IMPROVED SHORT COIL CORRECTION FACTOR FOR INDUCTION HEATING OF BILLETS

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Innovation and Creativity

Effect of Geometry and Frequency on Induced Power in the Billet

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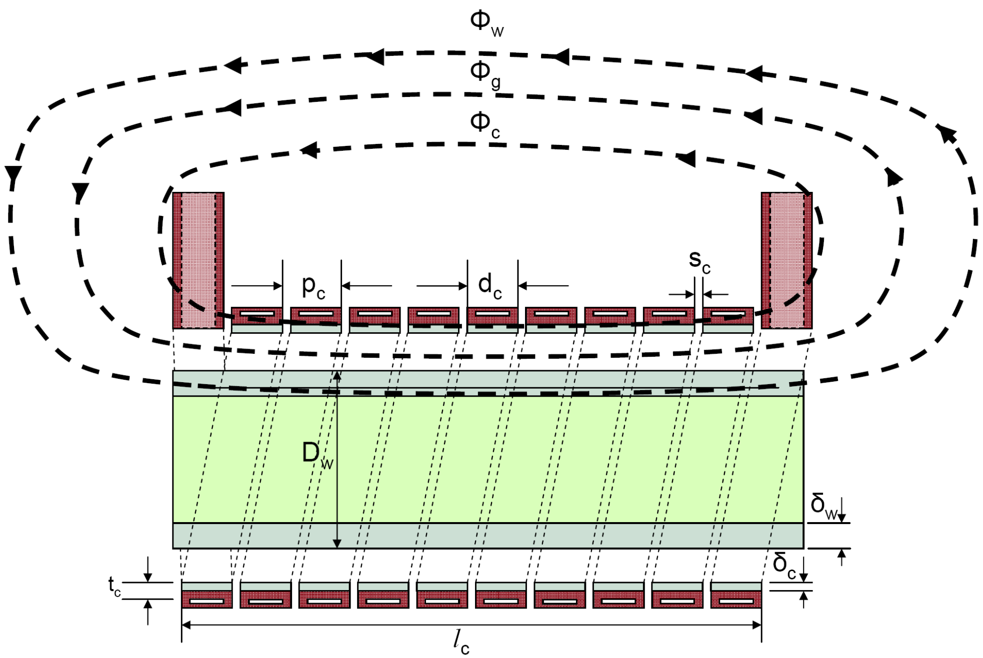
Heating will vary by the square of the flux density in the air-gap.

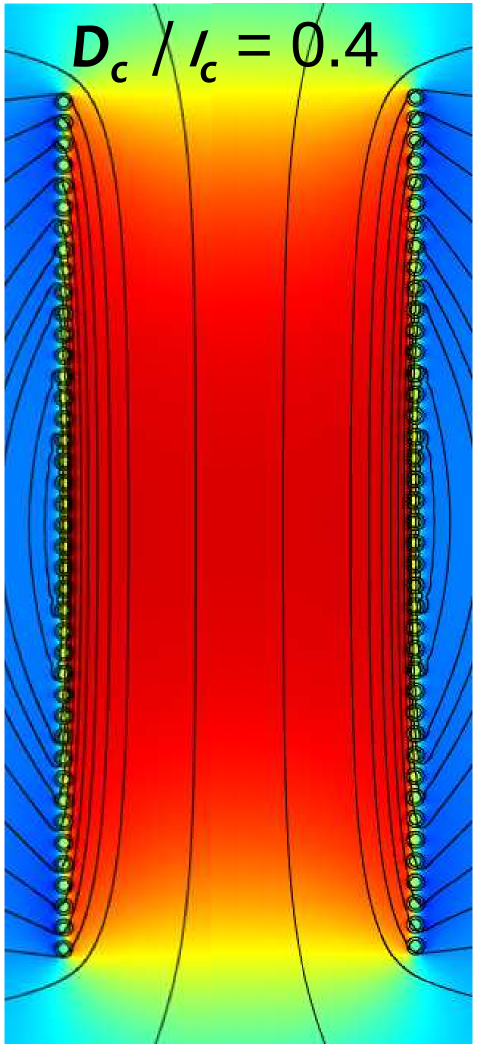
$$P_w = \frac{\sqrt{2}\pi l}{\mu^2}\left(\boxed{\frac{k_N^{*}\mu I_c N_c}{l_c}}\right)^2 \frac{1}{\sigma_w}\xi_w \varphi(\xi_w)$$

