.

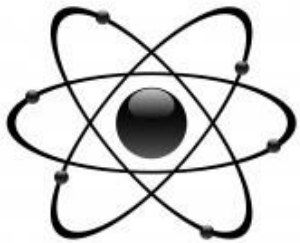


Sample Experimental Data Used

<i>Parameters</i>	<i>Values</i>
<u>Melt Charge Dimensions And Configuration</u>	
Uranium: Dia*Height	10 *40 (mm)
SS-304: Dia*Height	40*50 (mm)
Mass of Uranium	60g
Mass of SS	500g
Melt Temp.	1600 deg C
Power, Frequency	11kW 750.0 Hz
<u>Cooling System Parameters</u>	
Oil Temp. Coil Inlet & Outlet	Inlet:21 deg C Outlet:87 deg C
Air Temp. Crucible Inlet & Outlet	Inlet:27 deg C Outlet:51 deg C
Flow Rates	Oil:- 4 lpm Air:-1000 lpm

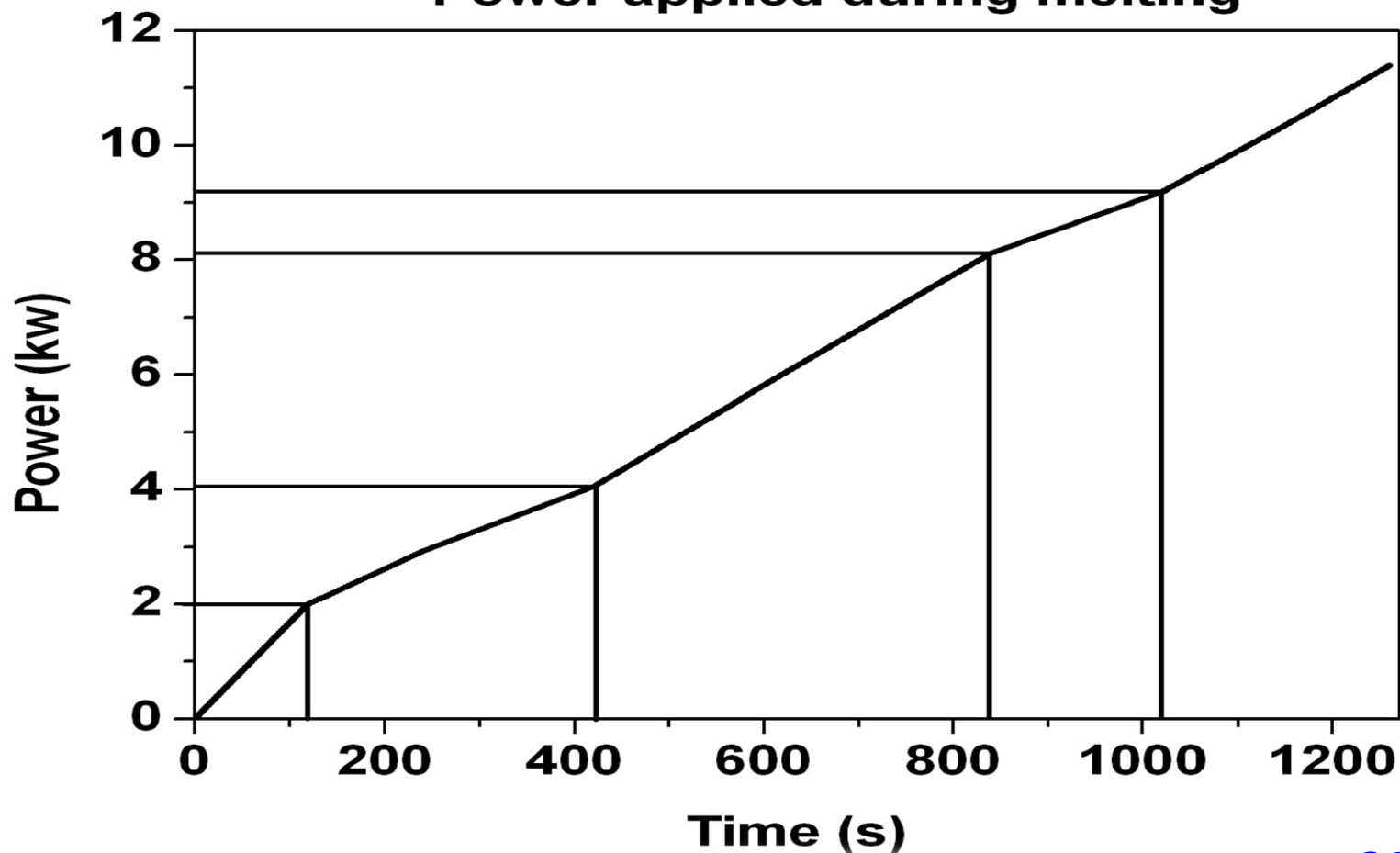


Graphs

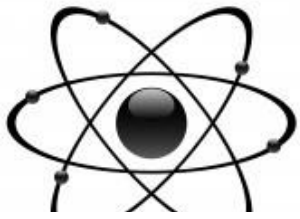


Power vs. Time

Power applied during melting

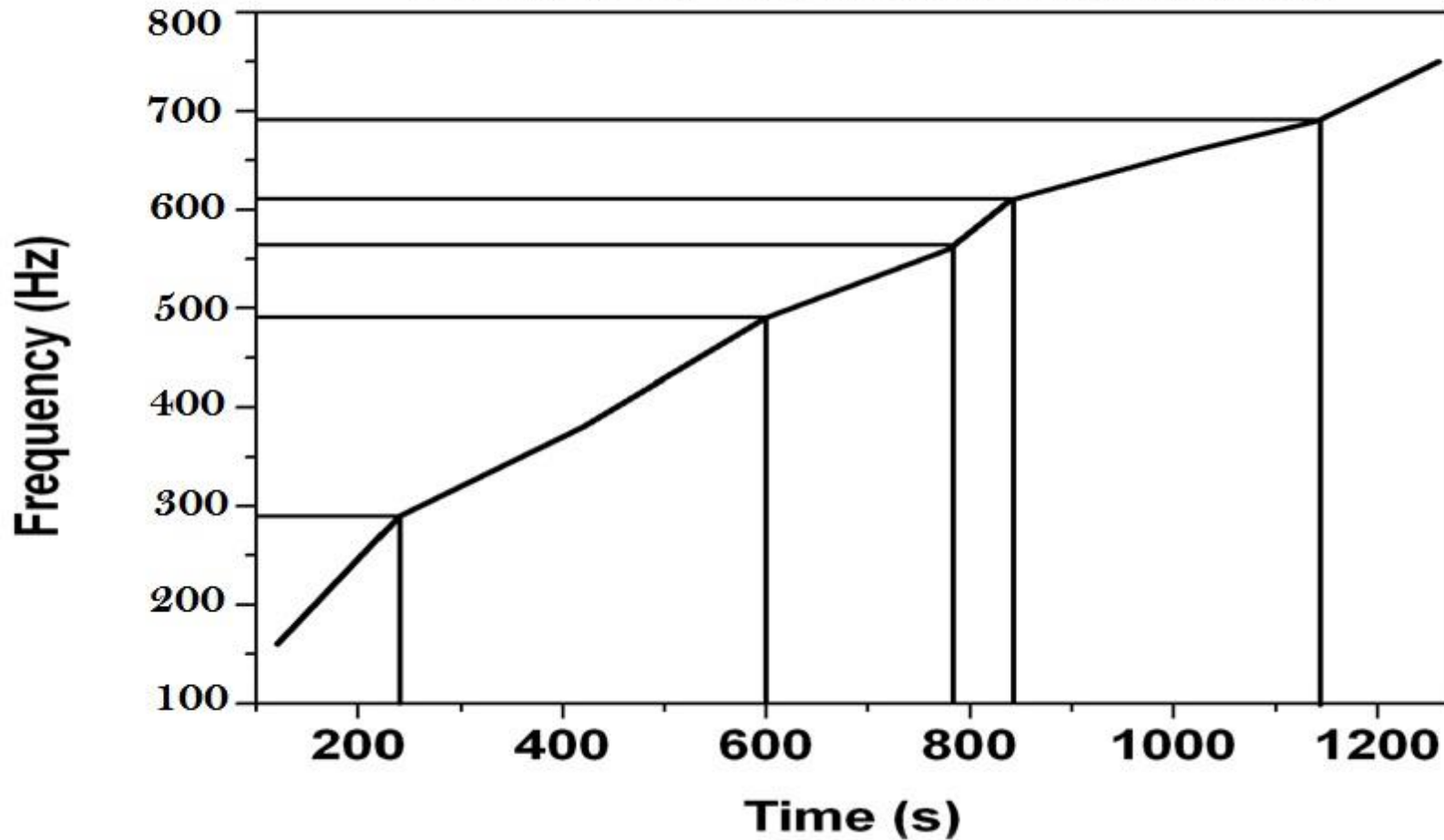


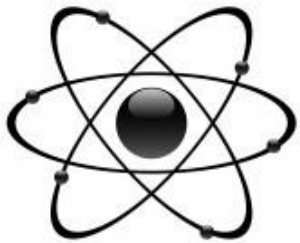
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Frequency vs. Time

