MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE564 Project #1

March 27, 2018

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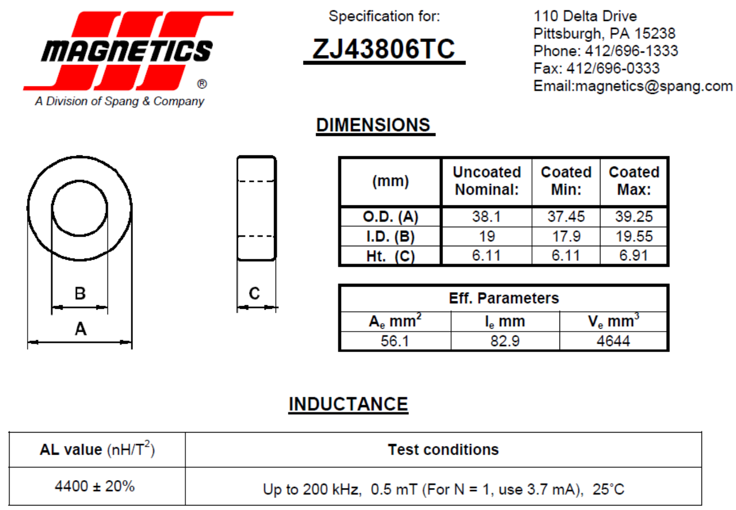
1 Inductor Design

In this part, I have designed an inductor with a toroidal core, whose datasheet is given in Figure 1.


MAGNETICS®
A Division of Spang & Company

Specification for:
ZJ43806TC

110 Delta Drive
Pittsburgh, PA 15238
Phone: 412/696-1333
Fax: 412/696-0333
Email:magnetics@spang.com

DIMENSIONS

(mm)	Uncoated Nominal:	Coated Min:	Coated Max:
O.D. (A)	38.1	37.45	39.25
I.D. (B)	19	17.9	19.55
Ht. (C)	6.11	6.11	6.91

Eff. Parameters		
A_e mm^2	l_e mm	V_e mm^3
56.1	82.9	4644

INDUCTANCE

AL value (nH/T^2)	Test conditions
4400 ± 20%	Up to 200 kHz, 0.5 mT (For N = 1, use 3.7 mA), 25°C

Figure 1: Datasheet of the Toroidal Core

I chose the number of turns as 15, and Dc current as 0.3 A, in order to obtain N.I= 4.5 A.turns, which makes the inductor operate in linear region, but close to saturation. These choices are verified by calculating, calculations are as follows:

$$\frac{B * L_{eff}}{\mu_0 * \mu_r} = N * I$$

$$B = \frac{4.5 * 5000 * 4 * \pi * 10^{-7}}{0.0829} = 0.341T$$

Analytical calculations of inductance (with MATLAB code) are given below. It should be considered that BH curve data used in non-linear material calculations does not belong to the material that I have chosen. Its relative permeability is around 4000, where that of my toroid of choice is 5000. An additional difference is also expected in analytical calculations because of this fact.

Part A

Parameters

```
in_dia= 19; %mm
in_rad=in_dia/2*1e-3;
out_dia= 38.1; %mm
out_rad=out_dia/2*1e-3;
ht= 6.11; %mm

Leff=82.9; %mm
Aeff=56.1; %mm^2

N=15 ;% turns
I=0.3; % A

mu_r=5000;
mu_0=4*pi*1e-7;

AL=4400; %nH/turns^2
```

Analytical Calculations

```
%
% # 1

reluctance=Leff*1e-3/(Aeff*1e-6*mu_r*mu_0);

L=N^2/reluctance; %H

fprintf('Inductance assuming homogeneous distribution is %d H. \n', L);

% # 2
% In this part, H.dl should be integrated over over the cross-section of
% coaxial circles with radii from in_dia/2 to out_dia/2.
% H*2*pi*(out_rad-in_rad)=N.I

index=linspace(in_rad,out_rad,500);
for i=1:numel(index)

    H(:,i)=N*I/(2*pi*index(:,i));
    B(:,i)=mu_0*mu_r*H(:,i); %T
    Phi(:,i)=B(:,i)*ht*1e-3*(out_rad-in_rad)/500; %Wb
end
```

```
tot_phi=0;

for k=1:500

   tot_phi=tot_phi+Phi(:,i);

end

L_2=tot_phi*N/I;

fprintf('Inductance assuming non-homogeneous distribution is %d H. \n', L_2);
%
% # 3_1
%
I_2=I*1.5;

H_2=N*I_2/(Leff*1e-3);

B_2=interp1(B_nl,H_nl,H_2);

phi_2=Aeff*1e-6*B_2;

L_3=N*phi_2/I_2;

fprintf('Inductance assuming homogeneous distribution & non-homogeneous material is %d H

%
% # 3_2
%


index=linspace(in_rad,out_rad,500);
for i=1:numel(index)

    H_3(:,i)=N*I_2/(2*pi*index(:,i));
    B_3(:,i)=interp1(B_nl,H_nl,H_3(:,i));
    Phi(:,i)=B_3(:,i)*ht*1e-3*(out_rad-in_rad)/500; %Wb
end

tot_phi=0;
```

```
for k=1:500

   tot_phi=tot_phi+Phi(:,i);

end

L_4=tot_phi*N/I_2;

fprintf('Inductance assuming non-homogeneous distribution & non-homogeneous material is

%
% # 4
%

rel_gap=2e-3/(mu_0*Aeff*1e-6);
rel_core=(Leff-2)*1e-3/(Aeff*1e-6*mu_r*mu_0);
rel_tot=rel_gap+rel_core;

L_5=N^2/rel_tot;

fprintf('Inductance of the gapped core assuming homogeneous distribution is %d H. \n', L

%
% # 5
%

% In this part, we may assume the fringing flux is considerable for an area
% of 2 mm (the length of airgap) to the left and to the right of the
% airgap. Therefore we may assume the equivalent reluctance of the magnetic
% circuit as R_core in series with (R_gap_left||R_gap||R_gap_right). This
% approach is not a reliable one, nevertheless it may give us an idea.

rel_gap_side=2e-3/(mu_0*2e-3*ht*1e-3);
rel_tot_2=rel_core+(1/rel_gap_side+1/rel_gap+1/rel_gap_side)^(-1);

L_6=N^2/rel_tot_2;

fprintf('Inductance of the gapped core including fringing flux is %d H. \n', L_6);
```

```
Inductance assuming homogeneous distribution is 9.566889e-04 H.
Inductance assuming non-homogeneous distribution is 6.891791e-04 H.
Inductance assuming homogeneous distribution & non-homogeneous material is 5.383088e-04
```

```
Inductance assuming non-homogeneous distribution & non-homogeneous material is 5.027784e
Inductance of the gapped core assuming homogeneous distribution is 7.867304e-06 H.
Inductance of the gapped core including fringing flux is 1.125535e-05 H.
```

Part B

1. Mesh plots, B field distribution, distribution of B vectors and flux line distribution of the toroid, assuming linear magnetic material properties, are given below on Figures 2-5. Note that thin copper layer inside the toroid is excited with positive 4.5 A.t and the one that is at the outside of the toroid is excited with negative 4.5 A.t.

