Worksheet 3 — Ferromagnetic Hysteresis Ratio

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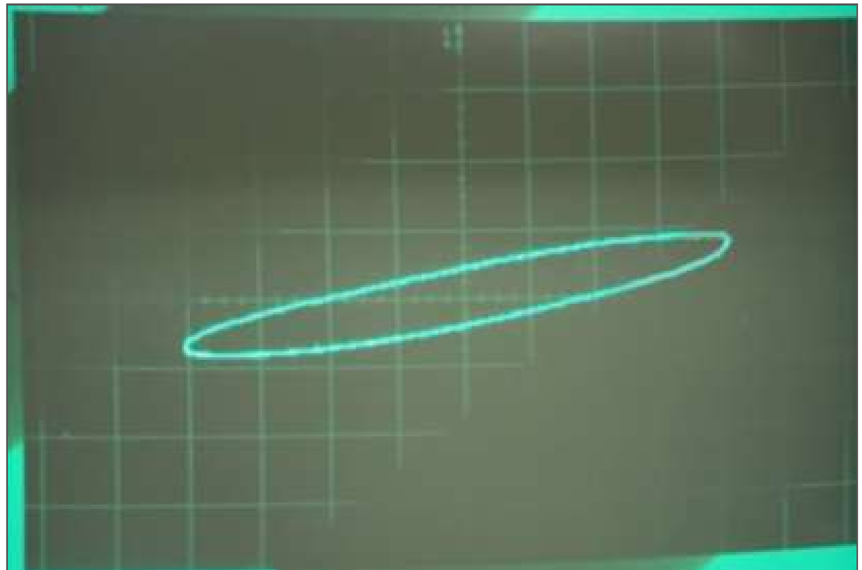

Figure 1: Example of Hysteresis Curve

Table of Contents:

1 – Preamble

1A – Modules

Import NumPy, Matplotlib, SymPy, and more

In [1]:
```
%pylab inline
import re
import sympy
from IPython.display import display, Markdown, Latex, Image
import scipy.interpolate as interpolate
import scipy.integrate as integrate
import scipy.constants
from ipywidgets import IntSlider, interact
import scipy.stats as stats

# Set all figures to a default size of
rcParams['figure.figsize'] = 14, 8
```

```
Populating the interactive namespace from numpy and matplotlib
```

1B – Units

Define units to convert measurements to SI

In [2]:
```
s = 1         # Seconds
m = 1         # Meters
cm = 1e-2*m   # Centimeters
mm = 1e-3*m   # Milimeters
T = 1         # Teslas
nT = 1e-9     # Nanoteslas
V = 1         # Volts
mV = V*1e-3   # Milivolts
Ω = 1         # Ohms
MΩ = Ω*1e6    # Megaohms
F = 1         # Farads
μF = F*1e-6   # Micofarads
```

2 – Functions

2A – Model

In [3]:
```
def H(n_1, L, L_d, S, S_d, V_s):
    h = n_1 * V_s / (L*S)
    h_d = h * sqrt( (L_d/L)**2 + (S_d/S)**2)
    return h, h_d
```

In [4]:
```
def B(R, R_d, C, C_d, n_2, A_c, A_c_d, V_c):
    b = R*C*V_c/(n_2*A_c)
    b_d = b*sqrt( (R_d/R)**2 + (C_d/C)**2 + (A_c_d/A_c)**2)
    return b, b_d
```

In [5]:
```
def P(A, A_d, V, V_d, f):
    p = A*V*f
    p_d = p*sqrt( (A_d/A)**2 + (V_d/V)**2 )
    return p, p_d
```

In [6]:
```
def μ_r(B, B_d, H, H_d):
    μ = B/(H*scipy.constants.mu_0)
    μ_d = μ * sqrt( (B_d/B)**2 + (H_d/H)**2)
    return μ, μ_d
```

2B – Data Processing Functions

Read data in from CSV into a dictionary of vectors:

In [7]:
```
def open_from_csv(filename):
    data = {}
    data['t'], data['V_s'], data['V_c'] = loadtxt(
        filename,
        delimiter=',',
        unpack=True,
        skiprows=2
    )
    data['t'] *= s  # Seconds
    data['V_s'] *= V # Volts
    data['V_c'] *= V # Volts

    data['name'] = filename.split('.')[-2]
    return data
```

Convert a float into a latex exponential notation: **`latex_exp(2.3e-3)`** $\rightarrow 2.3 \times 10^{-3}$|

In [8]:
```
def latex_exp(x, pres=2):
    exp = int(math.log10(abs(x)))
    mant = abs(x) / 10**exp * sign(x)
    return ('{:.'+str(pres)+'f} \\times 10^{{{:d}}}').format(mant, exp)
```

In [9]:
```
def display_tabular_data(headers, data):
    output = '|'+'|'.join(str(h) for h in headers)+'|\n' +\
             '|'+'|'.join('-' for h in headers)+'|\n'
    output += '\n'.join('|'+'|'.join(str(v) for v in row)+'|' for row in data)
    return Markdown(output)
```

2C – Data Analysis Functions

Function that let's user drag a slider to select the turning points from the graph. Based off sample from OnQ.

In [10]:
```
def user_select_ciritical_indices(data, start_guess, delta_guess):
    @interact(
        start_index=(0,1000,5),
        delta=(0, 1000, 5)
    )
    def show_plot(start_index=start_guess, delta=delta_guess):
        n1=start_index
        n2 = n1 + delta
        n3 = n2 + delta

        title('Plot of B-H data for '+data['name'])
        xlabel('time (ms)', fontsize = 16)

        plot(data['t']*1000, data['B'], 'r', label='B')
        ylabel('B (T)', fontsize = 16)
        twinx()

        plot(data['t']*1000, data['H'], 'b', label='H')
        plot(data['t'][n1]*1000, data['H'][n1], 'ro')
        plot(data['t'][n2]*1000, data['H'][n2], 'ro')
        plot(data['t'][n3]*1000, data['H'][n3], 'ro')
        ylabel('H (A/m)', fontsize = 16)

        period = data['t'][start_index+delta] - data['t'][start_index]

        data.update({
                'n1': n1,
                'n2': n2,
                'n3': n3,
                'period': period,
                'frequency': 1/period
            })
```

Split the data into top and bottom vectors. Adapted from OnQ.

In [11]:
```
def split_data_into_top_bottom(data):
    data['t_top'] = data['t'][data['n1']:data['n2']]
    data['B_top'] = data['B'][data['n1']:data['n2']]
    data['B_top_d'] = data['B_d'][data['n1']:data['n2']]
    data['H_top'] = data['H'][data['n1']:data['n2']]
    data['H_top_d'] = data['H_d'][data['n1']:data['n2']]
    data['t_bot'] = data['t'][data['n2']:data['n3']]
    data['B_bot'] = data['B'][data['n2']:data['n3']]
    data['B_bot_d'] = data['B_d'][data['n2']:data['n3']]
    data['H_bot'] = data['H'][data['n2']:data['n3']]
    data['H_bot_d'] = data['H_d'][data['n2']:data['n3']]
```

Display the hysteresis curve. Adapted from OnQ.

In [12]:
```
def hysteresis_curve(data):
    plot(
            data['H_bot'], data['B_bot'], 'r',
            data['H_top'], data['B_top'], 'b'
    )
    grid()
    xlabel('H (A/m)', fontsize = 16)
    ylabel('B (T)', fontsize = 16)
    title('Hysteresis Curve for '+data['name'])
```

Calculate the area of the hysteresis curve. Do Reimann sums under each curve, shifted above the x-axis. The difference is the area.