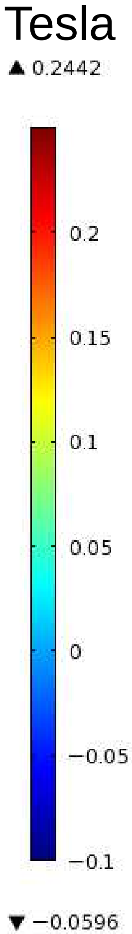
Modified short coil correction factor

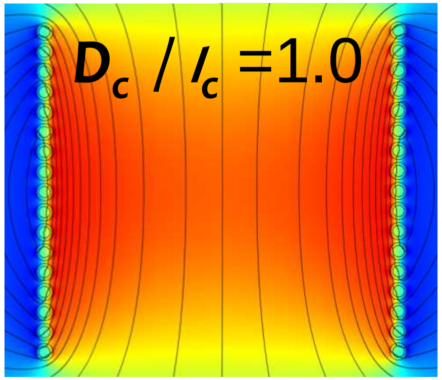
'Air-Gap' Flux Density



'Long' vs. 'Short' Coil Peak Flux Density







Infinite coil: $B_\infty = \mu_o H_\infty = \mu_o N_c I_c / l_c$

Real coil: $B_z = k_N B_\infty = k_N \mu_o N_c I_c / l_c$

k_N = Nagaoka's induction coefficient of 1909

$k_N = 1/[1 + 0.4502\ (D_c\ /\ l_c)]$

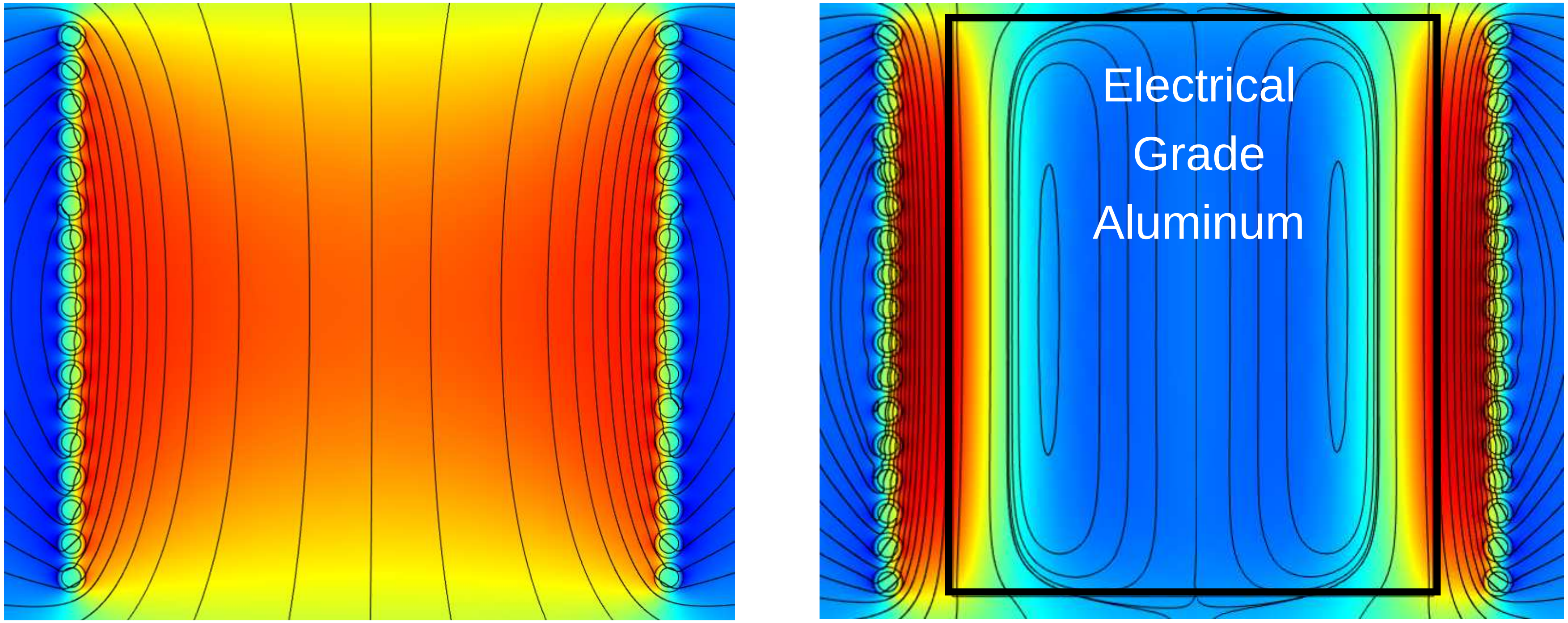
Short form empirical relation <1% error