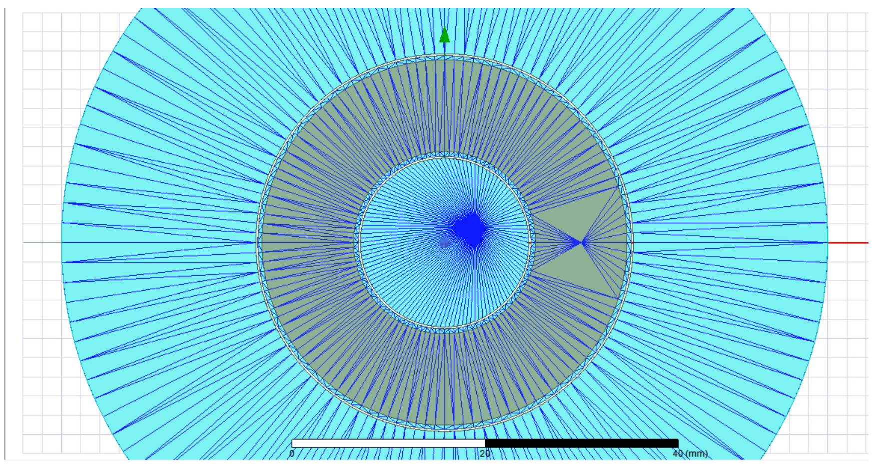


Figure 2: Mesh Operations on the Toroid

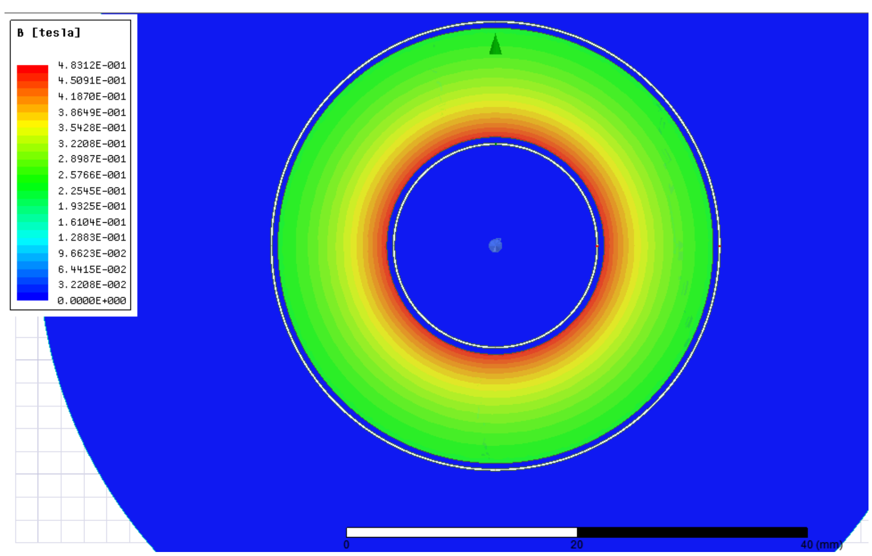


Figure 3: B Field Distribution in the Inductor

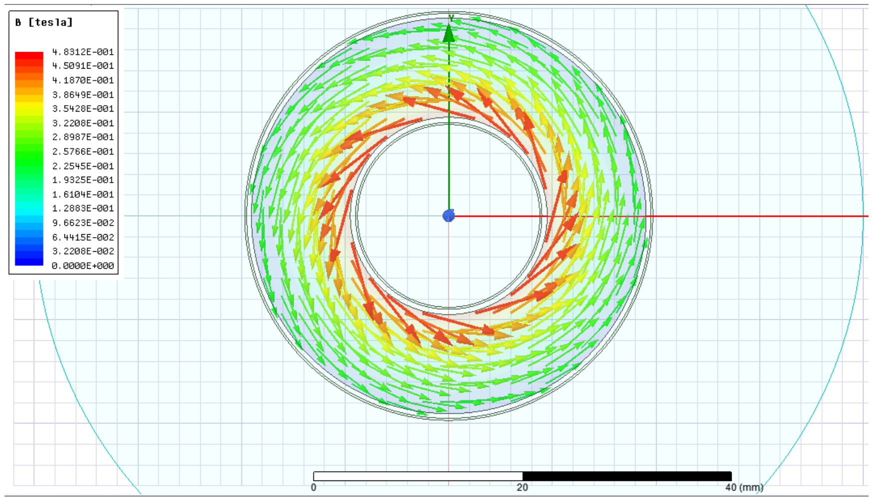


Figure 4: B Vectors in the Inductor

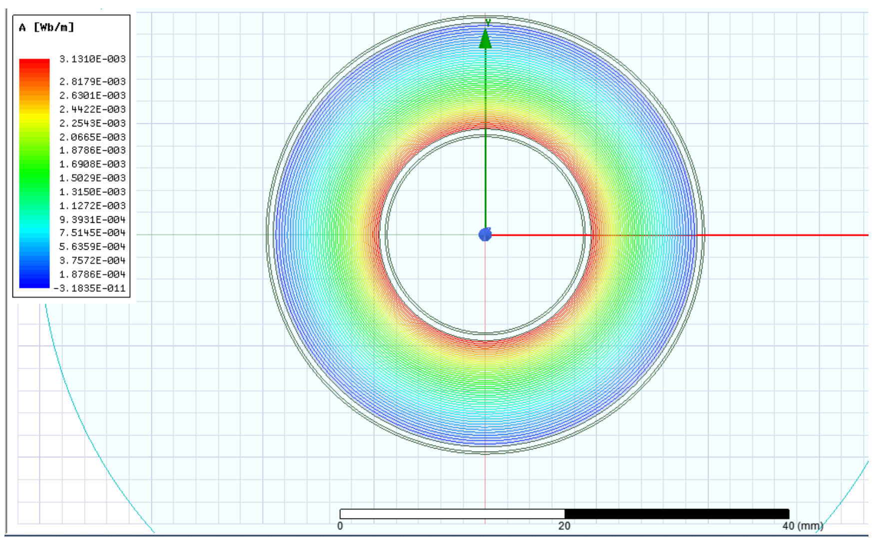


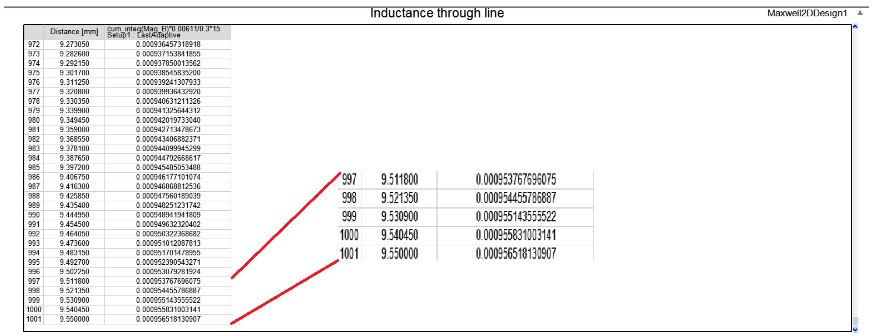
Figure 5: Flux Lines in the Toroidal Core

2. Inductance is calculated on the line from inner radius to outer radius, using the formula given below:

$$L = \frac{N * B * A}{I}$$

where A is denoted by the line, since the simulation is 2D.

To calculate the leakage inductance, same approach is used, (with a longer line crossing both inner and outer sides of the inductor) however no leakage is observed in this case. Inductance values are given on Figures 6 and 11, below.



Inductance through line

Maxwell2DDesign1

	Distance [mm]	cum_integ(Mag_B)*0.00611/0.3*15 Setup1 : LastAdaptive
972	9.273050	0.000936457318918
973	9.282600	0.000937153841855
974	9.292150	0.000937850013562
975	9.301700	0.000938545835200
976	9.311250	0.000939241307933
977	9.320800	0.000939936432920
978	9.330350	0.000940631211326