In [13]:
```
def calculatearea(data):
    area = abs(
        integrate.trapz(data['B_top']-min(data['B']), data['H_top'][::-1]) -
        integrate.trapz(data['B_bot']-min(data['B']), data['H_bot'])
    )
    area_d = abs(
        integrate.trapz(data['B_top_d'], data['H_top'][::-1]) +
        integrate.trapz(data['B_bot_d'], data['H_bot'])
    )
    text(min(data['H']), max(data['B'])*.4,
         "$A = "+latex_exp(area,3)+' \pm '+latex_exp(area_d,1)+'TA/m$',
         fontsize=14,
         backgroundcolor='w')
    data['A'] = area
    data['A_d'] = area_d
```

Function to determine the remenance of the material:

In [14]:
```
def remanance(data):
    closest_to_zero_index = abs(data['H_top']).argmin()
    data['B_r'] = data['B_top'][closest_to_zero_index]
    plot(0, data['B_r'], 'ro')
    text(min(data['H']), max(data['B'])*.8,
         "$B_r = "+latex_exp(data['B_r'], 3)+' T$',
         fontsize=14,
         backgroundcolor='w')
```

Function to determine the Coercive force for a given sample:

In [15]:
```
def coersive(data):
    closest_to_zero_index = abs(data['B_top']).argmin()
    data['H_c'] = data['H_top'][closest_to_zero_index]
    plot(data['H_c'], 0, 'ro')
    text(min(data['H']), max(data['B'])*.6,
         "$H_c = "+latex_exp(data['H_c'], 3)+' A/m$',
         fontsize=14,
         backgroundcolor='w')
```

3 – Data

3A – Provided Values

In [16]:
```
S = 0.10*Ω
S_d = S*0.05

n_1 = 160
n_2 = 150

R = 1.00*MΩ
R_d = R*0.01

C = 0.50*μF
C_d = C*0.02
```

3B – Accepted Values

3C – Readings

In [17]:
```
Iron_bad = open_from_csv(r'Iron_bad.CSV')

Iron = open_from_csv(r'Iron.CSV')

Steel = open_from_csv(r'Steel.CSV')
```

During the experiment, the equipment was initially setup incorrectly. This resulted in bad data until the problem was corrected.
New data was captured for each with the execption of Iron with no spacer.
Instead of this bad data, this analysis will proceed with data captured by another experimenter, Jesse Noël, with his permission.
Both are shown below:

In [18]:

```
subplot(1, 2, 1)
plot(Iron_bad['V_s']*1000, Iron_bad['V_c']*1000)
xlabel('$V_s (mV)$', fontsize=14)
ylabel('$V_c (mV)$', fontsize=14)
grid()
title('Bad data for Iron')
figtext(0.28, 0.03, "Figure 2")

subplot(1,2, 2)
plot(Iron['V_s']*1000, Iron['V_c']*1000)
xlabel('$V_s (mV)$', fontsize=14)
ylabel('$V_c (mV)$', fontsize=14)
grid()
title('Replacement Data for Iron')
figtext(0.7, 0.03, "Figure 3");


iron_25W_lightbulb_comparison = 0.7 # About 70% as hot as the lightbulb
steel_25W_lightbulb_comparison = 1.5 # About 150% as hot as the lightbulb
```