Wheeler 1928, Knight 2010

To have **98%** of the 'long coil' magnetic field, a coil must be **~22 times** as long as its diameter.

Short Coil with Air Core and Work Piece

D_c / l_c = 1.0, 50 Hz, 1000A RMS



The presence of the work piece alters the magnetic field in the air gap!

$$B_z = k_N^* B_\infty = k_N^* \mu_o H_\infty = k_N^* \mu_o N_c I_c / l_c$$

Modified Short Coil Correction Factors

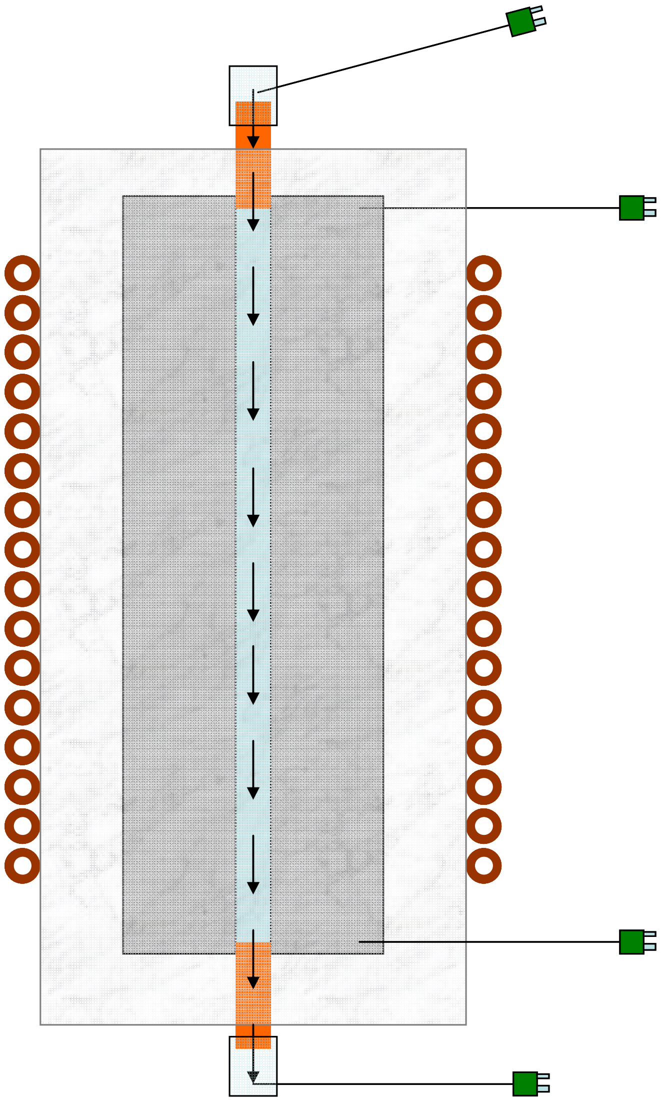
Vaughan and Williamson (1945):