979	9.339900	0.000941325644312
980	9.349450	0.000942019733040
981	9.359000	0.000942713478673
982	9.368550	0.000943406882371
983	9.378100	0.000944099945299
984	9.387650	0.000944792668617
985	9.397200	0.000945485053488
986	9.406750	0.000946177101074
987	9.416300	0.000946868812536
988	9.425850	0.000947560189039
989	9.435400	0.000948251231742
990	9.444950	0.000948941941809
991	9.454500	0.000949632320402
992	9.464050	0.000950322368682
993	9.473600	0.000951012087813
994	9.483150	0.000951701478955
995	9.492700	0.000952390543271
996	9.502250	0.000953079281924
997	9.511800	0.000953767696075
998	9.521350	0.000954455786887
999	9.530900	0.000955143555522
1000	9.540450	0.000955831003141
1001	9.550000	0.000956518130907

997	9.511800	0.000953767696075
998	9.521350	0.000954455786887
999	9.530900	0.000955143555522
1000	9.540450	0.000955831003141
1001	9.550000	0.000956518130907

Figure 6: Inductance with Linear Material Properties

3. Here, the major observation is the saturation of the core. Also, there is a considerable drop in inductance.

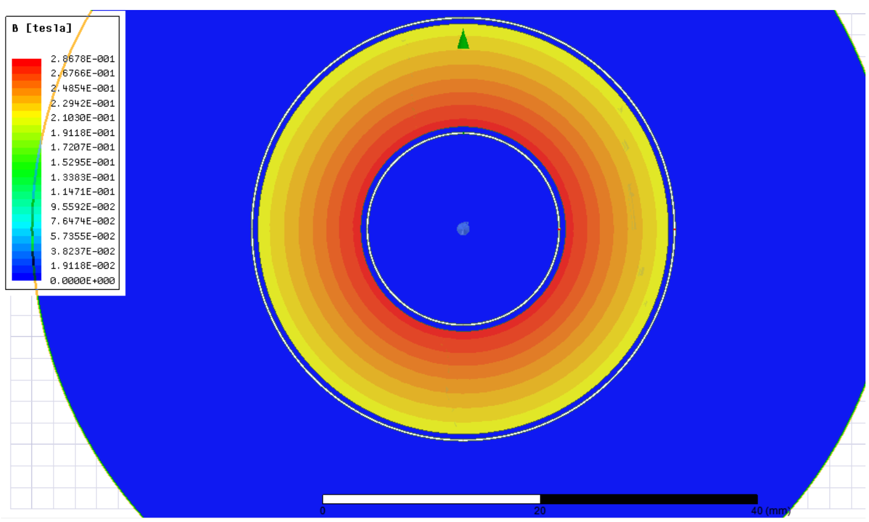


Figure 7: B Field Distribution in the Inductor with Non-Linear Material Properties