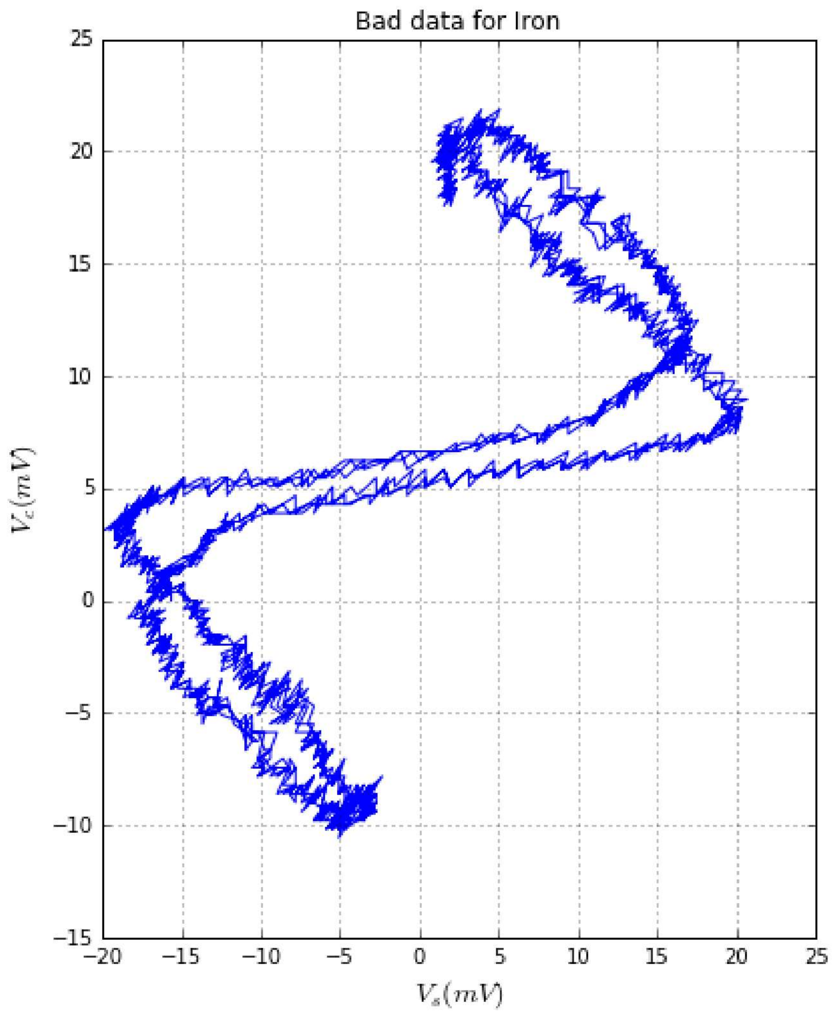

Figure 2

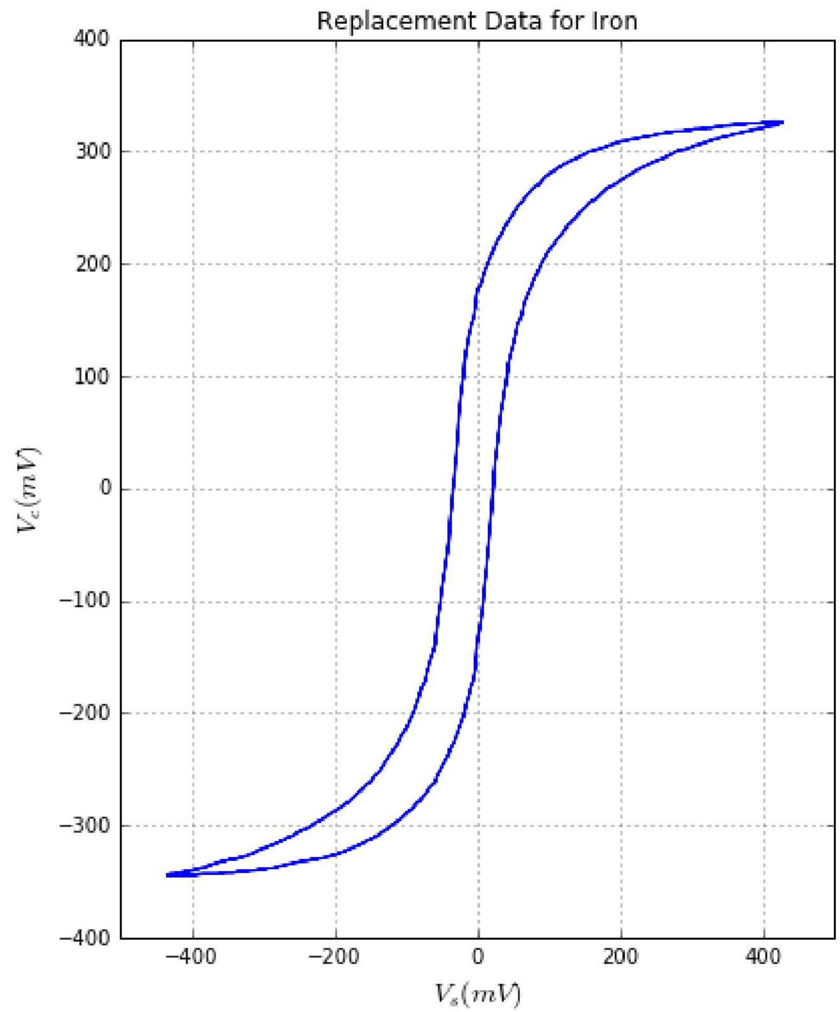

Figure 3

Excerpt of Hysteresis Measurements for Iron:

In [19]:

```
display_tabular_data(
    ['Time (s)', '$V_s$ (Volts)', '$V_c$ (Volts)'],
    column_stack([
            Iron['t'][:10], Iron['V_s'][:10], Iron['V_c'][:10]
    ])
)
```

Out[19]:

Time (s)	V_s | **(Volts)**	V_c | **(Volts)**
-0.0263	-0.354	-0.332
-0.0263	-0.358	-0.332
-0.0263	-0.362	-0.333
-0.0262	-0.367	-0.334
-0.0262	-0.371	-0.335
-0.0262	-0.375	-0.336
-0.0262	-0.379	-0.337
-0.0261	-0.382	-0.338
-0.0261	-0.387	-0.338
-0.0261	-0.391	-0.339

Excerpt of Hysteresis Measurements for Carbon Steel:

In [20]:
```
display_tabular_data(
    ['Time (s)', '$V_s$ (Volts)', '$V_c$ (Volts)'],
    column_stack([
            Steel['t'][:10], Steel['V_s'][:10], Steel['V_c'][:10]
    ])
)
```

Out[20]:

Time (s)	**V_s (Volts)**	**V_c (Volts)**
-0.025	-0.05313	-0.003125
-0.024975	-0.05391	-0.00390625
-0.02495	-0.05391	-0.00429688
-0.024925	-0.0543	-0.00507813
-0.0249	-0.05469	-0.00546875
-0.024875	-0.05547	-0.00585938
-0.02485	-0.05547	-0.00625
-0.024825	-0.05625	-0.00703125
-0.0248	-0.05586	-0.00703125
-0.024775	-0.05664	-0.00742188

3D – Area and Length Measurements

In [21]:
```
# Measurements of the iron bar
#Iron: L=34.6cm +/- 0.15, A=8.4  +/- 0.21cm
Iron['A_c'] = 8.4*cm*cm
Iron['A_c_d'] = 0.21*cm*cm
Iron['L'] = 34.6*cm
Iron['L_d'] = 0.15*cm
Iron['V'] = Iron['A_c']*Iron['L']
Iron['V_d'] = Iron['V']*sqrt( (Iron['A_c_d']/Iron['A_c'])**2 + (Iron['L_d']/Iron['L'])**2)

# Measurements of the steel bar
#Steel: L=10cm, A=7.1 +/- 0.19cm
Steel['A_c'] = 7.1*cm*cm
Steel['A_c_d'] = 0.218*cm*cm
Steel['L'] = 10*cm
Steel['L_d'] = 0.15*cm
Steel['V'] = Steel['A_c']*Steel['L']
Steel['V_d'] = Steel['V']*sqrt( (Steel['A_c_d']/Steel['A_c'])**2 + (Steel['L_d']/Steel['L'])**2)


display_tabular_data(
    ['Measurment', 'Iron', 'Carbon Steel'],
    array([
            ['$A_c (m^2)$', '%.2e'%(Iron['A_c']), '%.2e'%(Steel['A_c'])],
            ['$\Delta A_c (m^2)$', '±%.0e'%(Iron['A_c_d']), '±%.0e'%(Steel['A_c_d'])],
            ['$L (m)$', '%.2e'%(Iron['L']), '%.2e'%(Steel['L'])],
            ['$\Delta L (m)$', '±%.0e'%(Iron['L_d']), '±%.0e'%(Steel['L_d'])],
            ['$V (m^3)$', '%.2e'%(Iron['V']), '%.2e'%(Steel['V'])],
            ['$\Delta V (m^3)$', '±%.0e'%(Iron['V_d']), '±%.0e'%(Steel['V_d'])],
        ])
)
```

Out[21]:

Measurment	Iron	Carbon Steel
$A_c (m^2)$	8.40e-04	7.10e-04
$\Delta A_c (m^2)$	±2e-05	±2e-05
$L (m)$	3.46e-01	1.00e-01
$\Delta L (m)$	±2e-03	±2e-03

$V(m^3)$	2.91e-04	7.10e-05
$\Delta V(m^3)$	±7e-06	±2e-06

3E – Initial Magnetization

In [22]:
```
initial_magnetization = array([V, mV, mV]) *[
        [54.0, 410.0,  337.5],
        [57.2, 500.0,  343.8],
        [61.8, 670.0,  356.3],
        [66.4, 820.0,  362.5],
        [68.0, 850.0,  362.5],
        [71.0, 960.0,  362.5],
        [75.0, 1080.0, 368.8],
        [80.0, 1200.0, 368.8],
        [85.0, 1250.0, 368.8],
        [50.0, 300.0,  309.4],
        [45.0, 220.0,  287.5],
        [40.0, 170.0,  265.6],
        [35.0, 130.0,  237.5],
        [30.0, 88.0,   206.3],
        [25.0, 64.0,   175.0],
        [20.0, 49.0,   143.8]
]
initial_magnetization_Vs_d = 0.02
initial_magnetization_Vc_d = 0.1
display_tabular_data(
    ['Variac (Volts)', '$V_s$ (Volts)', '$V_c$ (Volts)'],
    initial_magnetization
)
```

Out[22]:

Variac (Volts)	V_s (Volts)	V_c (Volts)
54.0	0.41	0.3375
57.2	0.5	0.3438
61.8	0.67	0.3563
66.4	0.82	0.3625
68.0	0.85	0.3625
71.0	0.96	0.3625
75.0	1.08	0.3688
80.0	1.2	0.3688

85.0	1.25	0.3688
50.0	0.3	0.3094
45.0	0.22	0.2875
40.0	0.17	0.2656
35.0	0.13	0.2375
30.0	0.088	0.2063
25.0	0.064	0.175
20.0	0.049	0.1438

