Uranium Fuel Melting using Induction Heating Methodology

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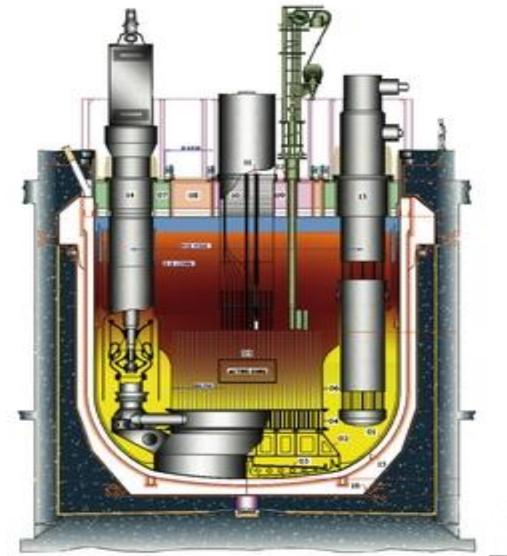
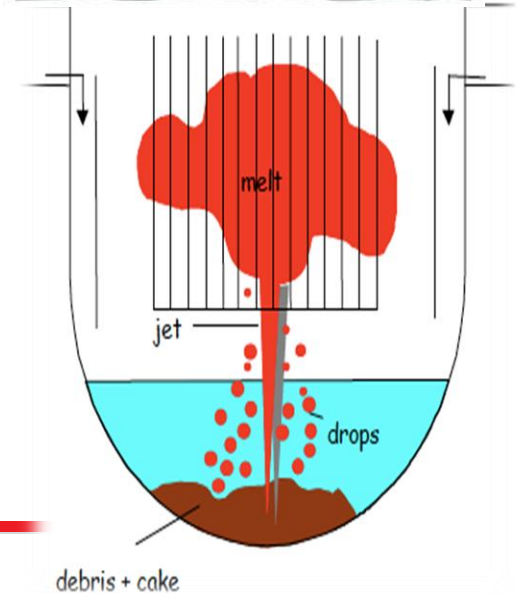
MFCI (Molten Fuel Coolant Interaction)

- **Case Study:-**
  - Imbalance between heat generated and removal
  - Rising Temperature and Pressure in fuel pin
  - Melting of fuel pins and propagation
  - Grid plate melt through
  - Interaction of Molten Fuel with coolant and relocation on core catcher





Available Technologies for melting Uranium

- Electric Arc Furnaces
- Induction Furnaces
- Reverberatory or Hearth Furnaces
- Cupolas
- Vacuum Arc Skull Melting and Casting

Advantages of Induction Heating
➢Heat is produced in the material to be heated.
➢Quick Response
➢Localized Heating
➢High Power Density
➢Eco Friendly

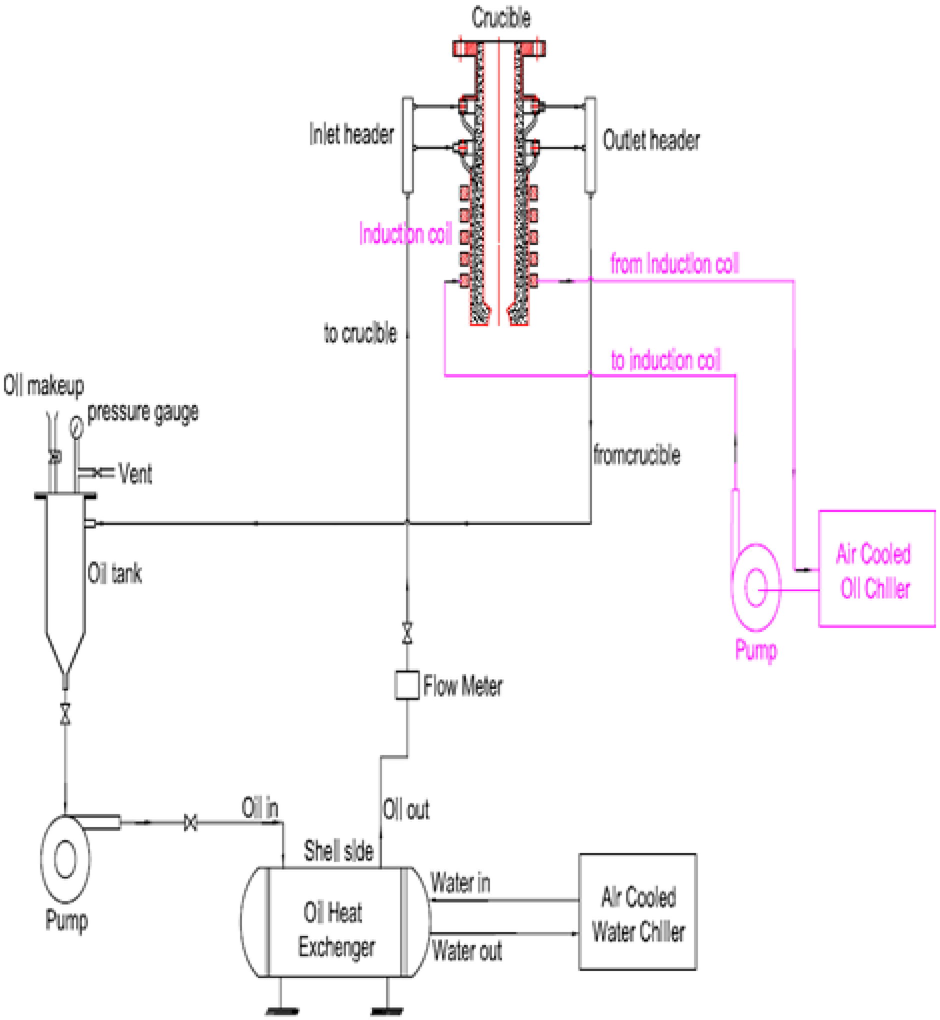
Disadv.

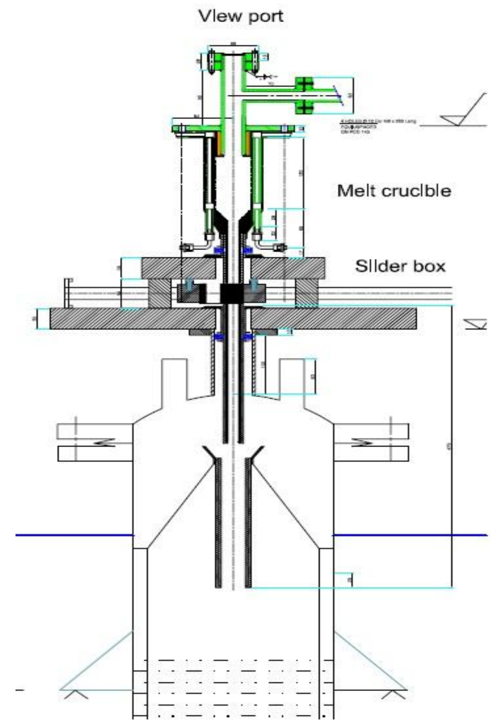
Existing Induction Heating System at SOFI

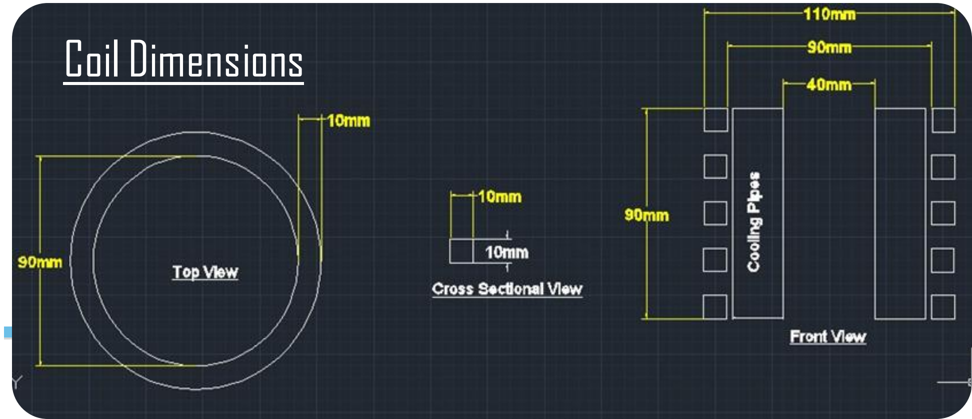
- **Technical Specifications:-** Type: VEL/MF/50 VEL Induction Heater

Components	*Specifications*
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