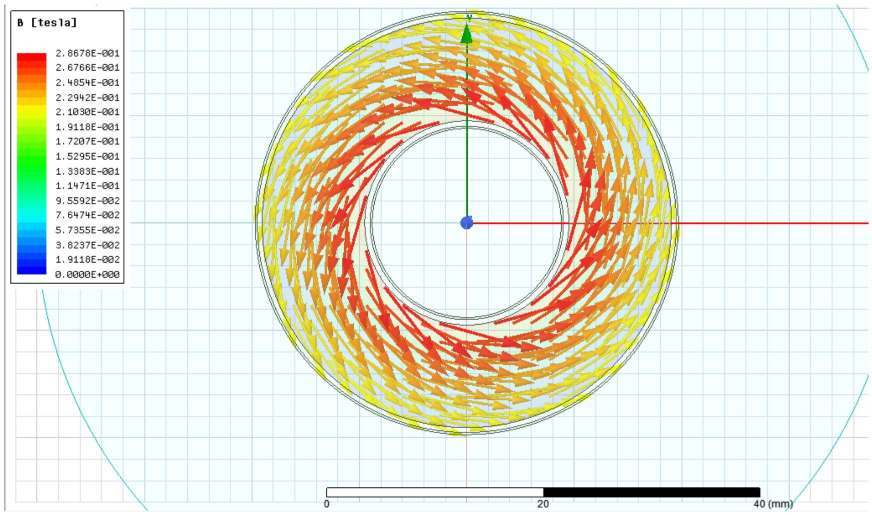


Figure 8: B Vectors in the Inductor with Non-Linear Material Properties

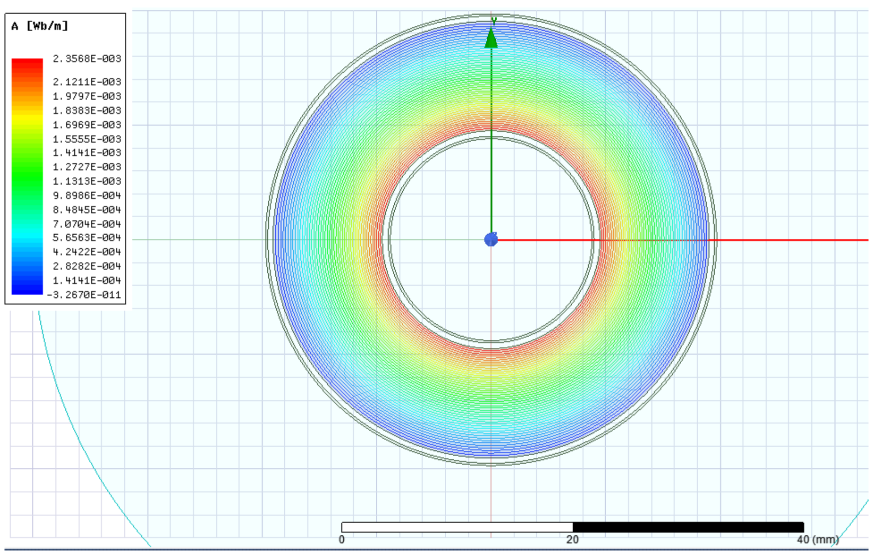
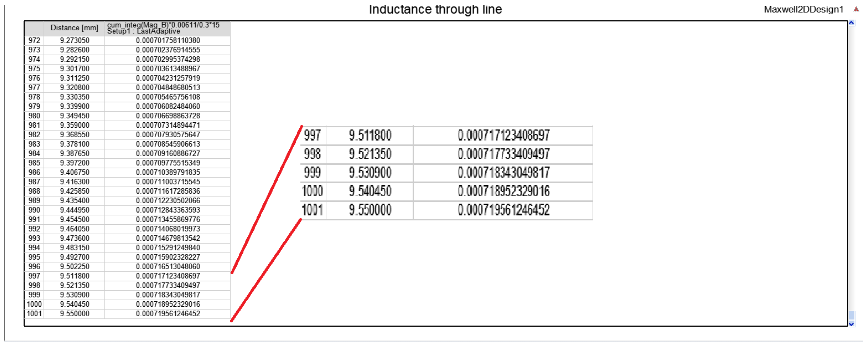
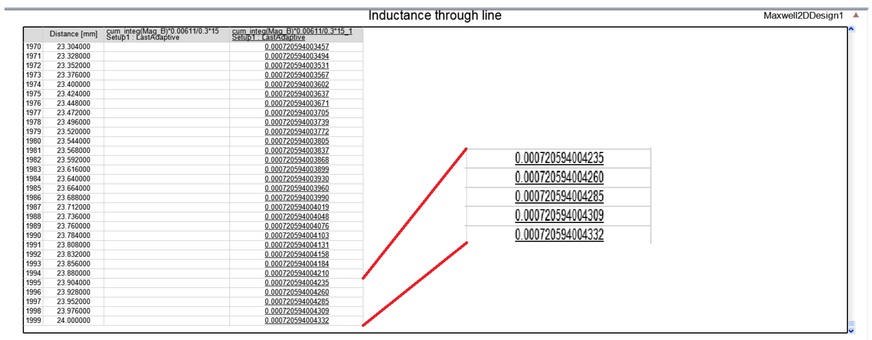


Figure 9: Flux Lines in the Toroidal Core with Non-Linear Material Properties



	Distance [mm]	cum_integ(Mag_B)*0.00611/0.3*15 Setup1 : LastAdaptive
972	9.273050	0.000701758110380
973	9.282600	0.000702376914555
974	9.292150	0.000702995374298
975	9.301700	0.000703613488967
976	9.311250	0.000704231257919
977	9.320800	0.000704848680513
978	9.330350	0.000705465756108
979	9.339900	0.000706082484060
980	9.349450	0.000706698863728
981	9.359000	0.000707314894471
982	9.368550	0.000707930575647
983	9.378100	0.000708545906613
984	9.387650	0.000709160886727
985	9.397200	0.000709775515349
986	9.406750	0.000710389791835
987	9.416300	0.000711003715545
988	9.425850	0.000711617285836
989	9.435400	0.000712230502066
990	9.444950	0.000712843363593
991	9.454500	0.000713455869776
992	9.464050	0.000714068019973
993	9.473600	0.000714679813542
994	9.483150	0.000715291249840
995	9.492700	0.000715902328227
996	9.502250	0.000716513048060
997	9.511800	0.000717123408697
998	9.521350	0.000717733409497
999	9.530900	0.000718343049817
1000	9.540450	0.000718952329016
1001	9.550000	0.000719561246452

Figure 10: Inductance with Non-Linear Material Properties



	Distance [mm]	cum_integ(Mag_B)*0.00611/0.3*15 Setup1 : LastAdaptive	cum_integ(Mag_B)*0.00611/0.3*15_1 Setup1 : LastAdaptive
1970	23.304000		0.000720594003457
1971	23.328000		0.000720594003494
1972	23.352000		0.000720594003531
1973	23.376000		0.000720594003567
1974	23.400000		0.000720594003602
1975	23.424000		0.000720594003637
1976	23.448000		0.000720594003671
1977	23.472000		0.000720594003705
1978	23.496000		0.000720594003739
1979	23.520000		0.000720594003772
1980	23.544000		0.000720594003805
1981	23.568000		0.000720594003837
1982	23.592000		0.000720594003868
1983	23.616000		0.000720594003899
1984	23.640000		0.000720594003930
1985	23.664000		0.000720594003960
1986	23.688000		0.000720594003990
1987	23.712000		0.000720594004019
1988	23.736000		0.000720594004048
1989	23.760000		0.000720594004076
1990	23.784000		0.000720594004103
1991	23.808000		0.000720594004131
1992	23.832000		0.000720594004158
1993	23.856000		0.000720594004184
1994	23.880000		0.000720594004210
1995	23.904000		0.000720594004235
1996	23.928000		0.000720594004260
1997	23.952000		0.000720594004285
1998	23.976000		0.000720594004309
1999	24.000000		0.000720594004332

Figure 11: Leakage Included Inductance with Non-Linear Material Properties

4. In this case, airgap introduces a significant increase in reluctance to the system, therefore inductance decreases considerably. Further, we can observe the effect of leakage and fringing flux on Figures 12, 13 and 14, which creates leakage inductance. Leakage inductance can be calculated bu subtracting inductance value on Figure 15 from overall inductance given in Figure 16.