4 – Analysis

4A – Calculate B and H

In [23]:
```
for data in (Iron, Steel):
    data['H'], data['H_d']  = H(n_1, data['L'], data['L_d'], S, S_d, data['V_s'])
    data['B'], data['B_d']  = B(R, R_d, C, C_d, n_2, data['A_c'], data['A_c_d'], data['V_c'])
```

4B – Select the turning points

Iron:

```
In [24]: user_select_ciritical_indices(Iron, start_guess=365, delta_guess=335)
         figtext(0.5, 0.03, "Figure 4");
```

start_index 365

delta 335

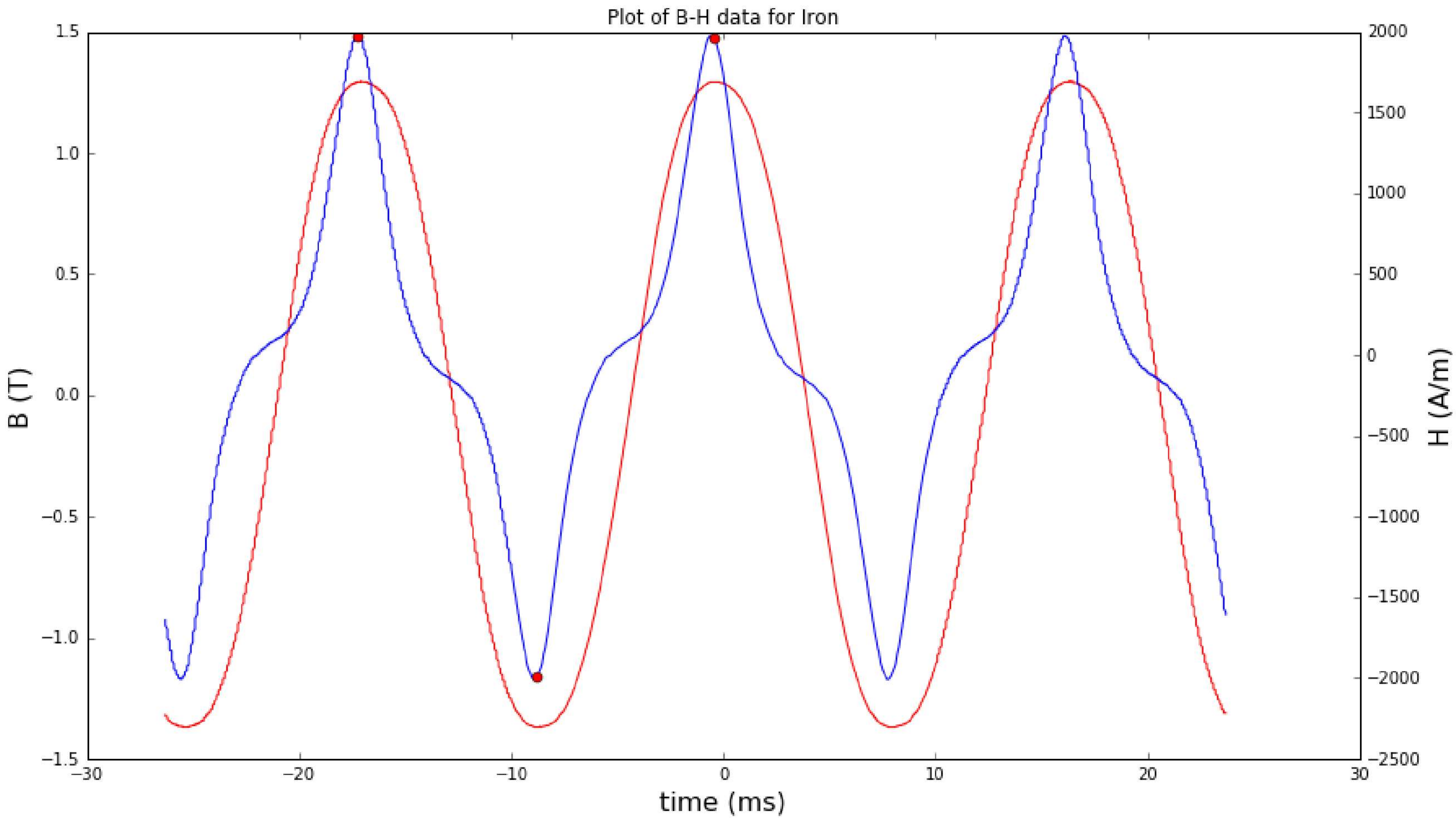

Figure 4

Carbon Steel:

In [25]:
```
user_select_ciritical_indices(Steel, start_guess=460, delta_guess=335)
figtext(0.5, 0.03, "Figure 5");
```

start_index 460

delta 335

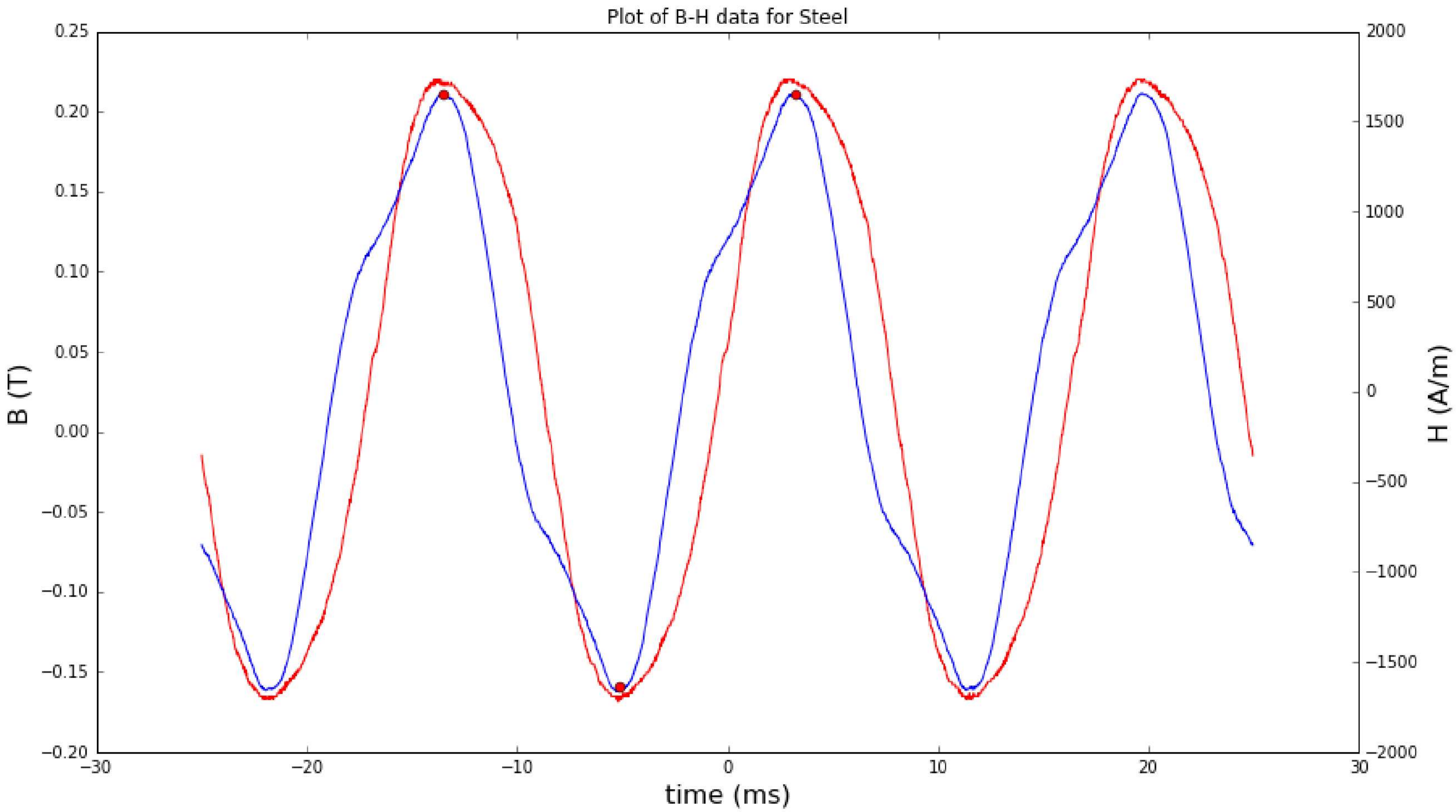

Figure 5

4C – Split into top and bottom curves

In [26]:
```
split_data_into_top_bottom(Iron)
split_data_into_top_bottom(Steel)
```