Governing Equations

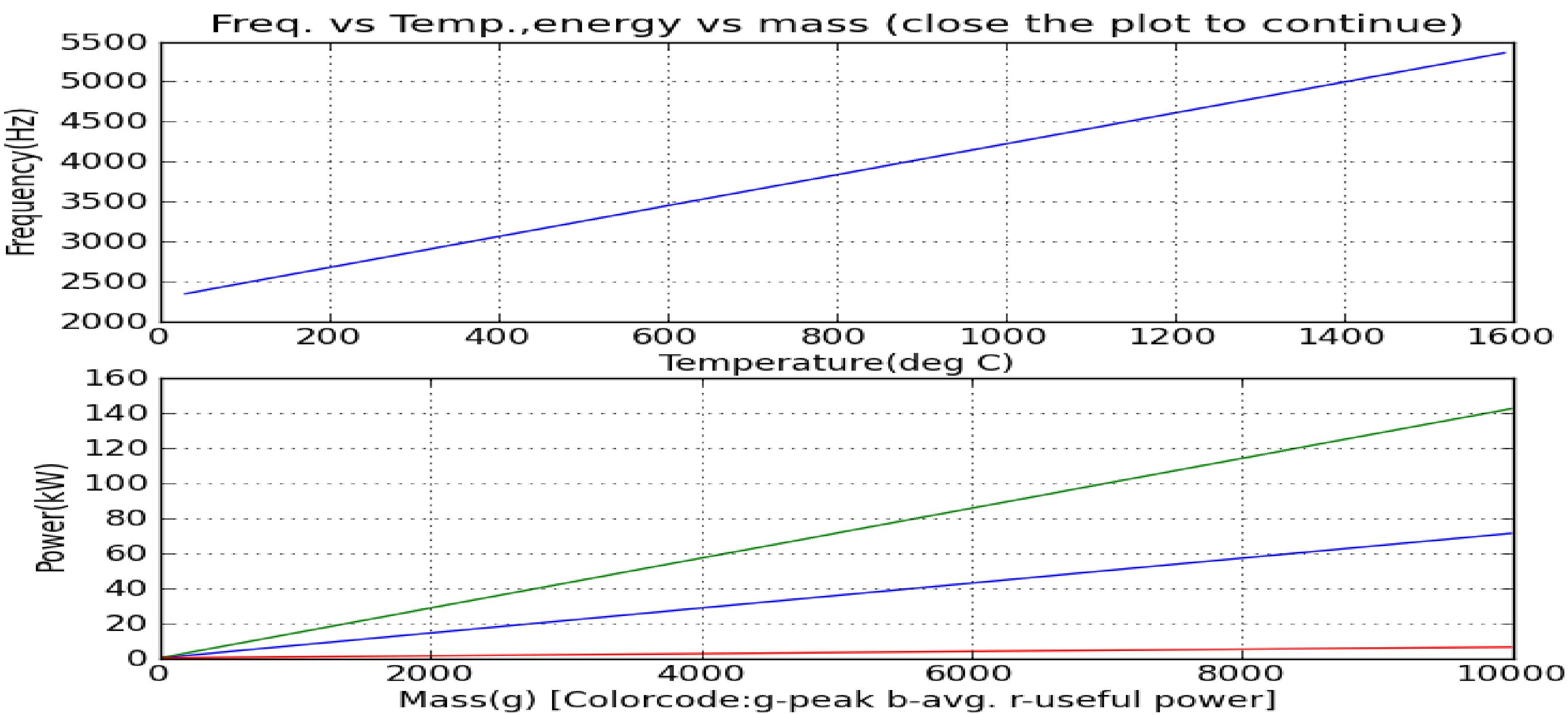
Name	Equation
1) Specific Heat equation	Q=mCp(T2-T1)
2) Law of conservation of energy	Rin + Rgen = Rout + Rstor
3)Heat transfer equation for cylindrical case	$\alpha\left[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r})+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}\right]+\frac{q'''}{\rho c_p}=\left[\frac{\partial T}{\partial t}+V_r\frac{\partial T}{\partial r}+\frac{V_\theta}{r}\frac{\partial T}{\partial \theta}+V_z\frac{\partial T}{\partial z}\right]$
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	$W = \varepsilon\sigma T^4$
7)Skin Depth Formula	$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\ \sqrt{\sqrt{1+(\rho\omega\epsilon)^2}+\rho\omega\epsilon}$

Development of Simple Program

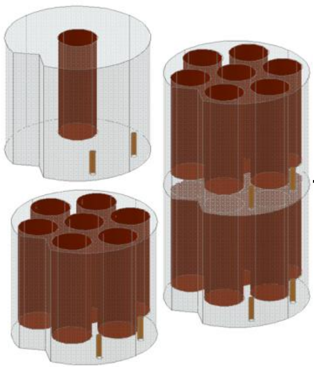
➢ Software Specifications:-

Platforms Used: Python 2.7.2, Matlab

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



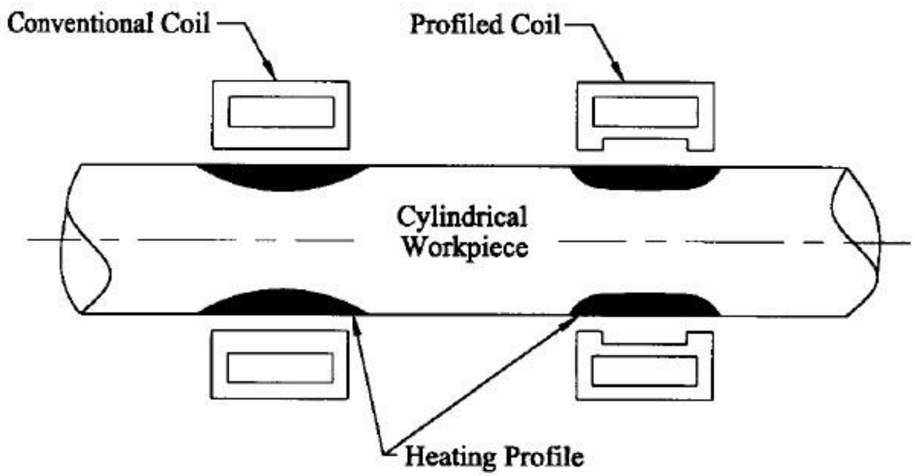
Power Requirements for different configurations

Work Configuration	*Peak Power Required*	*Ideal Frequency Range*
Single SS-304 Pellet (40 mm dia , 50 mm height)	7.19 kW	2.3-5.3 kHz
Single Uranium Pellet (40 mm dia , 50 mm height)	3.35 kW	1.0-4.6 kHz
1- U pellet inside SS-304 work U (12 mm dia 40 mm height) SS-304 (40mm dia , 50 mm height 	6.99 kW	2.3-5.0 kHz
7- U pellets inside SS-304 work U (12 mm dia 40 mm height) SS-304 (40mm dia , 50 mm height	5.68 kW	2.3-5.0 kHz
7- U pellets inside SS-304 work U (12 mm dia 40 mm height) SS-304 (40mm dia , 50 mm height) } ×2	11.34 kW	2.3-5.0 kHz

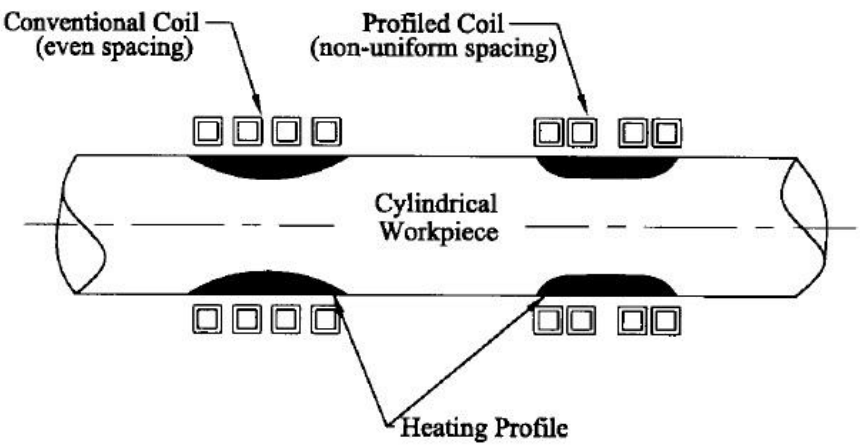
Note: Calculations have been done assuming 30 min as expt. Time and +200 deg. superheated

Suggested Improvements in the existing design

- **Coil Design:-**



Coil With Barrel Shape



Coil With Gaps

Existing Design

Suggested Improvements in the existing design

➢ Work Orientation:-

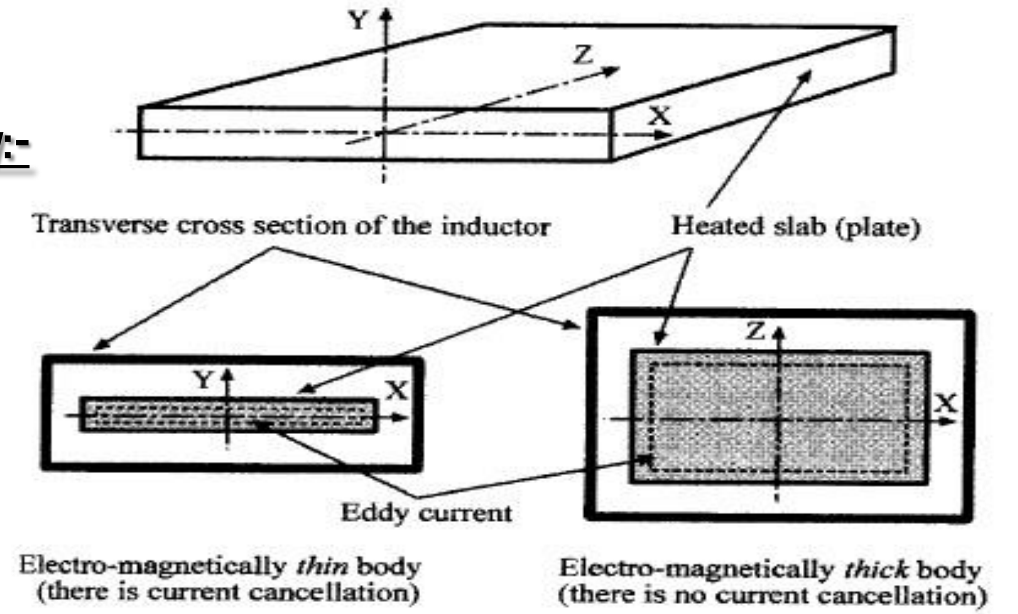
Advantages of electromagnetically "thick" body:-

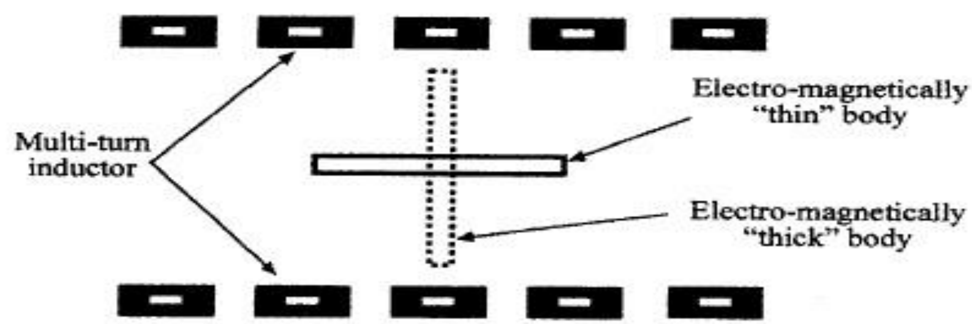
1) High flux linkage

2) Low heat losses

3) Reduced Edge Effects

4) Uniform heating profile.