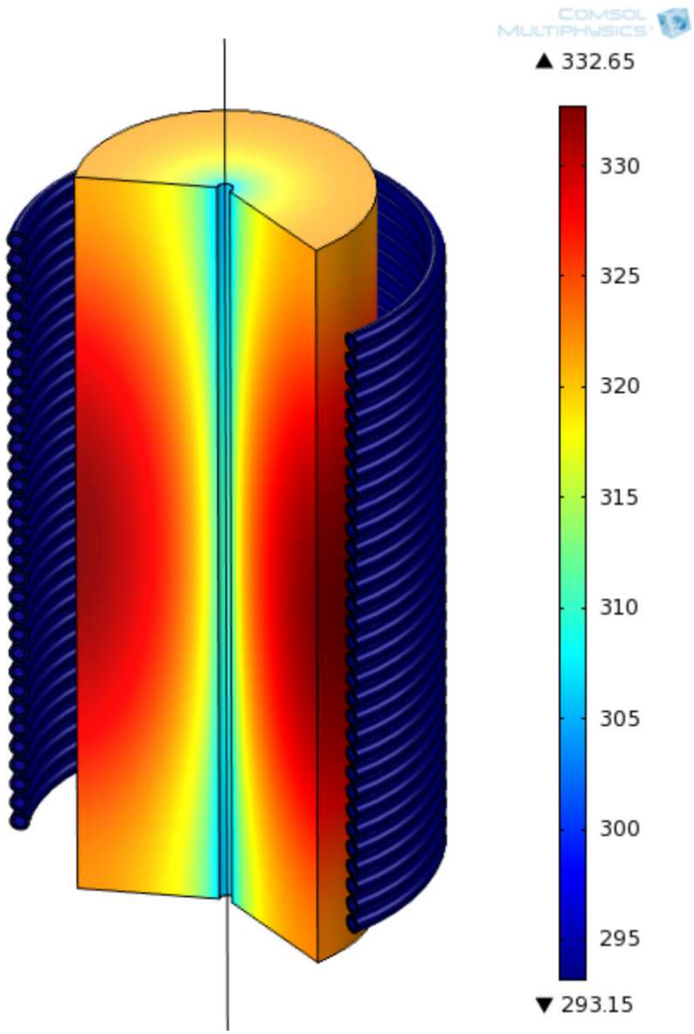
$$k_N^{\ *} = k_N \left(1 - \left(\frac{D_w}{D_c} \right)^2 \right) + \left(\frac{D_w}{D_c} \right)^2$$

Kennedy *et al.* (2011):

$$k_N^{\ *} = k_N \left(1 - \left(\frac{D_w - \delta_w}{D_c + \delta_c} \right)^2 \right) + \left(\frac{D_w - \delta_w}{D_c + \delta_c} \right)^2$$

Experimental Apparatus





High Precision Instrumentation

Electrical conductivity accuracy of **+/- 0.5%**
Standards +/- 0.01% IACS

Magnetic field measurements
Axial/Transverse
From 0.1μT-30T
+/- 1% AC
Standards from 500-2000 Gauss

Electrical analysis:

1. V, I, P (+/-100 W), p.f.
2. Inductance
3. Harmonics
4. Current **+/- 1%**
   (usable up to 100 kHz)

Work Pieces Used

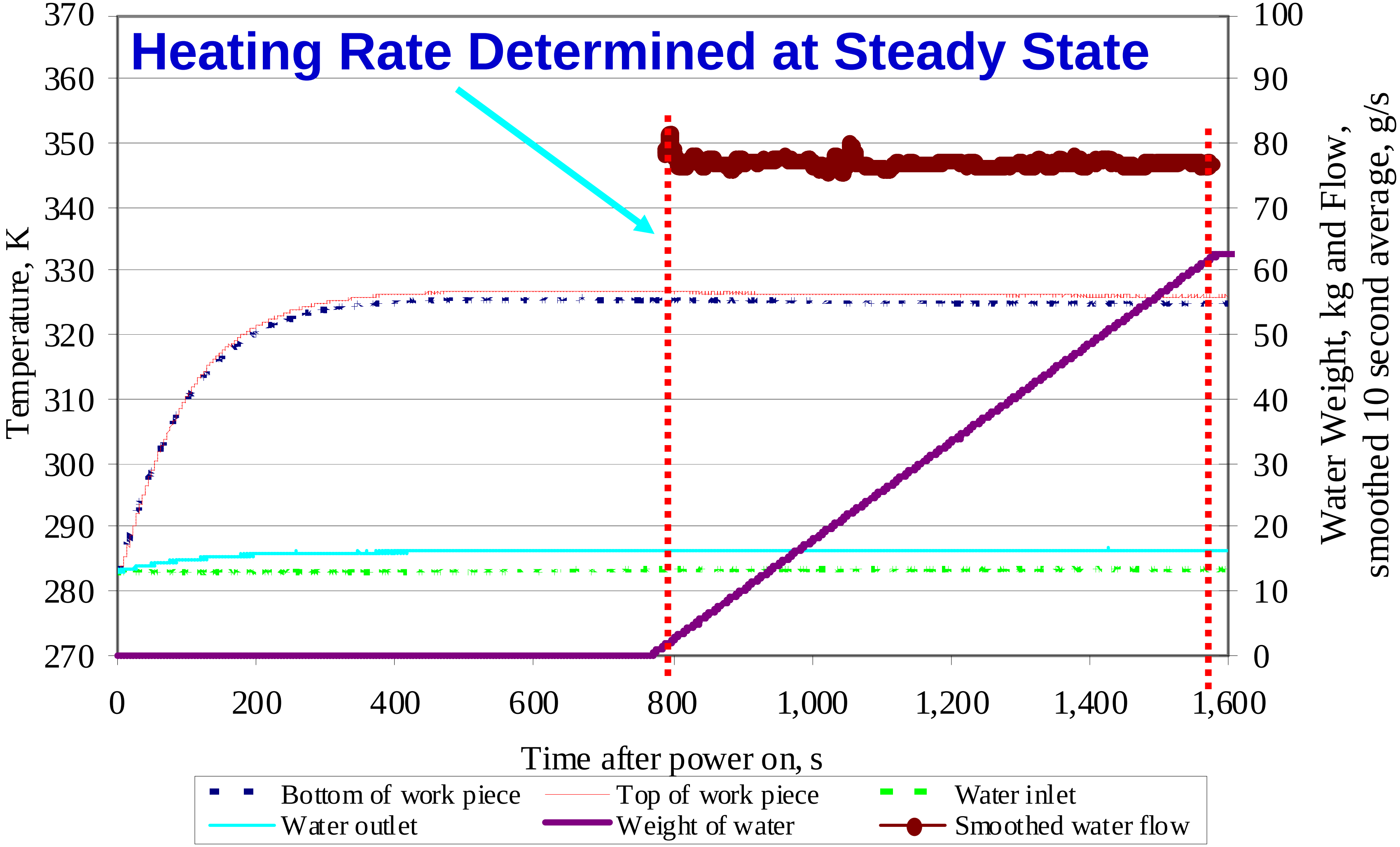
Work Pieces	1	2	3
Alloy	A356	6060	6060
Diameter, mm	75.0	95.0	95.0
Length, mm	130.0	130.0	260.0
Measured IACS Electrical Conductivity,	48.4	56.2	53.4
(mm) at 50 Hz and 20^{o}C from Equation (6)	13.43	12.47	12.79
ξ_w from Equation (8)	3.948	5.388	5.252
$\varphi(\xi_w)$ from Equation (9)	0.823	0.862	0.859
Coil 1	1-1	1-2	
Coil 2		2-2	
Coil 3			3-3