4D – Hysteresis Curves, $B_r|$, $H_c|$, $A|$

A plot of both curves, superimposed:

In [27]:
```
hysteresis_curve(Steel)
hysteresis_curve(Iron)
title('Hysteresis Curves for Iron and Carbon Steel')
text(min(Iron['H']), min(Iron['B'])*.8, 'Iron')
text(min(Steel['H'])*1.1, min(Steel['B'])*.5, 'Carbon Steel')
grid()
figtext(0.5, 0.03, "Figure 6");
```

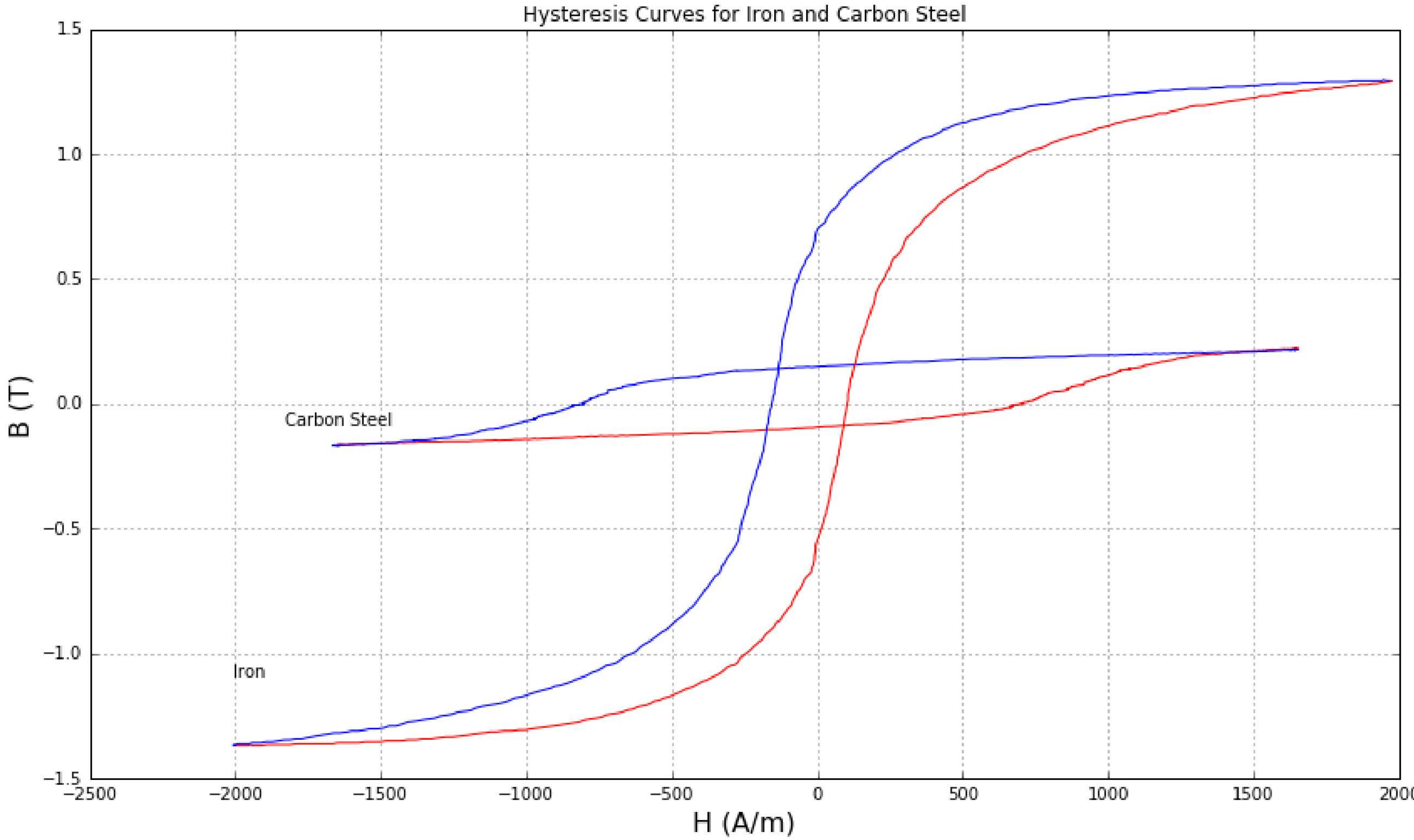

Figure 6

Hysteresis curve and calculations for Iron:

In [28]:
```
hysteresis_curve(Iron)
remanance(Iron)
coersive(Iron)
calculatearea(Iron)
figtext(0.5, 0.03, "Figure 7");
```