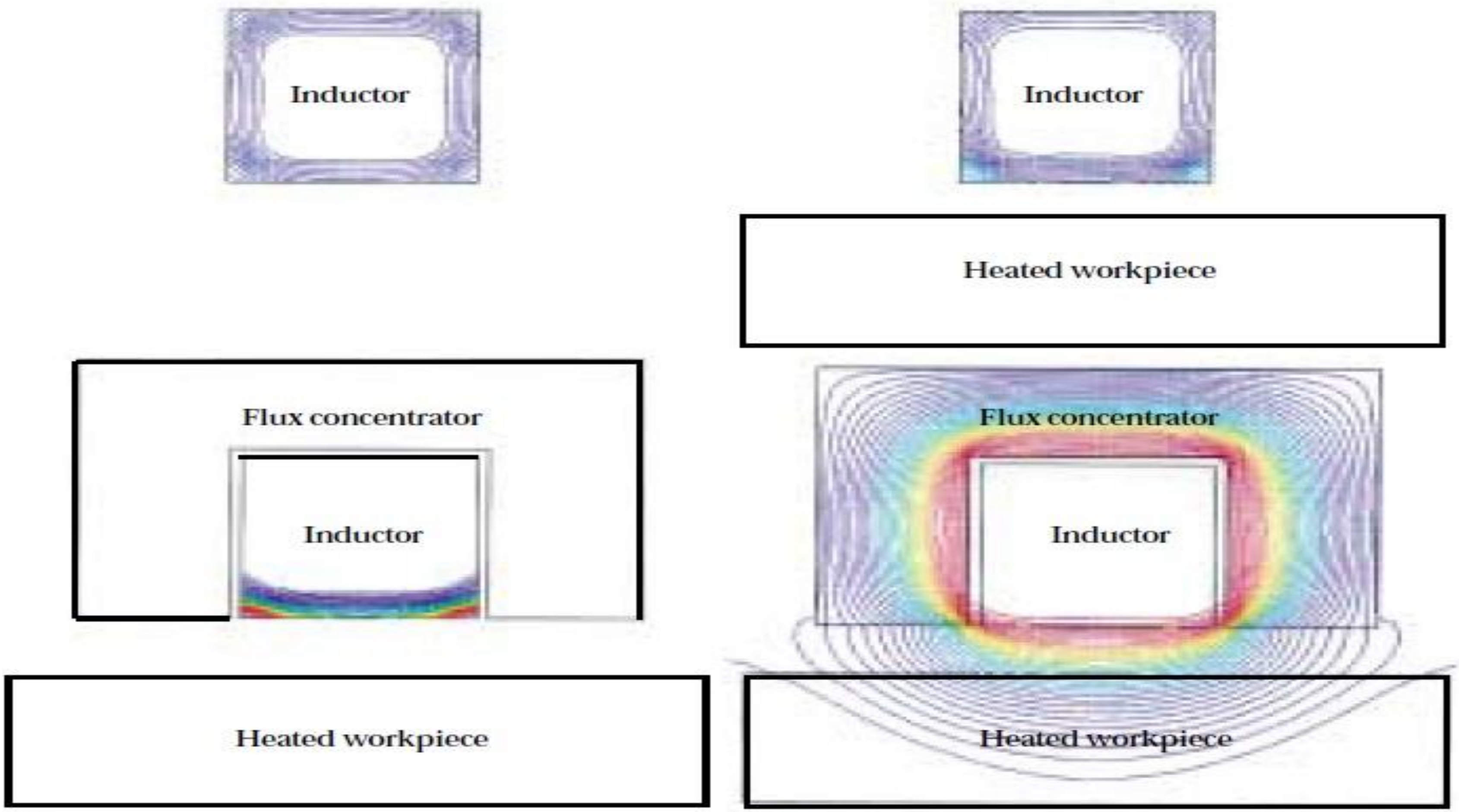




Governing Equations

Suggested Improvements in the existing design

- **Use of Flux Concentrators:-**



Thank You

Any Questions???

Disadvantages of Induction Heating??

Disadvantages
➢ Noise Produced during operation.
➢ Hefty Price Tag
➢ Complex Power System Design
➢ Poor Efficiency
➢ Suitable for components having specific shapes

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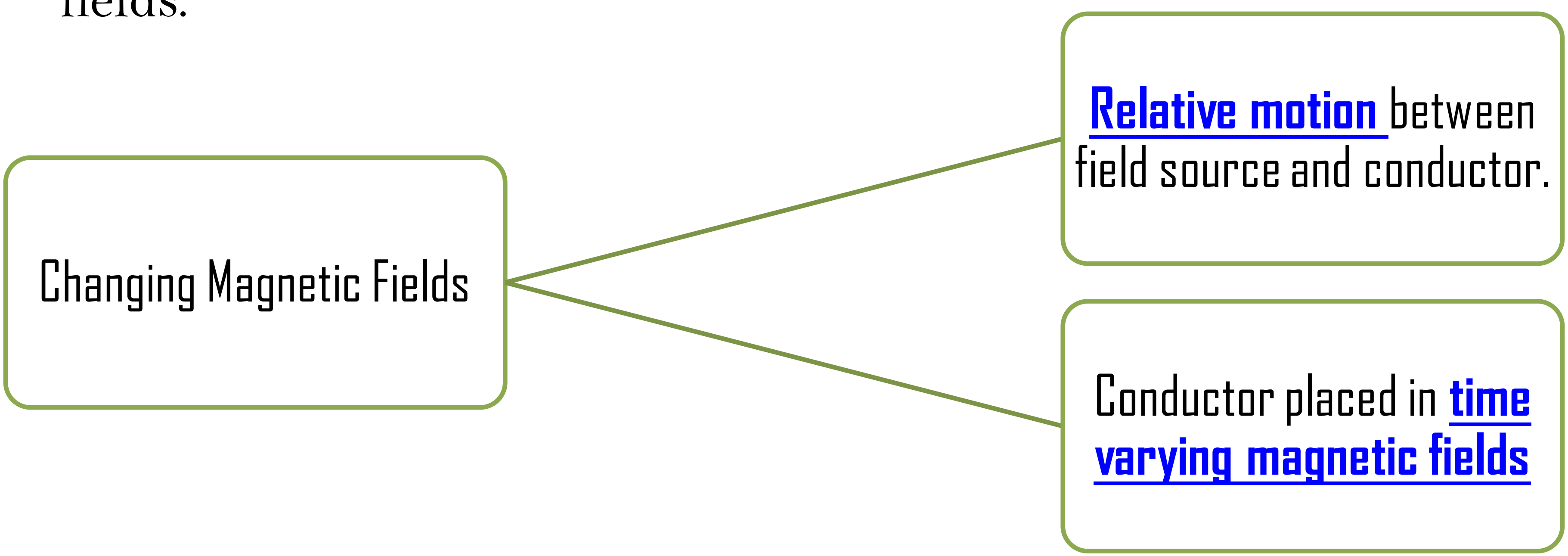
Basics of Induction Heating

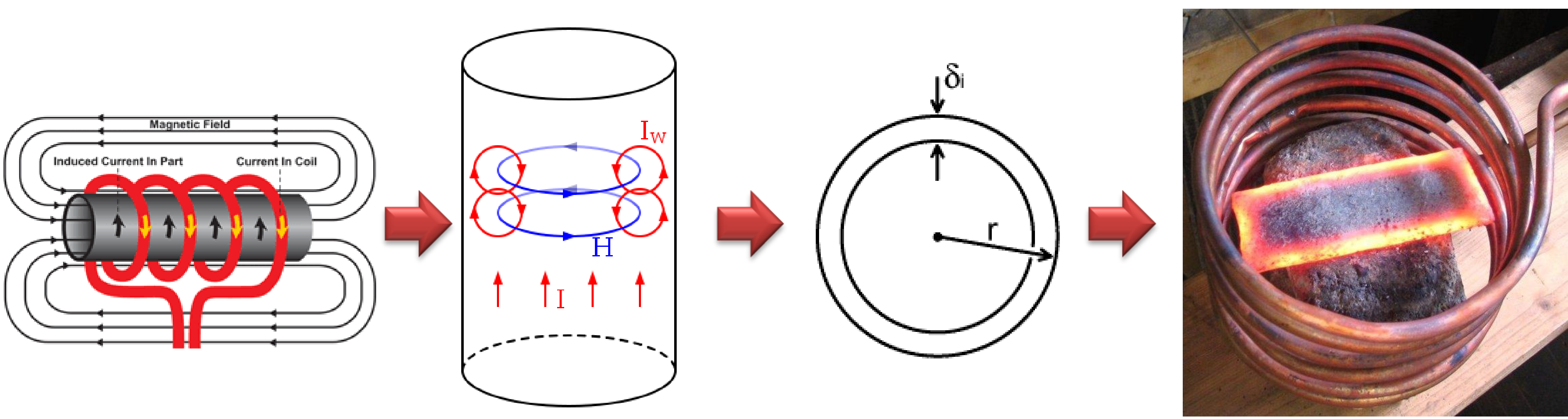
- **Governing Phenomenon**:- Eddy Currents