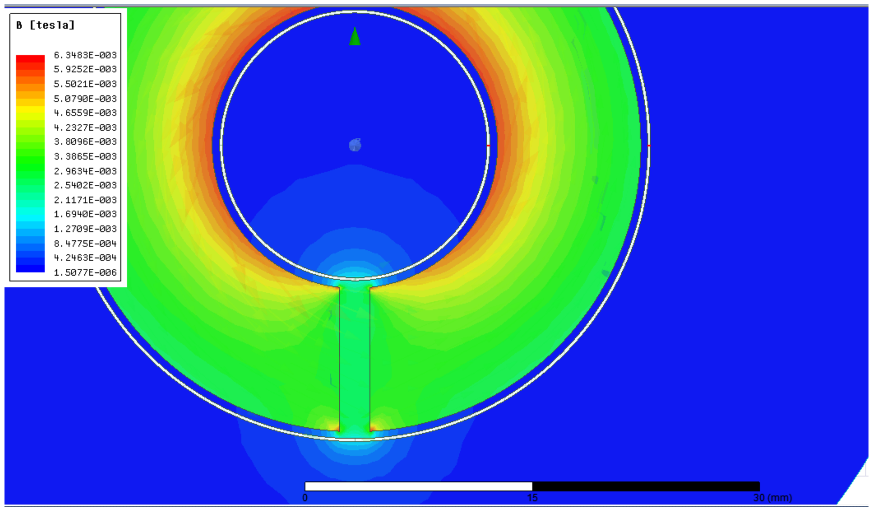


Figure 12: B Field Distribution in the Gapped Inductor with Non-Linear Material Properties

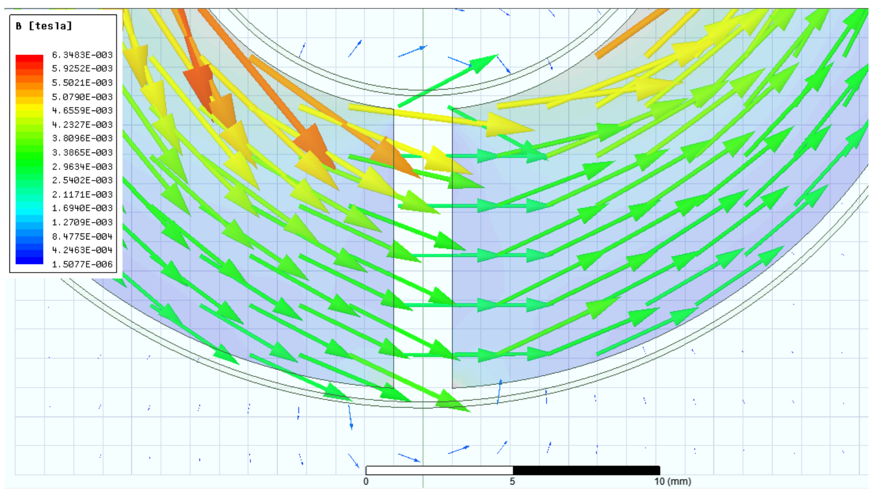


Figure 13: B Vectors in the Gapped Inductor with Non-Linear Material Properties

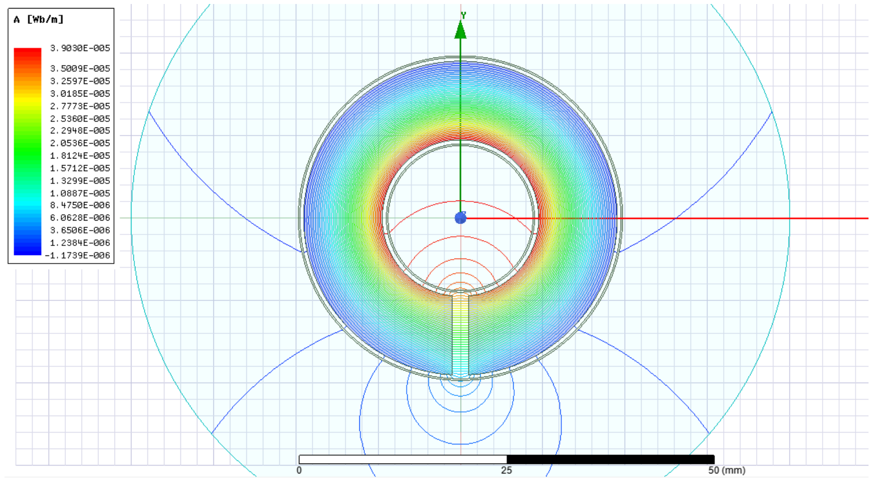
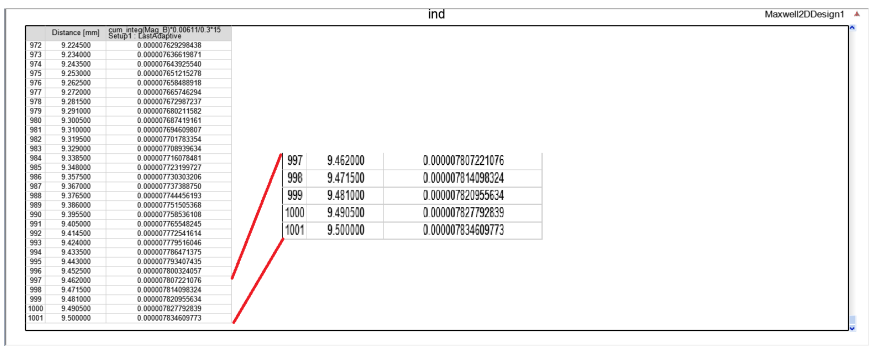