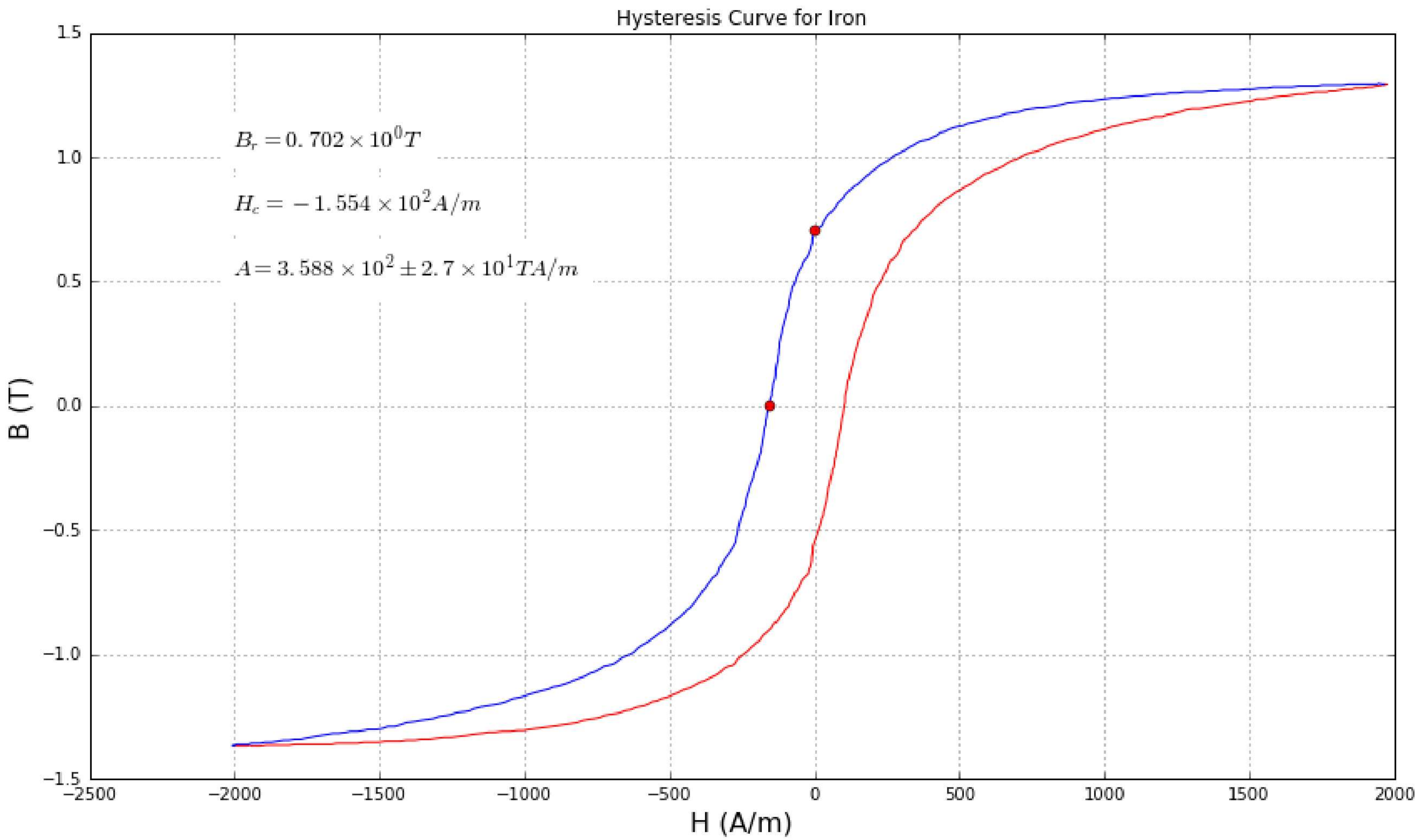

Figure 7

Hysteresis curve and calculations for Carbon Steel:

In [29]:
```
hysteresis_curve(Steel)
remanance(Steel)
coersive(Steel)
calculatearea(Steel)
figtext(0.5, 0.03, "Figure 8");
```

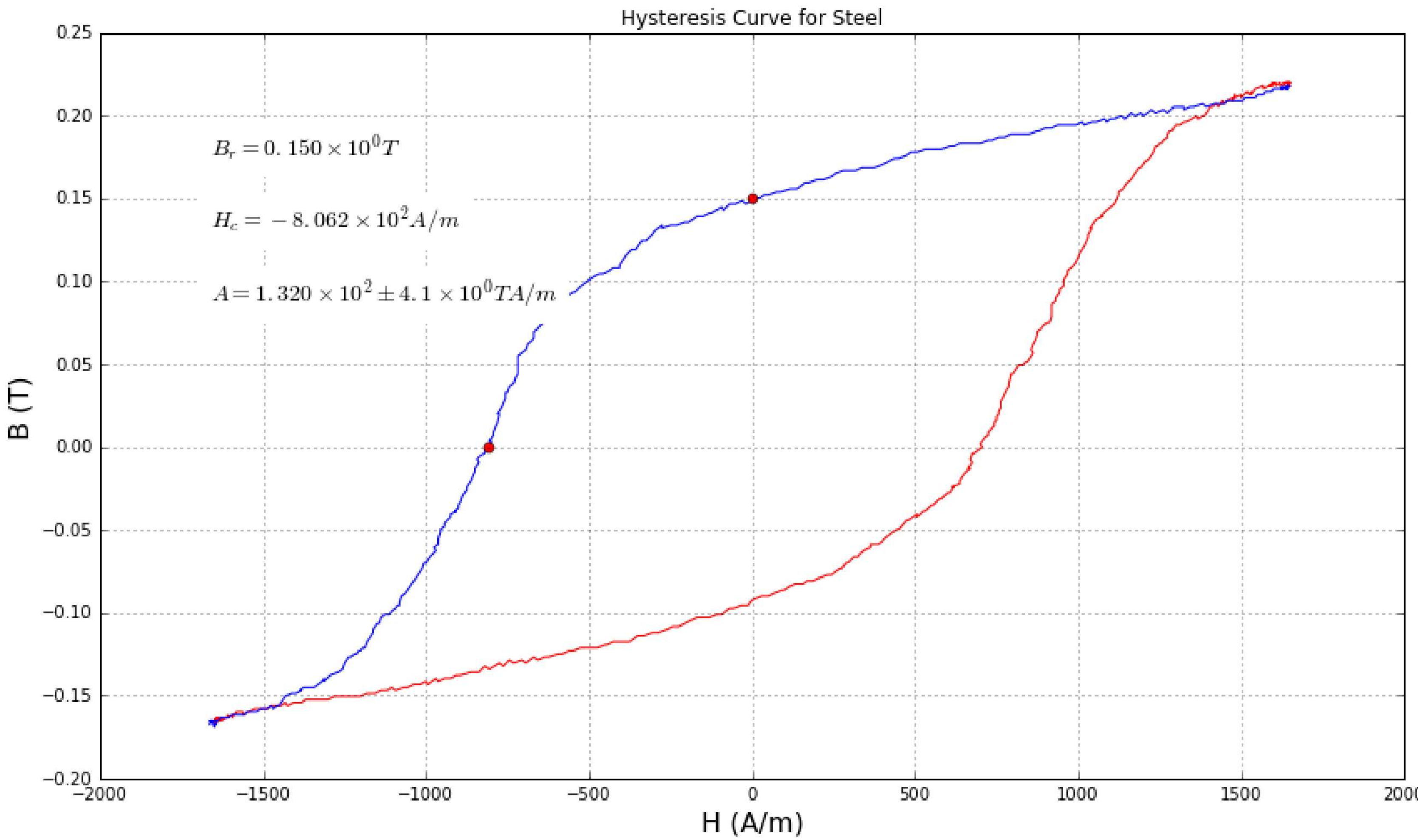

Figure 8

4E – Question 2

A good choice of material for a permenant magnet or magnetic memory device has a large $B_r|$ so that it will remain strongly magnetized after the current is removed, and a large $H_c|$ so that it is harder to demagnetize.

A good choice of material for an electric motor has a small $H_c|$ so that the field is easily reversed, a small area to limit the energy lost to heat, and each high $B|$ values quickly to maximize the amplification effect.

According to these criteria:

In [30]:
```
magnet_best = (
    int(abs(Iron['H_c']) > abs(Steel['H_c'])) +
    int(Iron['B_r'] > Steel['B_r'])
) /2

motor_best = (
    int(Iron['H_c'] < Steel['H_c']) +
    int(max(Iron['B']) > max(Steel['B'])) +
    int(Iron['A'] < Steel['A'])
)/3
```

In [31]:
```
Markdown(
    'Iron is {:.0f}% the best choice for a permenant magnet or memory device.\n\n'
    'Iron is {:.0f}% the best choice for an electric motor.'
    .format(magnet_best*100, motor_best*100)
)
```

Out[31]: Iron is 50% the best choice for a permenant magnet or memory device.

Iron is 33% the best choice for an electric motor.

There is a tie between Iron and Carbon Steel for magnet or memory device. Steel has a larger $H_c|$ but Iron has a larger $B_r|$.