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



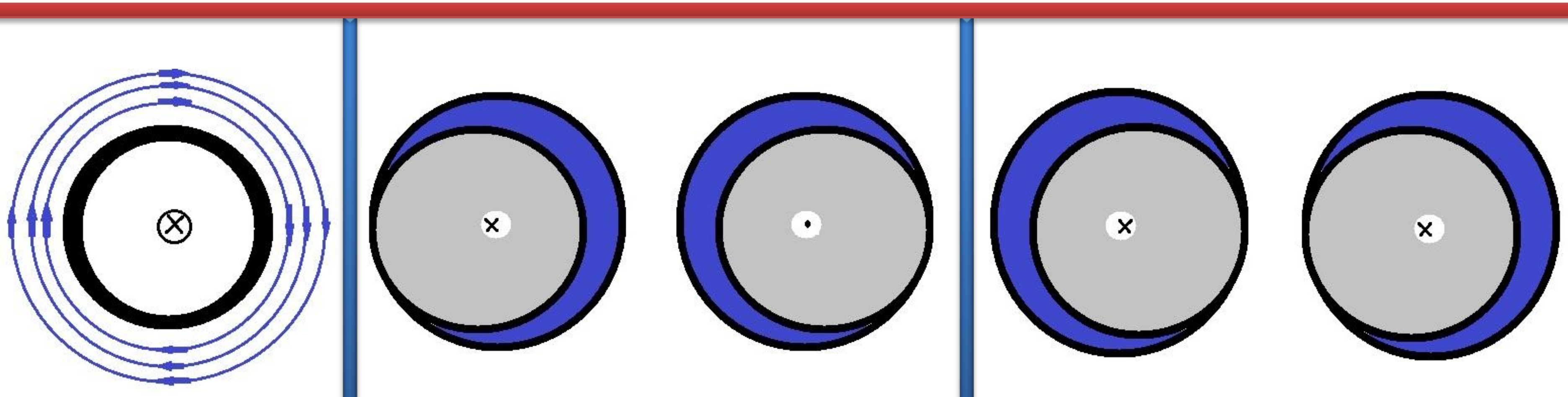
Basics of Induction Heating

- **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

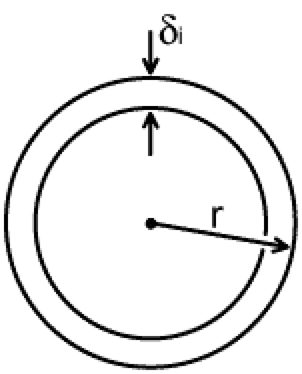
- **Proximity Effect Phenomenon:-**Unlike skin effect that does not take into account the nearby conductors, proximity effect accounts the interfering magnetic fields due to the conductors in close proximity. These interfering magnetic fields result in the distortion of the current and power density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

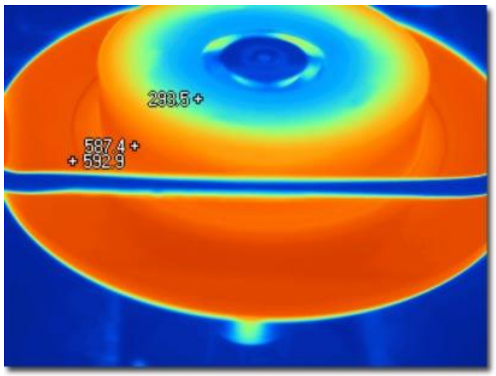


Basics of Induction Heating

- **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.

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

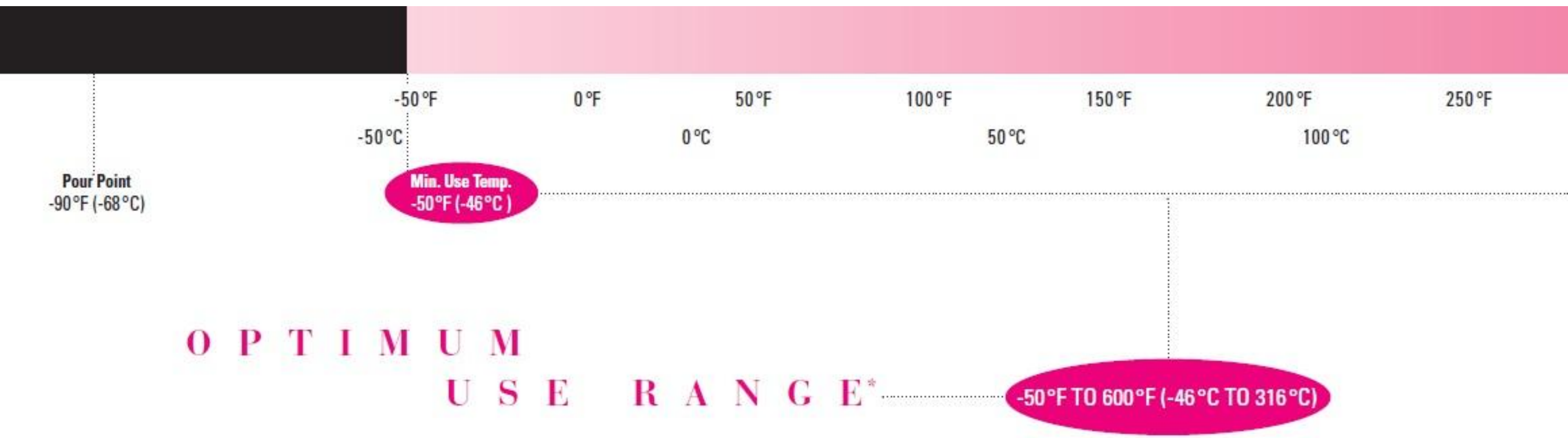




Existing Induction Heating System at SOFI

- **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.

Calculations and Derivations

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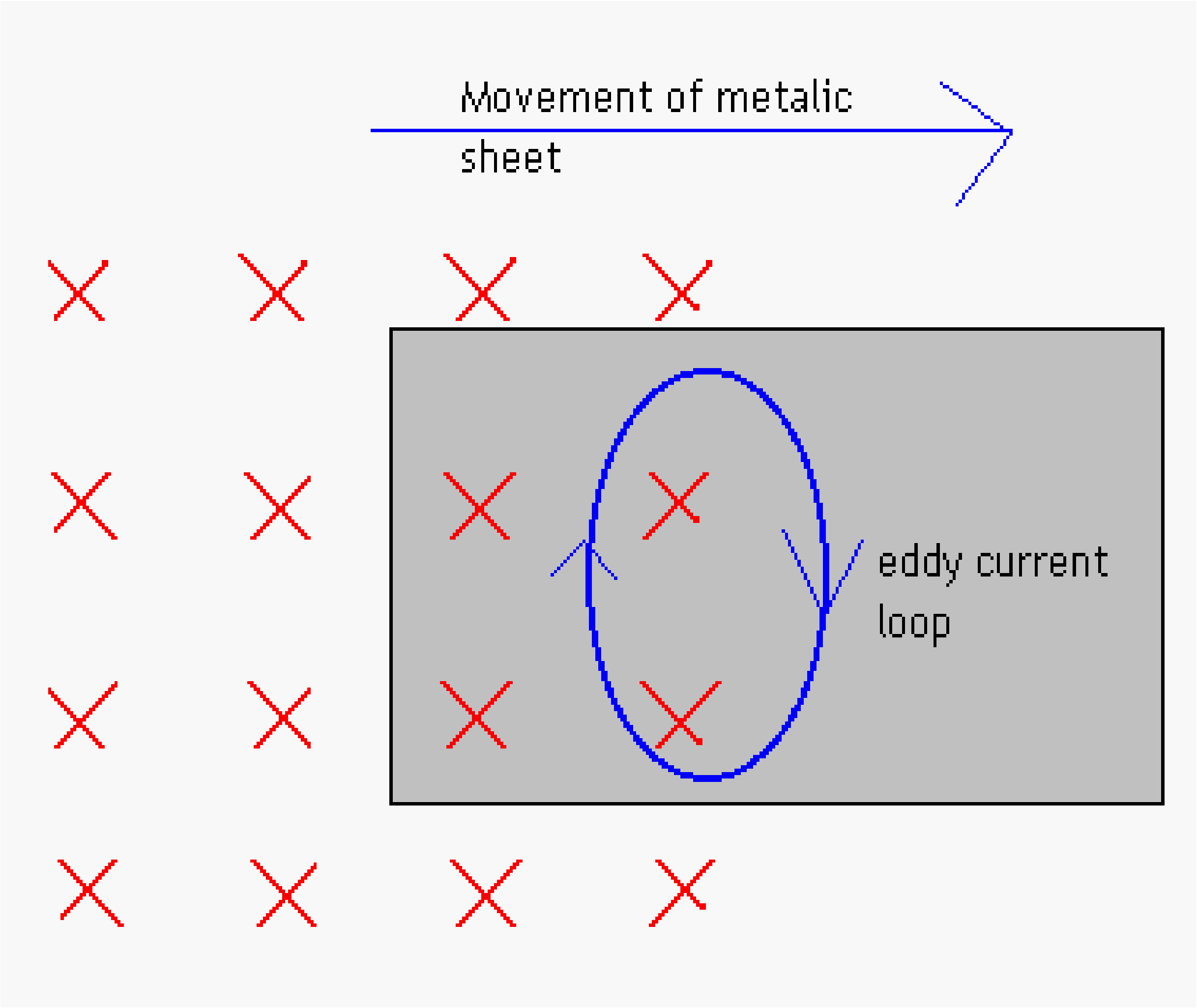