Figure 14: Flux Lines in the Gapped Toroidal Core with Non-Linear Material Properties



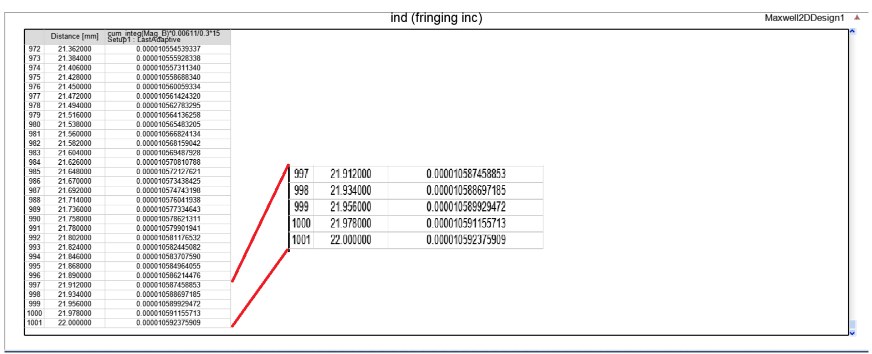
ind

Maxwell2DDesign1

	Distance [mm]	cum_integ(Mag_B)*0.00611/0.3*15 Setup1 : LastAdaptive
972	9.224500	0.000007629298438
973	9.234000	0.000007636619871
974	9.243500	0.000007643925540
975	9.253000	0.000007651215278
976	9.262500	0.000007658488918
977	9.272000	0.000007665746294
978	9.281500	0.000007672987237
979	9.291000	0.000007680211582
980	9.300500	0.000007687419161
981	9.310000	0.000007694609807
982	9.319500	0.000007701783354
983	9.329000	0.000007708939634
984	9.338500	0.000007716078481
985	9.348000	0.000007723199727
986	9.357500	0.000007730303206
987	9.367000	0.000007737388750
988	9.376500	0.000007744456193
989	9.386000	0.000007751505368
990	9.395500	0.000007758536108
991	9.405000	0.000007765548245
992	9.414500	0.000007772541614
993	9.424000	0.000007779516046
994	9.433500	0.000007786471375
995	9.443000	0.000007793407435
996	9.452500	0.000007800324057
997	9.462000	0.000007807221076
998	9.471500	0.000007814098324
999	9.481000	0.000007820955634
1000	9.490500	0.000007827792839
1001	9.500000	0.000007834609773

997	9.462000	0.000007807221076
998	9.471500	0.000007814098324
999	9.481000	0.000007820955634
1000	9.490500	0.000007827792839
1001	9.500000	0.000007834609773

Figure 15: Inductance of the Gapped Core with Non-Linear Material Properties



ind (fringing inc)

Maxwell2DDesign1

	Distance [mm]	cum_integ(Mag_B)*0.00611/0.3*15 Setup1 : LastAdaptive
972	21.362000	0.000010554539337
973	21.384000	0.000010555928338
974	21.406000	0.000010557311340
975	21.428000	0.000010558688340
976	21.450000	0.000010560059334
977	21.472000	0.000010561424320
978	21.494000	0.000010562783295
979	21.516000	0.000010564136258
980	21.538000	0.000010565483205
981	21.560000	0.000010566824134
982	21.582000	0.000010568159042
983	21.604000	0.000010569487928
984	21.626000	0.000010570810788
985	21.648000	0.000010572127621
986	21.670000	0.000010573438425
987	21.692000	0.000010574743198
988	21.714000	0.000010576041938
989	21.736000	0.000010577334643
990	21.758000	0.000010578621311
991	21.780000	0.000010579901941
992	21.802000	0.000010581176532
993	21.824000	0.000010582445082
994	21.846000	0.000010583707590
995	21.868000	0.000010584964055
996	21.890000	0.000010586214476
997	21.912000	0.000010587458853
998	21.934000	0.000010588697185
999	21.956000	0.000010589929472
1000	21.978000	0.000010591155713
1001	22.000000	0.000010592375909

997	21.912000	0.000010587458853
998	21.934000	0.000010588697185
999	21.956000	0.000010589929472
1000	21.978000	0.000010591155713
1001	22.000000	0.000010592375909

Figure 16: Leakage Included Inductance of the Gapped Core with Non-Linear Material Properties

Part C

Below, on Table 1, inductance calculation results of both methods are present.

Table 1: Comparison of Inductance Calculations

	FEA	Analytical
Linear	0.956 mH	0.957 mH
Non-Linear	0.720 mH	0.538 mH
With Airgap	7.83 μH	7.87 μH

Possible discrepancies between these calculations are caused by approximations made in analytical approach. In FEA, as calculations are made for infinitesimal elements and then integrated, it gives us more precise results. However for analytical approach, this is not possible. Hence, for calculations such as non-linear or non-homogeneous material properties, FEA technique is more reliable.

If we used 3D FEA instead of 2D, we could also observe the leakage and fringing flux through the cross-section of the core.

2 Transformer Design

With given parameters, a transformer is designed and optimized. MATLAB code for this operation is present in this section of the report.

Code for Transformer Design and Optimization

Parameters

```
B_op=1.5; %T
mu=1.83/800;
f=50; %Hz
P1= 500e3; %W
V1=34500; %V
V2=25000; %V
I1=P1/V1; %A
J=4; %A/mm^2
a_cable=I1/J; %mm^2
fprintf('Cable area should be around %d mm^2.\n',a_cable);

% This value is close to AWG11 size.

a_cable=4.1684; %mm^2
dia_cable=2.30378; %mm
res_cable=4.1328; %Ohms/km
```

```
Cable area should be around 3.623188e+00 mm^2.
```