Carbon steel is a somewhat better choice for an electric motor. It has a larger $H_c|$, a smaller area, but doesn't reach as high $B|$ values.

4F – Question 3

In [32]:
```
Iron['P'], Iron['P_d'] = P(Iron['A'], Iron['A_d'], Iron['V'], Iron['V_d'], Iron['frequency'])
Steel['P'], Steel['P_d']  = P(Steel['A'], Steel['A_d'], Steel['V'], Steel['V_d'], Steel['frequency'])

Markdown(
    '$P_{{Iron}} = {} \pm {} W$\n\n'.format(latex_exp(Iron['P']), latex_exp(Iron['P_d'],0))+
    '$P_{{Steel}} = {} \pm {} W$'.format(latex_exp(Steel['P']), latex_exp(Steel['P_d'],0))
)

# (Iron['A'], Iron['A_d'], Iron['V'], Iron['V_d'], Iron['frequency'])
```

Out[32]: $P_{Iron} = 1.24 \times 10^1 \pm 1 \times 10^0 W$

$P_{Steel} = 1.12 \times 10^0 \pm 1 \times 10^{-1} W$

The result for Iron seems reasonable: It felt less than the 25W lightbulb, and we calculated 12.4W.

The result for the carbon steel does not seem reasonable: It felt hotter than the 25W lightbulb and we calculated 1.1W, which is clearly incorrect. This indicates that using the magnetizing length for volume of hysteresis loss in Steel was incorrect.

4G – Question 4

In [33]:
```
init_B, init_B_d = B(R, R_d, C, C_d, n_2, Iron['A_c'], Iron['A_c_d'], initial_magnetization[:,2])
init_H, init_H_d = H(n_1, Iron['L'], Iron['L_d'], S, S_d, initial_magnetization[:,1])
errorbar(init_H, init_B, init_B_d, init_H_d, fmt='b.')
title('Initial Magnetization Curve')
xlabel('M (A/m)')
ylabel('B (T)')
figtext(0.5, 0.03, "Figure 9");
```

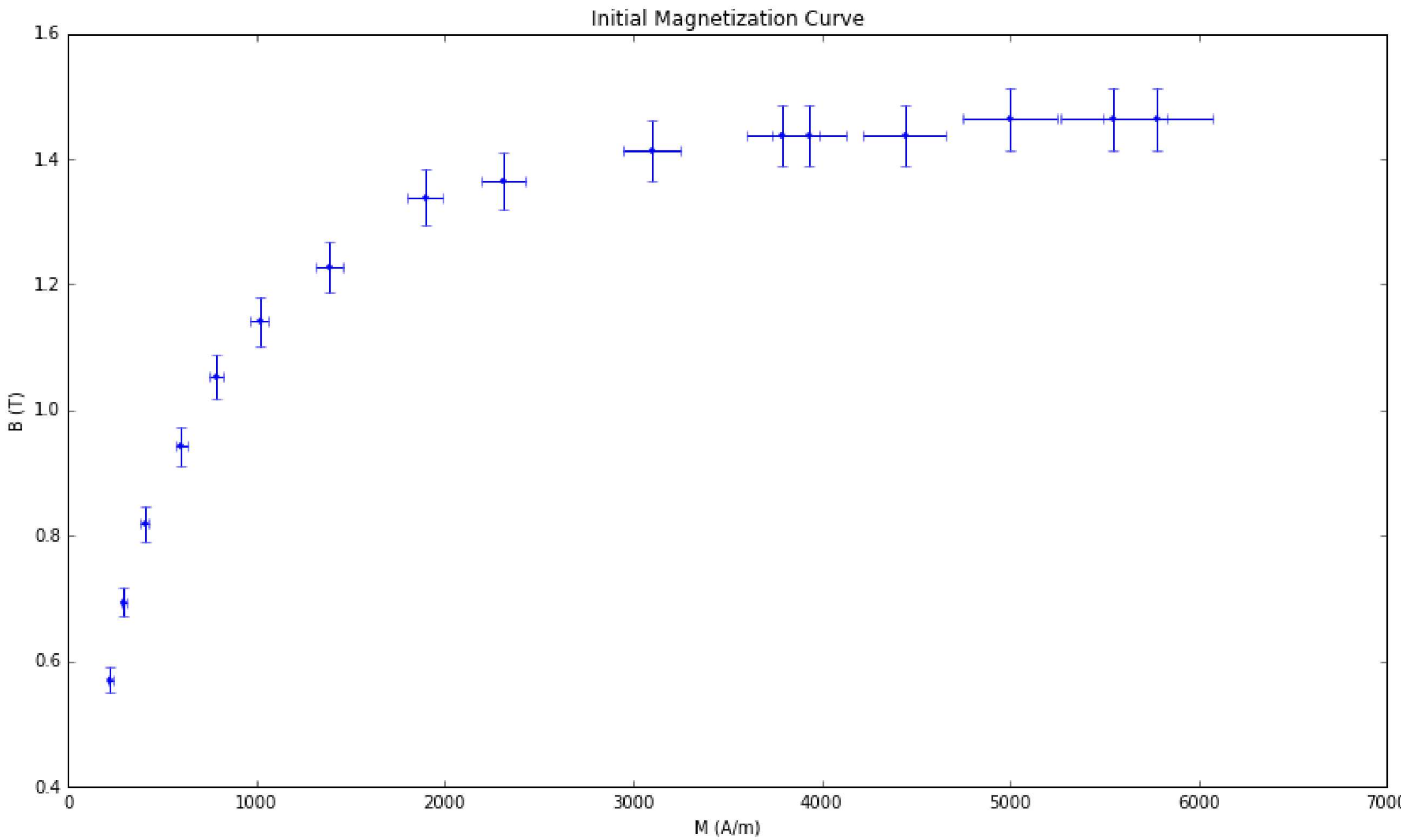

Figure 9

In [34]:
```
μ, μ_d = μ_r(init_B, init_B_d, init_H, init_H_d)
errorbar(init_H, μ, μ_d, init_H_d, fmt='b.')
title('$μ_r$ Curve')
xlabel('M (A/m)')
ylabel('Permeability')
figtext(0.5, 0.03, "Figure 10");
```