Coils Used

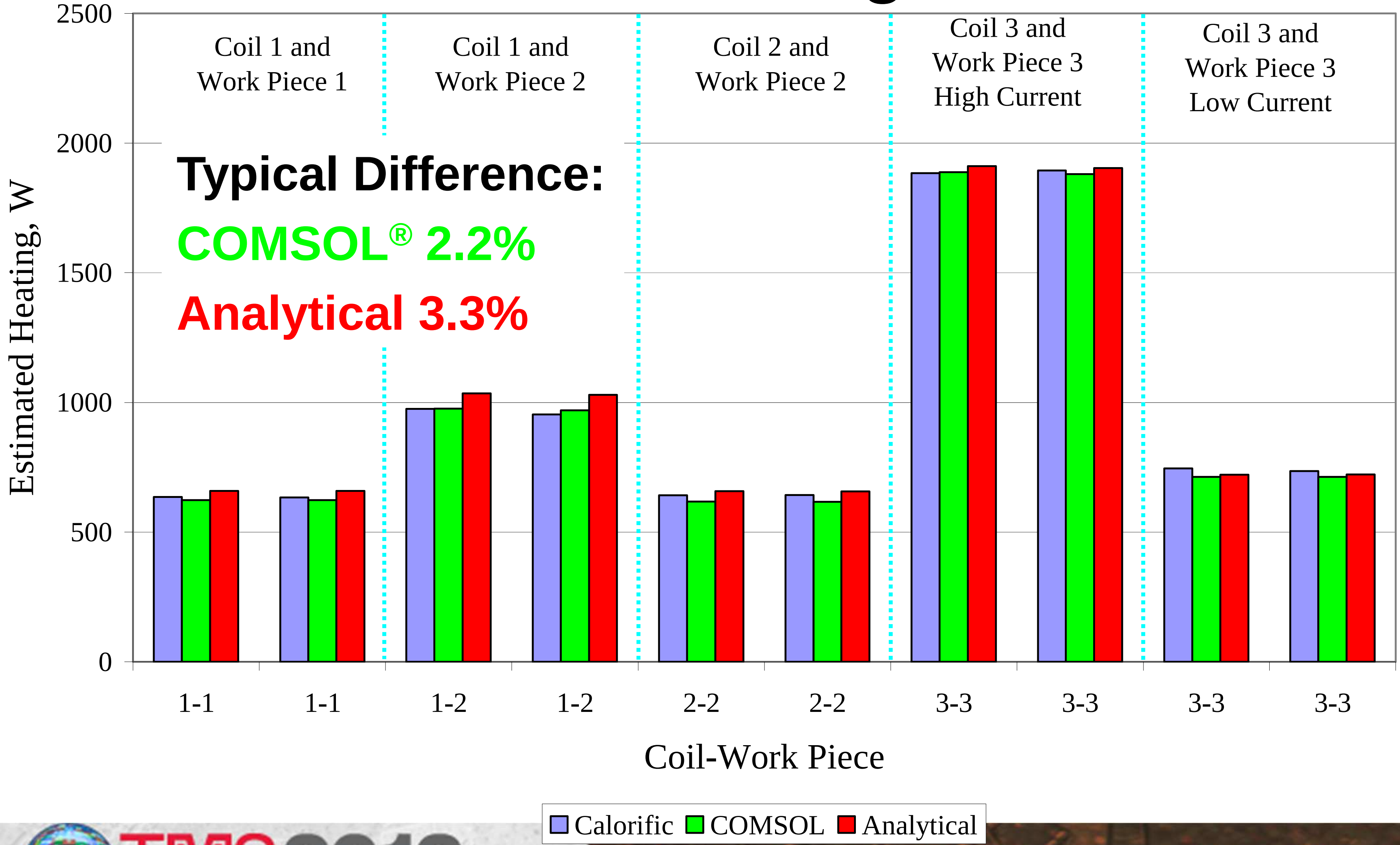
Coil 3

Coils	Short Coil 1	Short Coil 2	Long Coil 3
Average Diameter, mm	132	155	132
Height, mm	106	108	218
Diameter to Height ratio	1.24	1.44	0.60
Number of Turns	16	16	32
Short Coil Correction Factor from Equation (2)	0.641	0.607	0.786
Electrically Determined IACS conductivity, %	80	80	80
Penetration Depth δc (mm) at 50 Hz and 20°C from Equation (3)	10.45	10.45	10.45
Modified Nagaoka Coefficient kN* for Work Piece 1 from	0.720		
Modified Nagaoka Coefficient kN* for Work Piece 2 from	0.783	0.718	
Modified Nagaoka Coefficient kN* for Work Piece 3 from			0.870

‘Typical’ Thermal/Weight Data



Comparison of Measured and Predicted Heating Rates



Induced Power vs. Frequency

Comparison between the Estimates of Power as a Function of Frequency for Coil #1 and Work piece #1

Frequency (Hz)	Experimental Power (W)	Analytical Power (W)	COMSOL Power (W)	Analytical-COMSOL Difference (%)
50	634	659	623	5.8
500	N/A	2567	2466	4.1
5000	N/A	8672	8370	3.6
50000	N/A	27957	26816	4.3
500000	N/A	88623	85247	4.0
			Average:	4.3

Consistent difference from low-high frequency

Conclusions

- An improved 'short coil' correction factor has been developed and validated for induction heating of billets at frequencies from 50 Hz to 500 kHz.

- The improved correction factor, reduces errors in the estimates of induced power to <4%.

Conclusions

- The results compare highly favorably with the factor of 2 error that would result from making a 'long coil' assumption, i.e. $k_N^* = 1.0$.

- The improved correction factor can be used to estimate the average flux density of a 'short coil' with an error of ~2% based on $\sqrt{error}$ the in the induced power.

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