Sizing

```
% Recalling the equation: V_ind=2*pi/sqrt(2)*f*B*A*N
% A*N is constant and they are dependent on each other. Optimum values of
% them will be found with an optimization parameter "k".

ff=0.5; %fill factor
dens_steel=7650; %kg/m^3
dens_copper=8940; %kg/m^3
core_loss_dens=0.77; %W/kg
price_steel=3; %$/kg
price_copper=7; %$/kg

i=1;
for k=5:15

    N1(:,i)=69*k;
    N2(:,i)=50*k;
    A(:,i)=V2*sqrt(2)/(2*pi*f*B_op*N1(:,i)); %m^2

    % Window area

    x1(:,i)=dia_cable*23/ff/1000; %m
    x2(:,i)=dia_cable*3*k/ff/1000; %m
    x3(:,i)=ceil(sqrt(A(:,i)*10000))/100; %m

    w1(:,i)=x1(:,i);
    w2(:,i)=2*x2(:,i)+0.03;

%     fprintf('Window area is %d m^2.\n',w1(:,i)*w2(:,i));

    % Overall dimensions

    e1(:,i)=w1(:,i)+2*x3(:,i);
    e2(:,i)=w2(:,i)+2*x3(:,i);

%     fprintf('Dimensions of the transformer is %d x %d x %d m.\n',e1(:,i),e2(:,i),x3(:,

    vol(:,i)=(e1(:,i)*e2(:,i)-w1(:,i)*w2(:,i))*x3(:,i);
```

```
    m_steel(:,i)=dens_steel*vol(:,i);

%     fprintf('Steel mass is %d kg.\n',m_steel(:,i));

    core_loss(:,i)=core_loss_dens*m_steel(:,i);

%     fprintf('Core loss is %d Watts.\n',core_loss(:,i));

    % Cable length

    mean_length(:,i)=2*(x2(:,i)/2+x3(:,i))+pi*x3(:,i)*sqrt(2); %m
    l1(:,i)=mean_length(:,i)*N1(:,i);
    l2(:,i)=mean_length(:,i)*N2(:,i);

    r1(:,i)=l1(:,i)*res_cable/1000; %Ohms
    r2(:,i)=r1(:,i)*(N2(:,i)/N1(:,i))^2; %Ohms

    vol_copper(:,i)=2*l1(:,i)*a_cable/1000000; %m^3
    m_copper(:,i)=vol_copper(:,i)*dens_copper; %kg

%     fprintf('Copper mass is %d kg.\n',m_copper(:,i));

    copper_loss(:,i)=I1^2*r1(:,i)*2; %W

%     fprintf('Copper loss is %d Watts.\n',copper_loss(:,i));

    % Inductances

    % Assuming L1 and L2 are 0.02 pu;

    ind1=V1^2/(P1*2*pi*f)*0.02; %H
    ind2=ind1*(N2/N1)^2; %H

    Leff(:,i)=2*(w1(:,i)+w2(:,i)+2*x3(:,i)); %m

    ind_m(:,i)=N1(:,i).^2*mu*A(:,i)/Leff(:,i); %H

    % Efficiency

    eff(:,i)=P1/(P1+core_loss(:,i)+copper_loss(:,i))*100; %percent

    % Cost
```

```
    cost(:,i)=price_copper*m_copper(:,i)+price_steel*m_steel(:,i); %$

    %Unit price of electricity: 0.4482 TL = 0.1125 USD

    lost_power(:,i)=P1*(100-eff(:,i))/1000; %kW

    lost_energy(:,i)=lost_power(:,i)*24*365*20*0.1125; %$

    cost_actual(:,i)=cost(:,i)+lost_energy(:,i); %$


    i=i+1;
end
```

Conclusion

```
% Considering the optimizaton results, optimum case for the design seems to
% be i=6, k=10. Transformer parameters are as follows:

k=10;
i=6;

    N1(:,i)=69*k;
    N2(:,i)=50*k;
    A(:,i)=V2*sqrt(2)/(2*pi*f*B_op*N1(:,i)); %m^2



    % Window area

    x1(:,i)=dia_cable*23/ff/1000; %m
    x2(:,i)=dia_cable*3*k/ff/1000; %m
    x3(:,i)=ceil(sqrt(A(:,i)*10000))/100; %m

    w1(:,i)=x1(:,i);
    w2(:,i)=2*x2(:,i)+0.03;


    % Overall dimensions

    e1(:,i)=w1(:,i)+2*x3(:,i);
    e2(:,i)=w2(:,i)+2*x3(:,i);
```

```
vol(:,i)=(e1(:,i)*e2(:,i)-w1(:,i)*w2(:,i))*x3(:,i);

m_steel(:,i)=dens_steel*vol(:,i);

core_loss(:,i)=core_loss_dens*m_steel(:,i);

% Cable length

mean_length(:,i)=2*(x2(:,i)/2+x3(:,i))+pi*x3(:,i)*sqrt(2); %m
l1(:,i)=mean_length(:,i)*N1(:,i);
l2(:,i)=mean_length(:,i)*N2(:,i);

r1(:,i)=l1(:,i)*res_cable/1000; %Ohms
r2(:,i)=r1(:,i)*(N2(:,i)/N1(:,i))^2; %Ohms

vol_copper(:,i)=2*l1(:,i)*a_cable/1000000; %m^3
m_copper(:,i)=vol_copper(:,i)*dens_copper; %kg

copper_loss(:,i)=I1^2*r1(:,i)*2; %W

% Inductances

% Assuming L1 and L2 are 0.02 pu;

ind1=V1^2/(P1*2*pi*f)*0.02; %H
ind2=ind1*(N2/N1)^2; %H

Leff(:,i)=2*(w1(:,i)+w2(:,i)+2*x3(:,i)); %m

ind_m(:,i)=N1(:,i).^2*mu*A(:,i)/Leff(:,i); %H

% Efficiency

eff(:,i)=P1/(P1+core_loss(:,i)+copper_loss(:,i))*100; %percent

% Cost

cost(:,i)=price_copper*m_copper(:,i)+price_steel*m_steel(:,i); %$


%Unit price of electricity: 0.4482 TL = 0.1125 USD
```

```
    lost_power(:,i)=P1*(100-eff(:,i))/1000; %kW

    lost_energy(:,i)=lost_power(:,i)*24*365*20*0.1125; %$

    cost_actual(:,i)=cost(:,i)+lost_energy(:,i); %$

    fprintf('Turns ratio is %d : %d. \n',N1(:,i),N2(:,i));

    fprintf('Window area is %d m^2.\n',w1(:,i)*w2(:,i));

    fprintf('Dimensions of the transformer is %d x %d x %d m.\n',e1(:,i),e2(:,i),x3(:,i)

    fprintf('Steel mass is %d kg.\n',m_steel(:,i));

    fprintf('Core loss is %d Watts.\n',core_loss(:,i));

    fprintf('R1= %d Ohms, R2= %d Ohms. \n',r1(:,i),r2(:,i));

    fprintf('Copper mass is %d kg.\n',m_copper(:,i));

    fprintf('Copper loss is %d Watts.\n',copper_loss(:,i));

    fprintf('L1= %d H, L2= %d H, Lm= %d H. \n',ind1,ind2,ind_m(:,i));

    fprintf('Efficiency is %d percent. \n',eff(:,i));

    fprintf('Material cost is %d USD. Lost money in 20 years is %d USD. \n',cost(:,i),co
```

```
Turns ratio is 690 : 500.
Window area is 3.247608e-02 m^2.
Dimensions of the transformer is 7.659739e-01 x 9.664536e-01 x 3.300000e-01 m.
Steel mass is 1.786846e+03 kg.
Core loss is 1.375872e+03 Watts.
R1= 6.457173e+00 Ohms, R2= 3.390660e+00 Ohms.
Copper mass is 1.164488e+02 kg.
Copper loss is 2.712528e+03 Watts.
L1= 1.515473e-01 H, L2= 7.957747e-02 H, Lm= 5.521107e+01 H.
Efficiency is 9.918895e+01 percent.
Material cost is 6.175681e+03 USD. Lost money in 20 years is 7.999056e+06 USD.
```