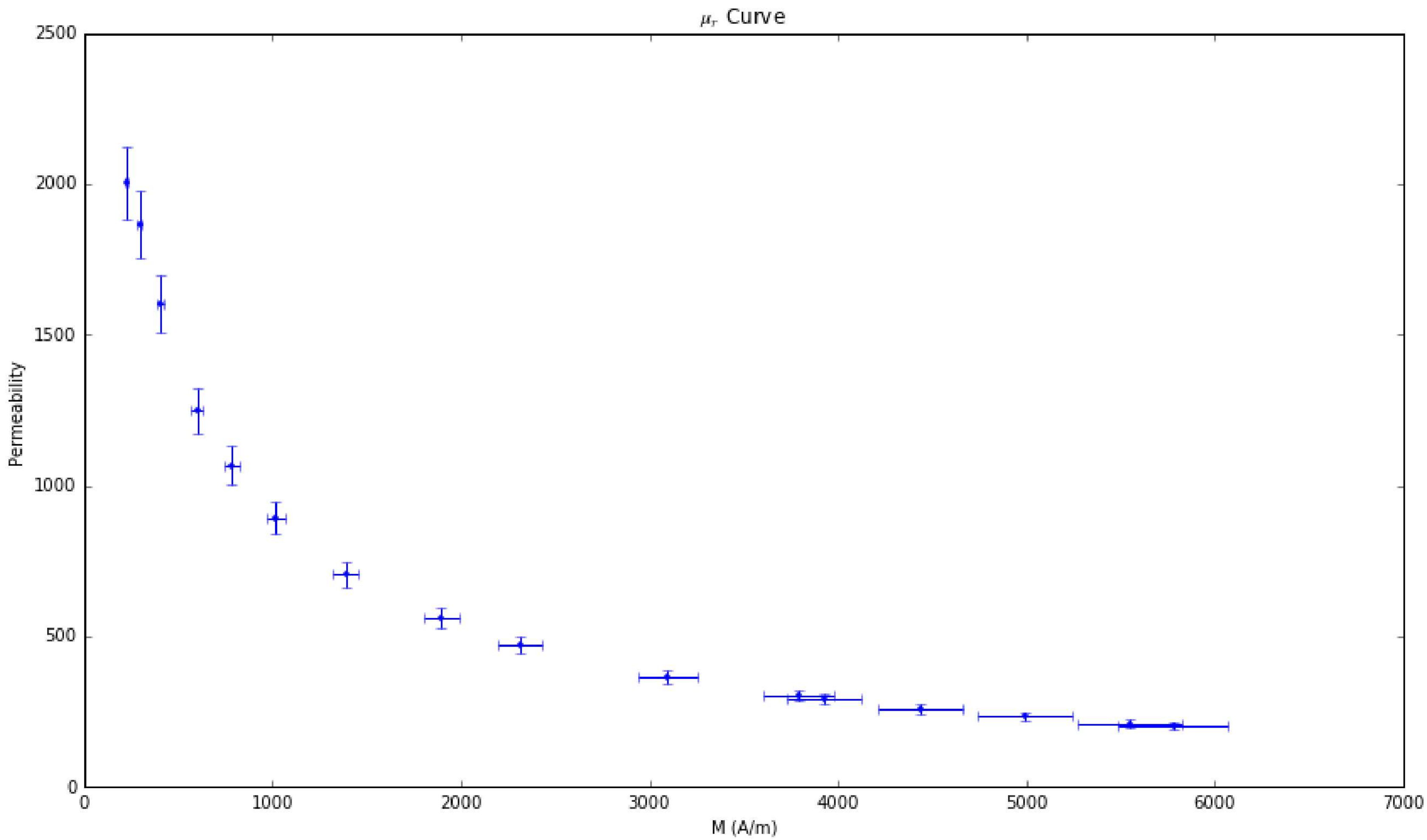

Figure 10

In [35]:
```
iimax = μ.argmax()
Markdown('$ \mu_r = '+latex_exp(max(μ))+' \pm '+latex_exp(μ_d[iimax],0)+
         '$\n\n It occurs at a flux density of $'+latex_exp(init_H[iimax],3)+
         ' \pm '+latex_exp(init_H_d[iimax],3)+' T$.')
```

Out[35]: $\mu_r = 2.00 \times 10^3 \pm 1 \times 10^2$

It occurs at a flux density of $2.266 \times 10^2 \pm 1.137 \times 10^1 T$.

According to Smithhells Metals Reference (https://app.knovel.com/web/view/swf/show.v/rcid:kpSMRBE012/cid:kt003OACU2/viewerType:pdf/root_slug:smithells-metals-reference?cid=kt003OACU2&page=5&b-toc-cid=kpSMRBE012&b-toc-root-slug=smithells-metals-reference&b-toc-url-slug=permanent-magnet-materials&b-toc-title=Smithells%20Metals%20Reference%20Book%20(8th%20Edition%29), the relative permeabillity of Iron, μ_r, varies between 1560 and 2060 depending on the type of Iron, and it occurs at a flux density of 200-320 A/m. This agrees with the result, though a more accurate analysis would require knowing exactly what type of Iron the sample is.

4H – Question 7

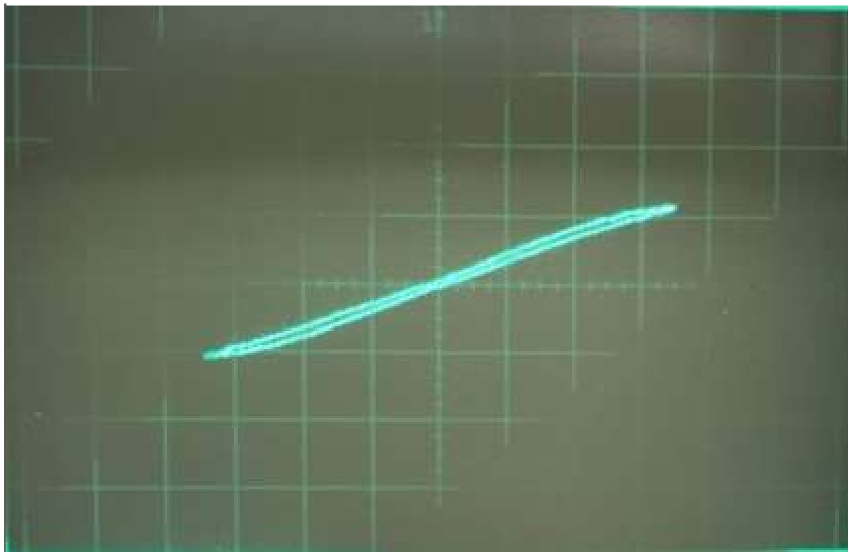

Figure 11: Plastic Spacer

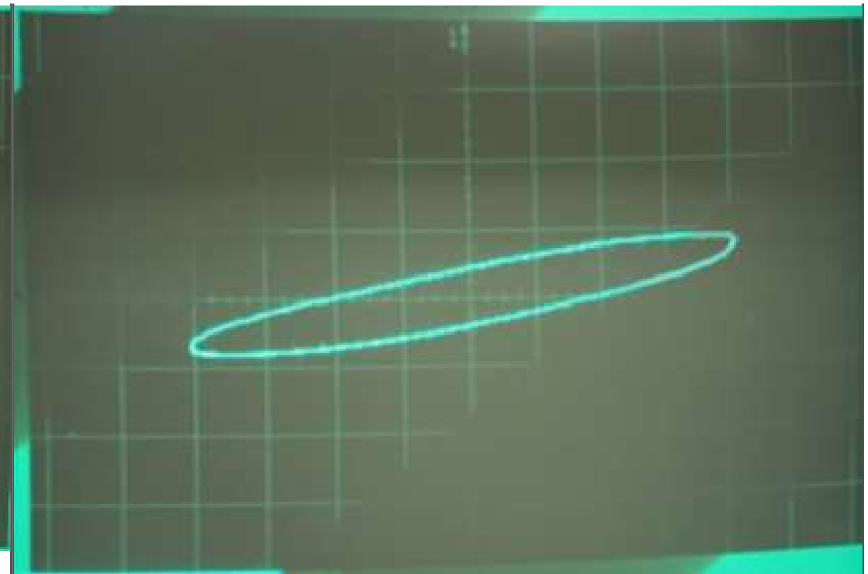

Figure 12: Copper Spacer

The hysteresis curve including the plastic spacer is far thinner, indicating that less energy is lost to heat. This is because the plastic spacer is an insulator which increases the linearity.

The copper spacer introduces losses to eddy currents, as such the area inside the hysteresis curve is larger.