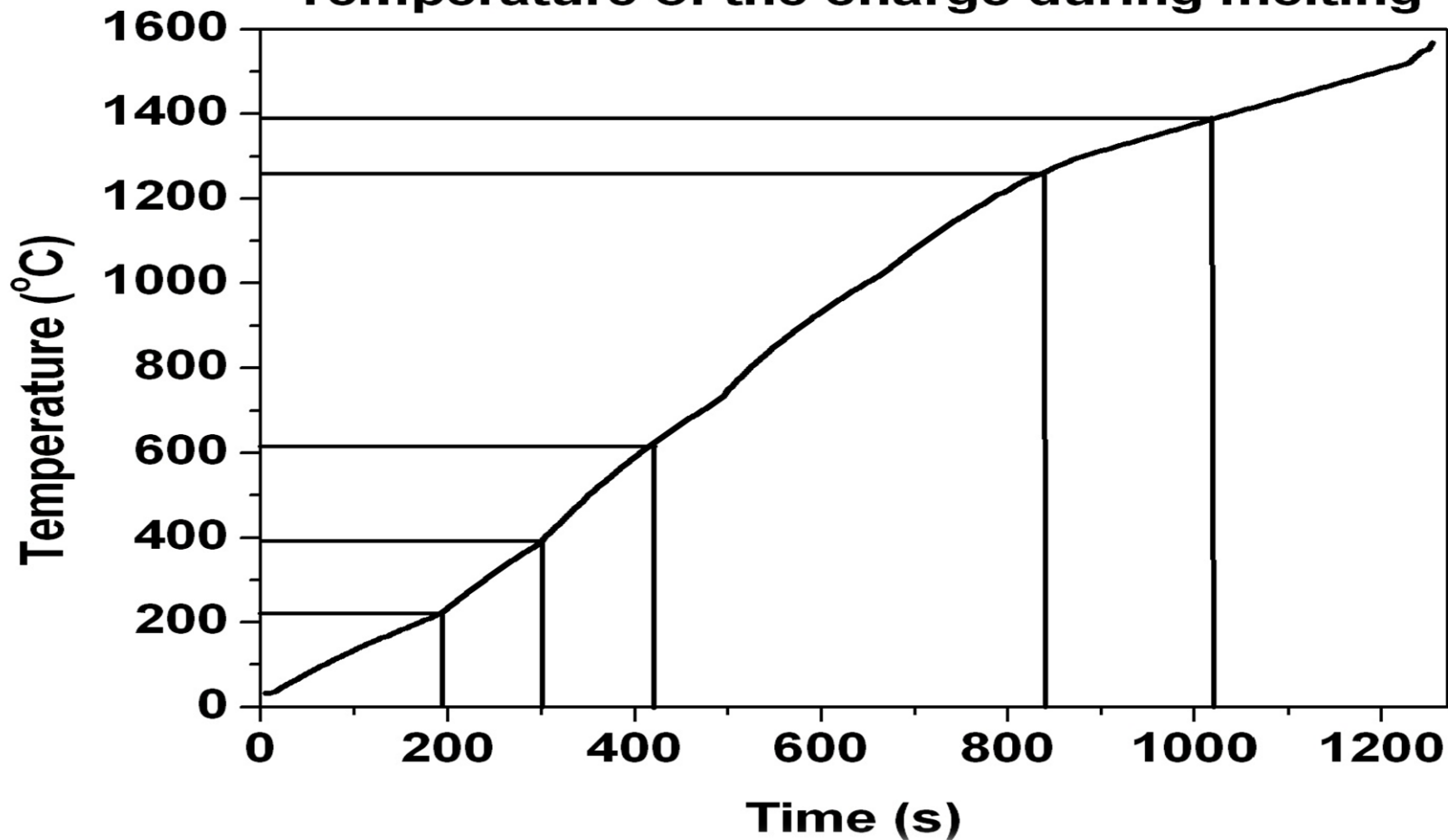
Frequency applied during melting

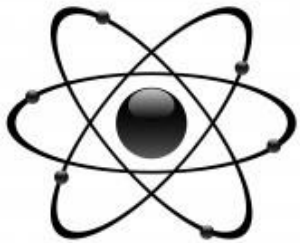




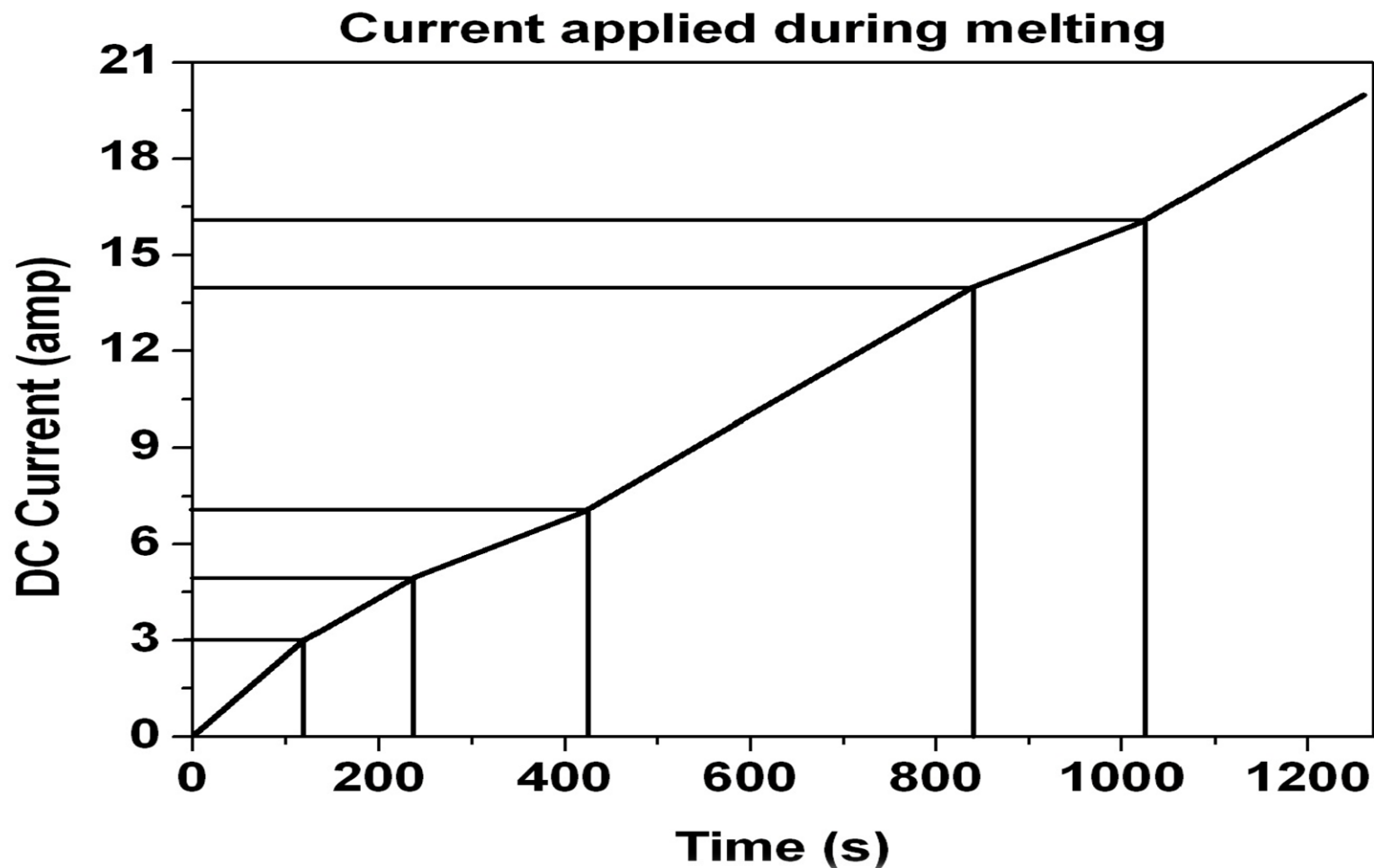
Temperature vs. Time

Temperature of the charge during melting





Current vs. Time



Calculations.

Specific Heat Equation:-

$$\Delta Q = Csp\Delta T$$

$$\Delta Q = mL$$

$$\Delta T = T_{fin} - T_{in}$$

Time Duration=1200 sec

Material	Mass	Csp(S)	Csp(L)	Lat. Heat	Melting Temp.
Uranium	60g	0.115 j/gK	0.198 j/gK	52.91474 j/g	1405.5K
SS-304	500g	0.5 j/gK	0.8 j/gK	272.5 j/g	1673.15K

Room Temp:-303.65 K

Final Temp:-1873.15K

Therefore,