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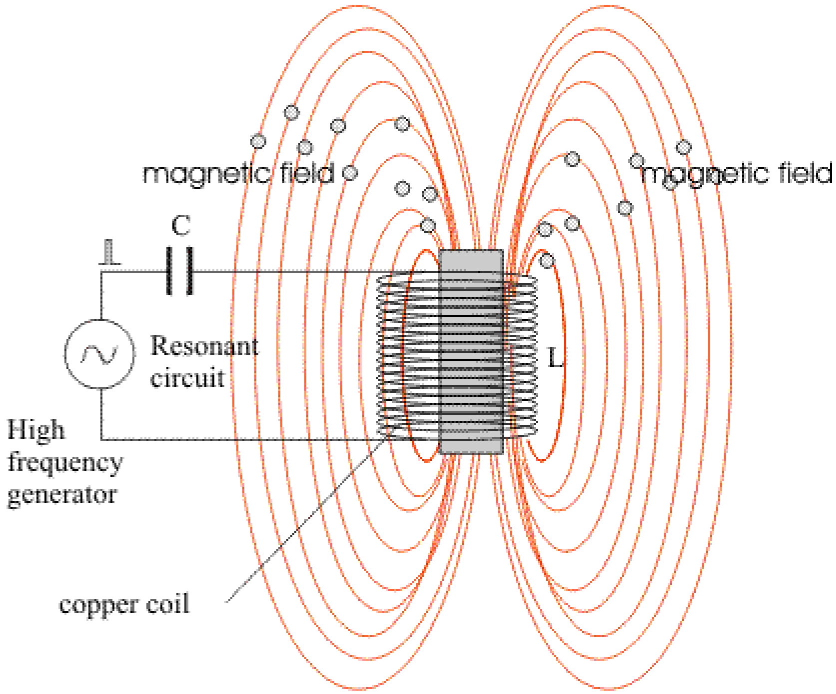
Induction Heating

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



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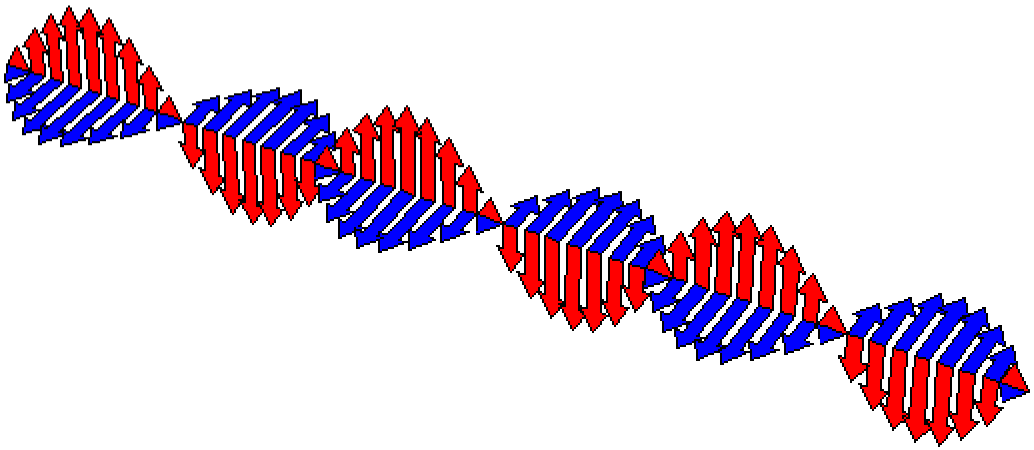

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Derivation of Skin Depth Formula:-

Say a medium has:

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

And an electromagnetic field exists such that

$\vec{B} = Ce^{j\omega t}$ - (1)

$\vec{E} = De^{j\omega t}$ - (2)

Using Maxwell's equations

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

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

We Have,

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

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

Now

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

Using,

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

From (6)

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

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

Since, divergence of curl is 0

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

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

Hence, from equation (7) and (8)

Maxwell's Equation:

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

Where,

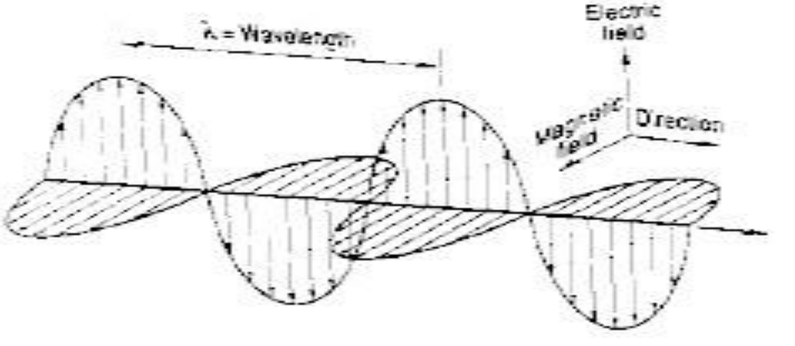
D= Electric Displacement field

B= Magnetic Field

E=Electric Field

J=Current Density

P=Charge Density



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Hence , from equation (7) and (8)

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

$\Longrightarrow \nabla^2\vec{E} = j\omega\mu(\sigma + j\varepsilon\omega)\vec{E}$ - (10)

Say,

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

$\Longrightarrow \nabla^2\vec{E} = \gamma^2\vec{E}$ - (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

$\Longrightarrow \vec{E} = \overrightarrow{E_z}(x)\hat{k}$ - (13)

$\nabla^2\vec{E} = \gamma^2\overrightarrow{E_z} = \frac{\partial^2 E_{z(x)}}{\partial x^2}\hat{\imath}$

On solving above equation we get,

$\overrightarrow{E_z}(x) = \vec{A}\, e^{-\gamma x} + \vec{B}\, e^{\gamma x}$ - (14)

Where A and B are arbitrary constants

Say,

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

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

Hence,

$\overrightarrow{E_z}(x) = Ae^{j\theta}e^{-\alpha x}e^{-j\beta x} + Be^{j\emptyset}e^{\alpha x}e^{j\beta x}$

Solving the 2nd order differential equation,

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

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

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

Hence, $\frac{dX}{dx} = \gamma X \Longrightarrow X = e^{\gamma X}$

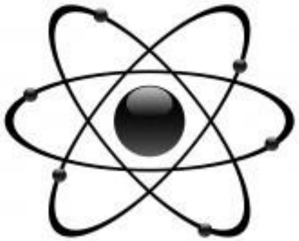
And $\frac{dX}{dx} = -\gamma X \Longrightarrow X = e^{-\gamma X}$

Considering time dependency,

$E_z(x,t) = Re[\overrightarrow{E_z}(x)e^{j\omega t}]$ -(16)

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

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



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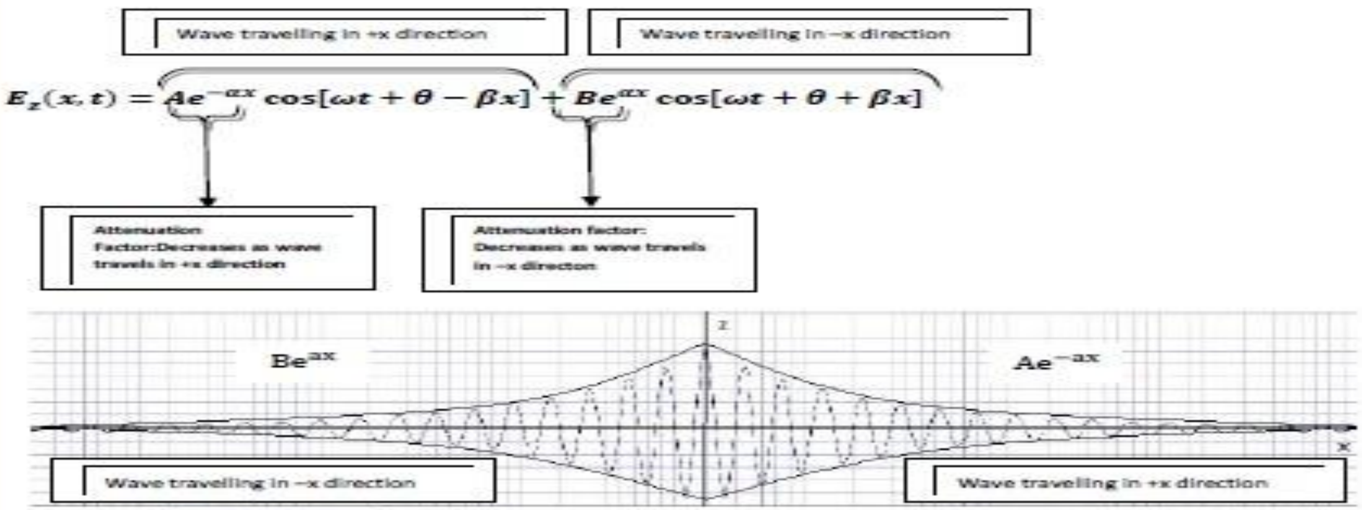
$$E_z(x,t) = Ae^{-\alpha x}\cos[\omega t + \theta - \beta x] + Be^{\alpha x}\cos[\omega t + \theta + \beta x]$$



ewave.jpg

Here,

$\alpha = Attenuation\ constant\ (\frac{nepers}{m})$

$\beta = Phase\ constant$

$\gamma = \alpha + j\beta = Propogation\ Constant$

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,

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

$$= \frac{\partial \vec{E_z}(x)}{\partial x}[-\hat{j}] + \frac{\partial \vec{E_z}(x)}{\partial y}[\hat{\imath}]$$

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

From (5)

BACK

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

$$\Longrightarrow \overrightarrow{H_y}(x) = \frac{1}{\eta}[\vec{E}_z^+ e^{-\gamma x} - \vec{E}_z^- e^{\gamma x}]$$

Where,

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

$$\Longrightarrow \eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$ } Intrinsic Impedance of medium.