Here, for the design of the transformer, the main objective is to find an optimum point where $P_{core} = P_{copper}$, since this is the case where efficiency is maximum.

These two variables are dependent on each other, since induced voltage in the tranformer includes a constant term "N*A". This implies that number of turns of the transformer should be inversely proportional to the cross-section area of the core, which are actually the parameters that determines core and copper losses.

A graph that shows the relationship of core loss, copper loss and efficiency is given in Figure 17. The optimum point is chosen as the point where efficiency is maximum. However at this point, core loss and copper loss are not exactly equal to each other. This discrepancy is caused by (wire mean length) assumptions made in calculation of copper loss.

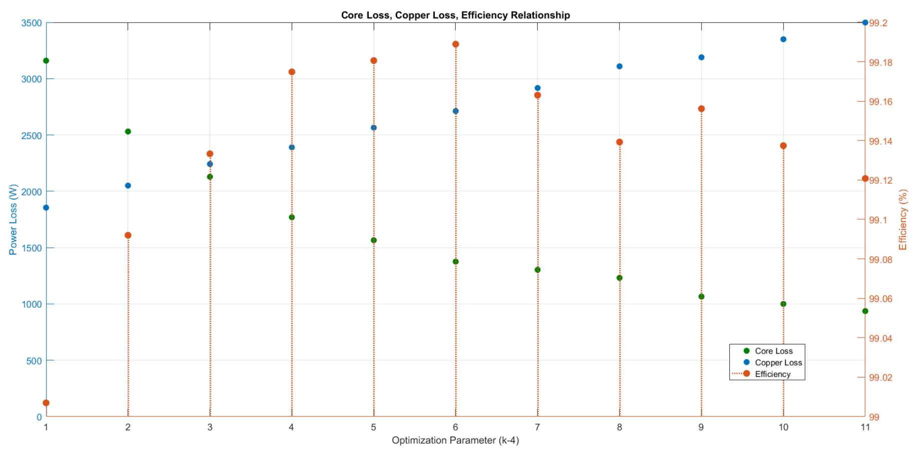


Figure 17: Relationship Between Core Loss, Copper Loss and Efficiency

Another concern in design of a transformer is obviously the price. What is important is not only the material price of the transformer, but also the money lost due to power lost while the transformer operates. Therefore cost should be considered in both cases. A graph showing this cost analysis is provided in Figure 18. Here, the most optimum case is also same as the previous one, since its efficiency is the highest.

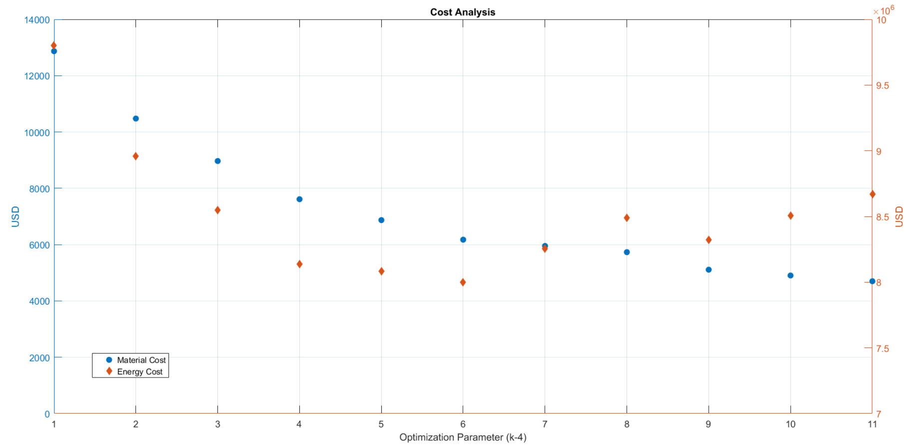


Figure 18: Cost Analysis

Different lamination types also effects the specifications of the transformer. As can be seen in Figure 19, core losses increase with increasing lamination thickness. This would have a significant effect on efficiency.

In this design, first lamination type (C120-23) is considered.

Grade	THICKNESS		TYPICAL CORE LOSS AT				GUARANTEED CORE LOSS AT		TYPICAL POLARIZATION AT
powercore®	mm	inch	1.5 T 50 Hz W/kg	1.7 T 50 Hz W/kg	1.5 T 60 Hz W/lb	1.7 T 60 Hz W/lb	1.7 T 50 Hz W/kg	1.7 T 60 Hz W/lb	800 A/m typ. T
C 120-23	0.23	0.009	0.77	1.18	0.46	0.71	1.20	0.72	1.83
C 120-27	0.27	0.011	0.80	1.18	0.48	0.71	1.20	0.72	1.83
C 130-27	0.27	0.011	0.83	1.23	0.50	0.74	1.30	0.78	1.83
C 120-30	0.30	0.012	0.82	1.18	0.49	0.71	1.20	0.72	1.83
C 130-30	0.30	0.012	0.84	1.23	0.50	0.74	1.30	0.78	1.83
C 150-30	0.30	0.012	0.93	1.43	0.56	0.85	1.50	0.89	1.78
C 165-35	0.35	0.014	1.00	1.48	0.60	0.88	1.65	0.99	1.78

Figure 19: Properties of Steel Laminations