$$\begin{aligned}\Delta Q &= 60(0.115(1405.5 - 303.15) + 52.91474 + 0.198(1873.15 - 1405.5)) + \\ &\quad 500(0.5(1673.15 - 303.15) + 272.5 + 0.8(1873.15 - 1673.15)) \\ &= 16336.7814 + 558750 \\ &= 575086.7814\text{J}\end{aligned}$$

$$P_o = \frac{\Delta Q}{t(s)}$$

$$= 479.2389845\text{W}$$

Average Input Power (From Graph) [*Graph*](#)

$$P_i = 5.5 \text{ kW}$$

$$\eta = \frac{P_o}{P_i} = 0.08713436081818$$

Efficiency=8.713436081818%



Heat Absorbed By Cooling System

Specific Heat Equation:-

$$\Delta Q = Csp\Delta T$$

$$\Delta Q = mL$$

$$\Delta T = T_{fin} - T_{in}$$

Time Duration=1200 sec

Material	LPM	Csp	Temperature Range
Therminol-59	4	1.65 j/gK	Inlet:21 deg C Outlet:87 deg C
Air	1000	1.005 j/gK	Inlet:27 deg C Outlet:51 deg C

Therminol Density= 982 kg/m³

Mass of Therminol used in 1200 sec (20 min):

$$\text{Vol.}=4*20=80 \text{ L} = .08 \text{ m}^3$$

$$\text{Mass}=78560\text{g}$$

Air Density= 1.2754 kg/m³

Mass of Air used in 1200 sec (20 min):

$$\text{Vol.}=1000*20=20000 \text{ L} = 20 \text{ m}^3$$

$$\text{Mass}=25508\text{g}$$

Therefore, Heat removed by cooling system

$$\begin{aligned} \Delta Q &= 78560(1.65(87 - 21) + \\ &\quad 25508(1.005(51 - 27))) \\ &= 8555184 + 615252.96 = 9170436.96\text{J} \end{aligned}$$

$$P_o = \frac{\Delta Q}{t(s)}$$

$$= 7.6420308 \text{ kW} \quad (\text{Power loss during peak consumption})$$