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

Squaring and solving for α *and* β

We get,

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

Ignoring – sign,

$$\alpha = \sqrt{\frac{\omega^2\mu\varepsilon}{2}[\sqrt{1 + \frac{\sigma^2}{\omega^2\varepsilon^2}} - 1]} \qquad - (20)$$

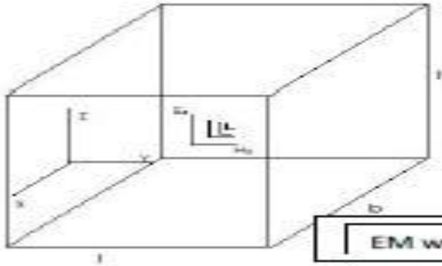
And

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

$$\beta = \sqrt{\frac{\omega^2\mu\varepsilon}{2}[\sqrt{1 + \frac{\sigma^2}{\omega^2\varepsilon^2}} + 1]} \qquad - (21)$$

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


EM waves inside Conductor

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

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

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,

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

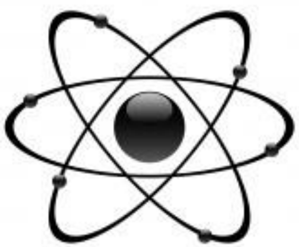
$$\frac{|\vec{E}_z^+|}{e} = |\vec{E}_z^+| \, e^{-\alpha\delta}$$

$$\Longrightarrow \alpha\delta = 1$$

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

Taking binomial approximation, we find

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



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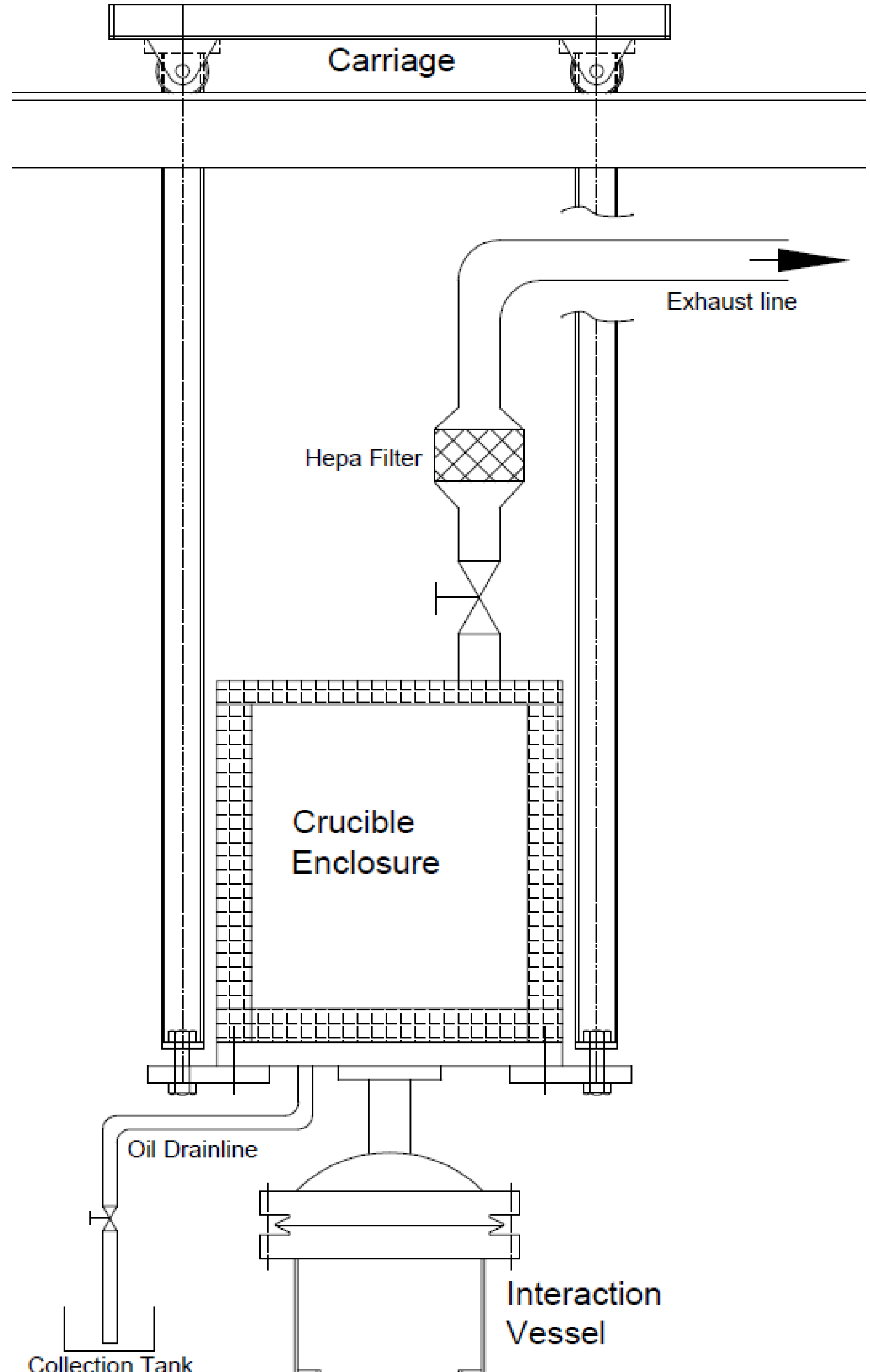
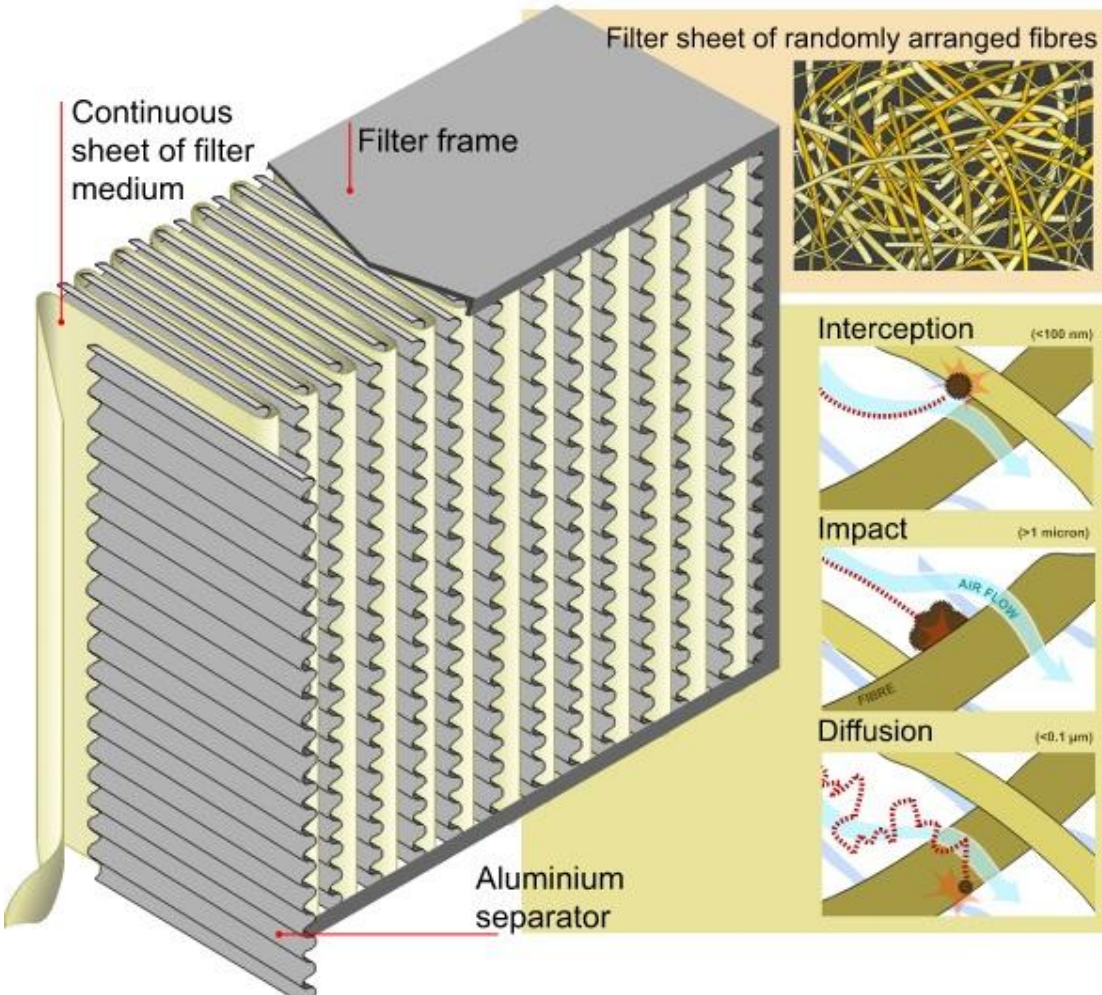

Carriage
Exhaust line
Hepa Filter
Crucible
Enclosure
Oil Drainline
Interaction
Vessel
Collection Tank

BACK

HEPA(High Efficiency Particulate Arresting)



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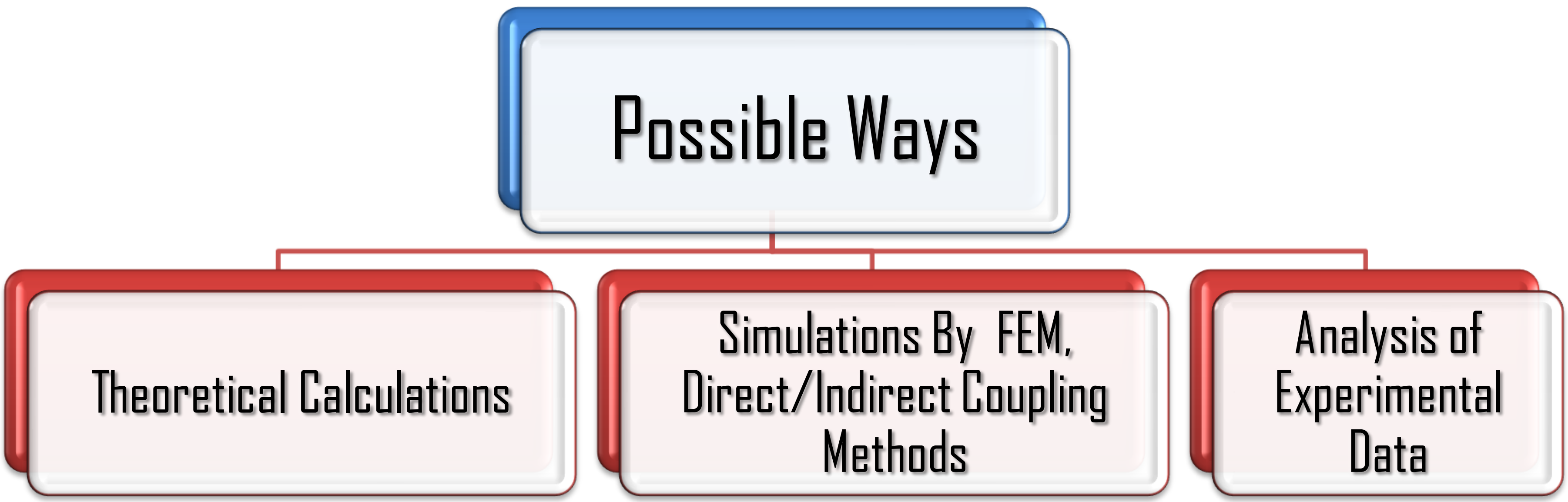
Efficiency Derivation



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.

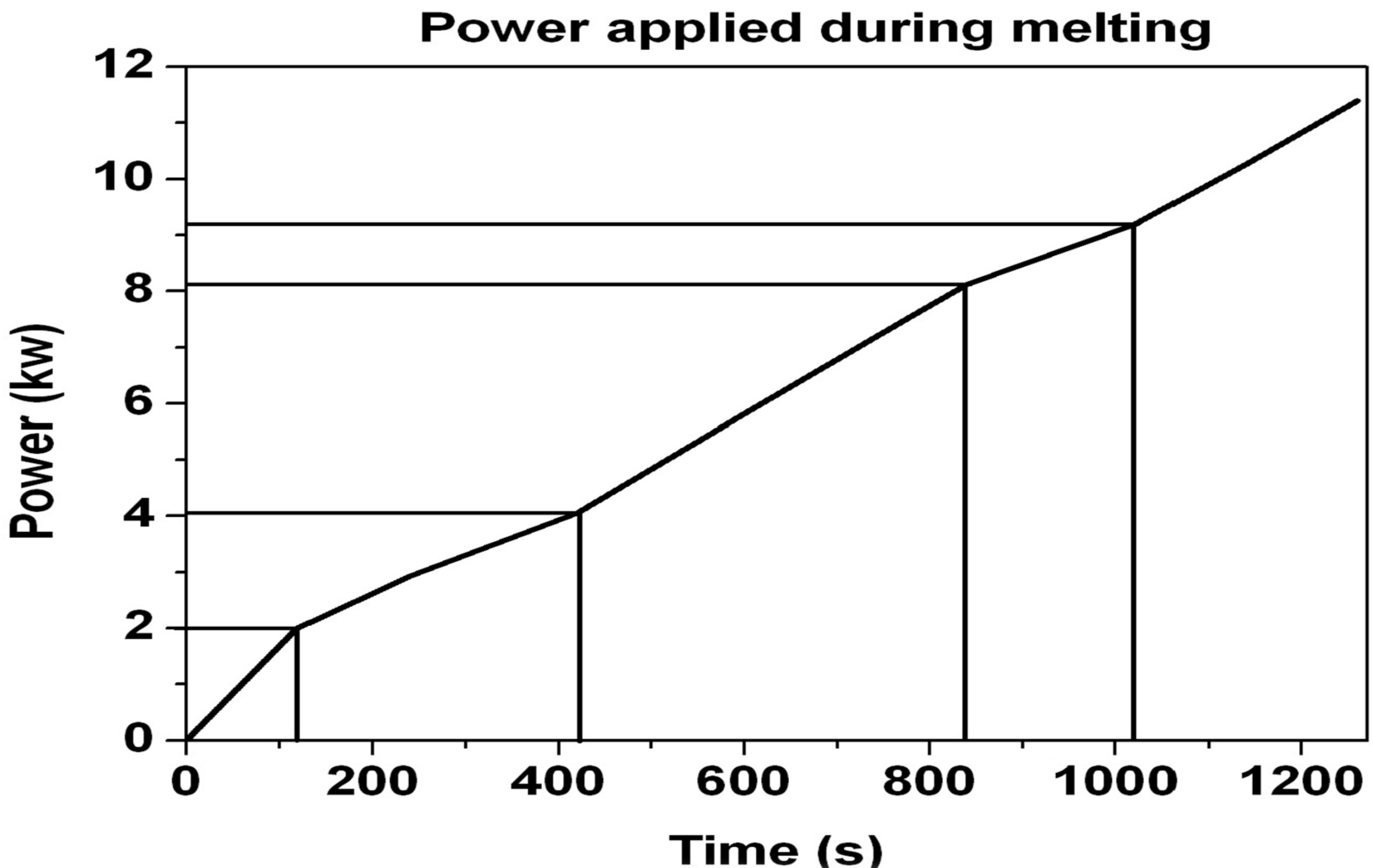
Sample Experimental Data Used

Parameters	Values
Melt Charge Dimensions And Configuration	
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
Cooling System Parameters	
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

Calculations and Derivations

Graphs

Power vs. Time



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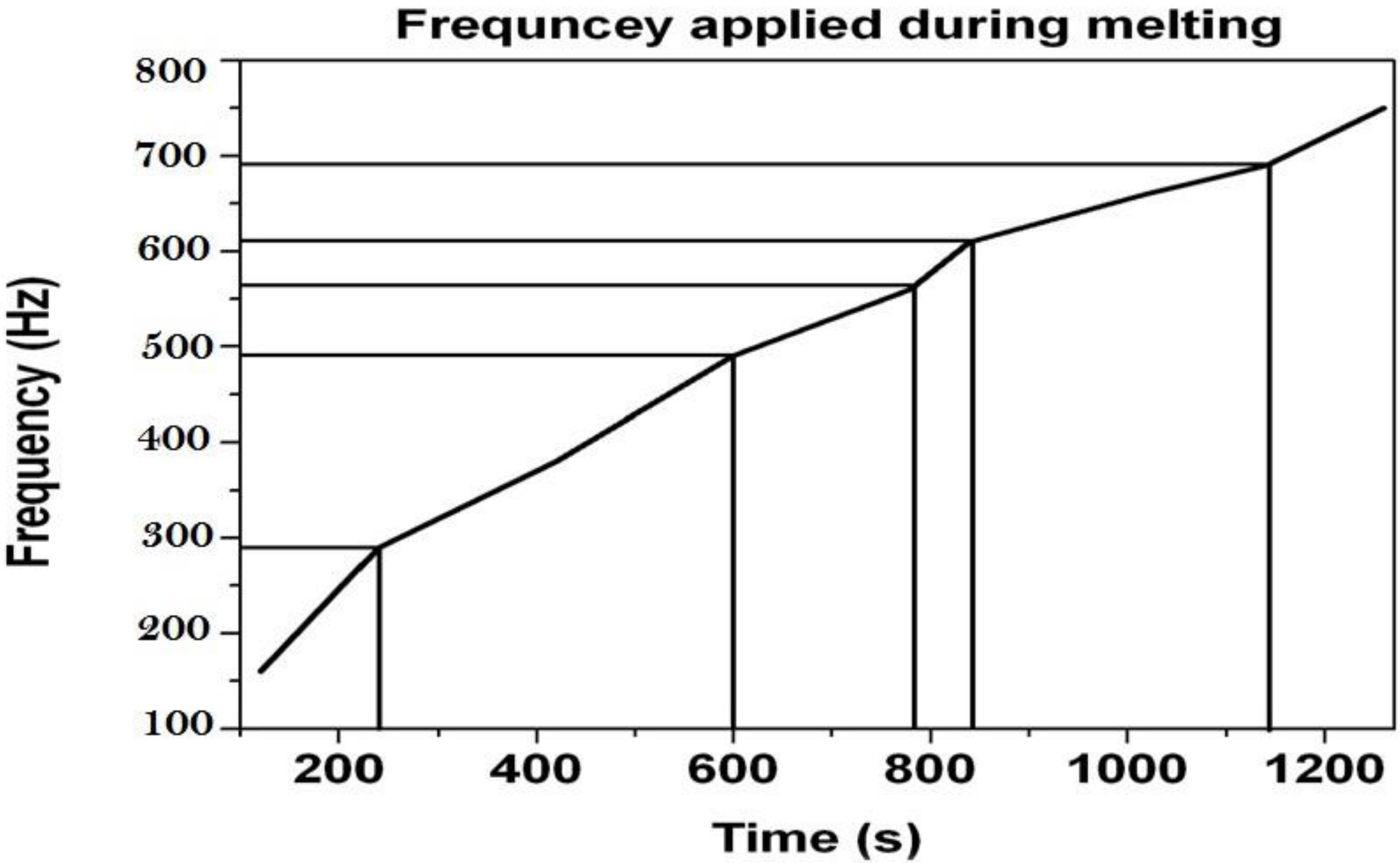
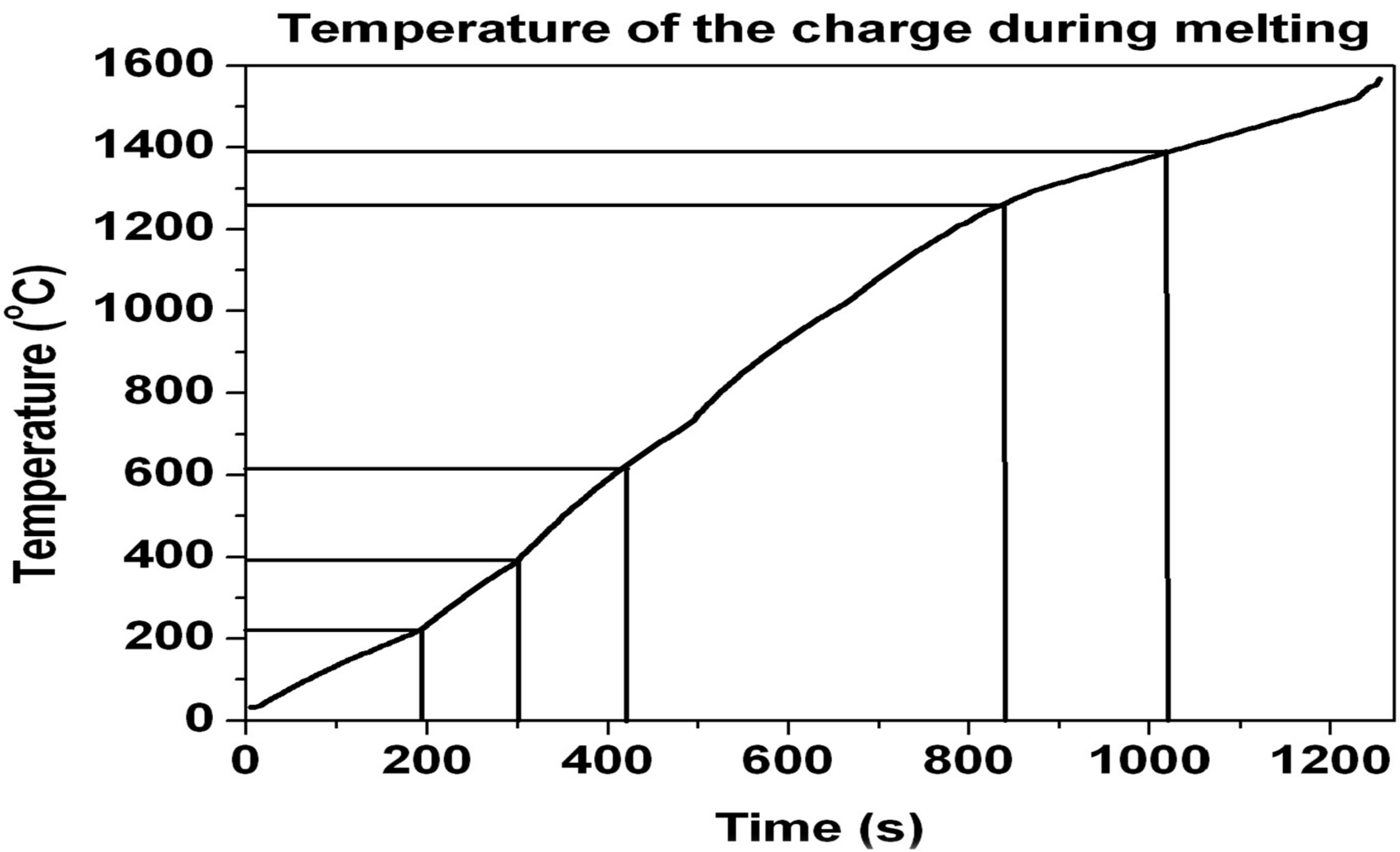
Calculations and Derivations

Frequency vs. Time

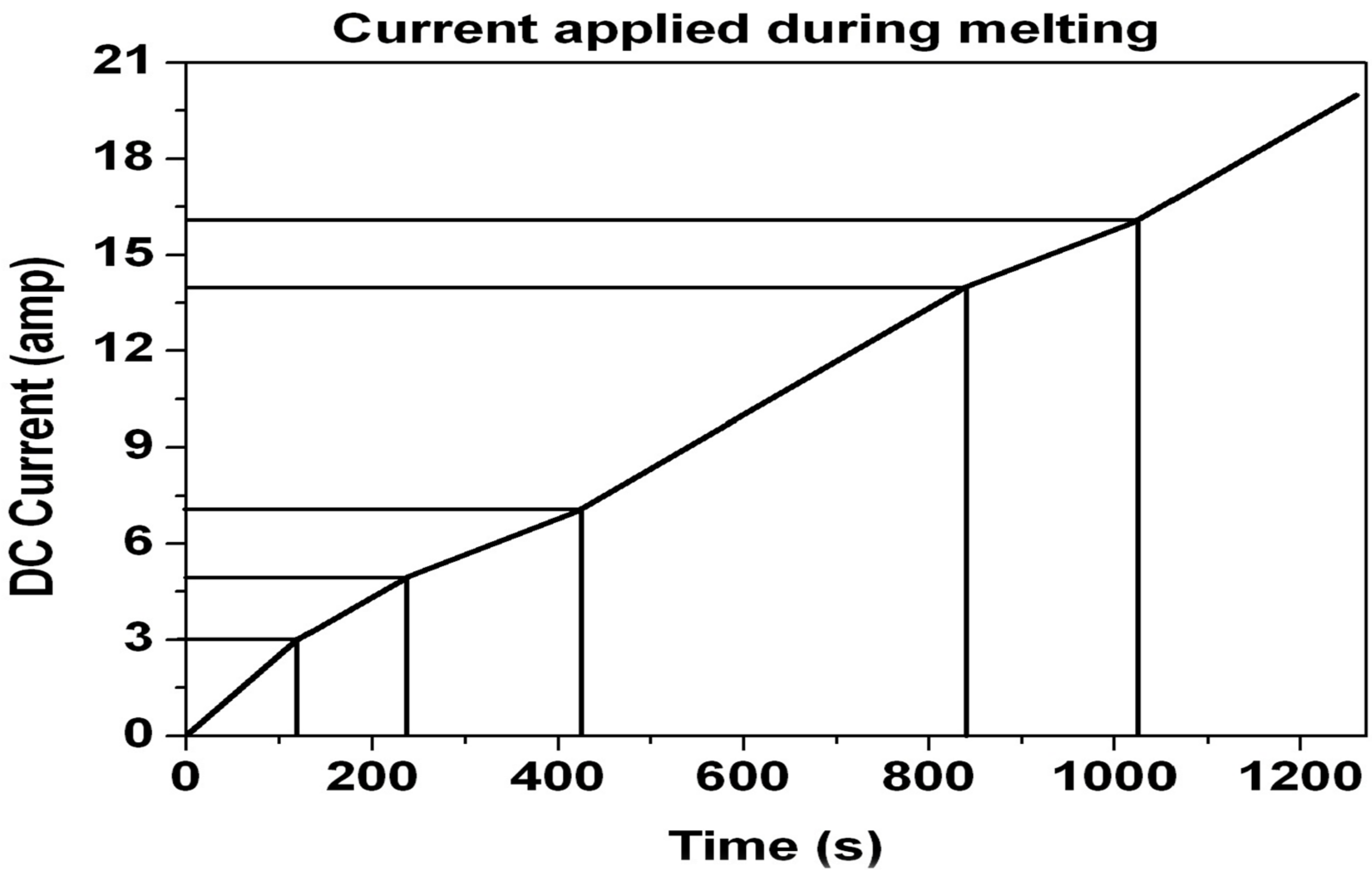


Temperature vs. Time



Calculations and Derivations

Current vs. Time



Calculations.

Specific Heat Equation:-

$\Delta Q = Csp\Delta T$

$\Delta Q = mL$

$\Delta T = Tfin - Tin$

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,

$$\Delta Q = 60\left(0.115(1405.5 - 303.15) + 52.91474 + 0.198(1873.15 - 1405.5)\right) +$$

$$500\left(0.5(1673.15 - 303.15) + 272.5 + 0.8(1873.15 - 1673.15)\right)$$

$$= 16336.7814 + 558750$$

$$= 575086.7814 J$$

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

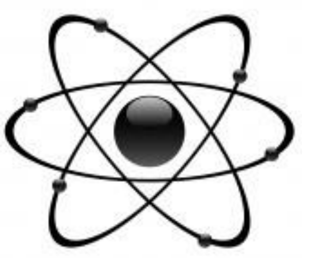
$$= 479.2389845 W$$

Average Input Power (From Graph) Graph

$P_i = 5.5$ kW

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

Efficiency=8.713436081818%



Calculations and Derivations

Heat Absorbed By Cooling System

Specific Heat Equation:-

$\Delta Q = Csp\Delta T$

$\Delta Q = mL$

$\Delta T = Tfin - Tin$

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/m^3

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

Vol.=4*20=80 L= .08 m^3

Mass=78560g

Air Density= 1.2754 kg/m^3

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

Vol.=1000*20=20000 L= 20 m^3

Mass=25508g

Therefore, Heat removed by cooling system

$\Delta Q = 78560(1.65(87-21) +$

$25508(1.005(51-27))$

$= 8555184+615252.96=9170436.96J$

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

$=7.6420308$ kW (Power loss during peak consumption)