



# IMPROVED SHORT COIL CORRECTION FACTOR FOR INDUCTION HEATING OF BILLETS



## *Effect of Geometry and Frequency on Induced Power in the Billet*

**Mark William Kennedy**<sup>1,3</sup>, S.Akhtar<sup>2</sup>, J.A. Bakken<sup>1</sup>, R.E. Aune<sup>1,3</sup>

<sup>1</sup>Norwegian University of Science and Technology (NTNU)

<sup>2</sup>Norsk Hydro, <sup>3</sup>Royal Institute of Technology, (KTH)



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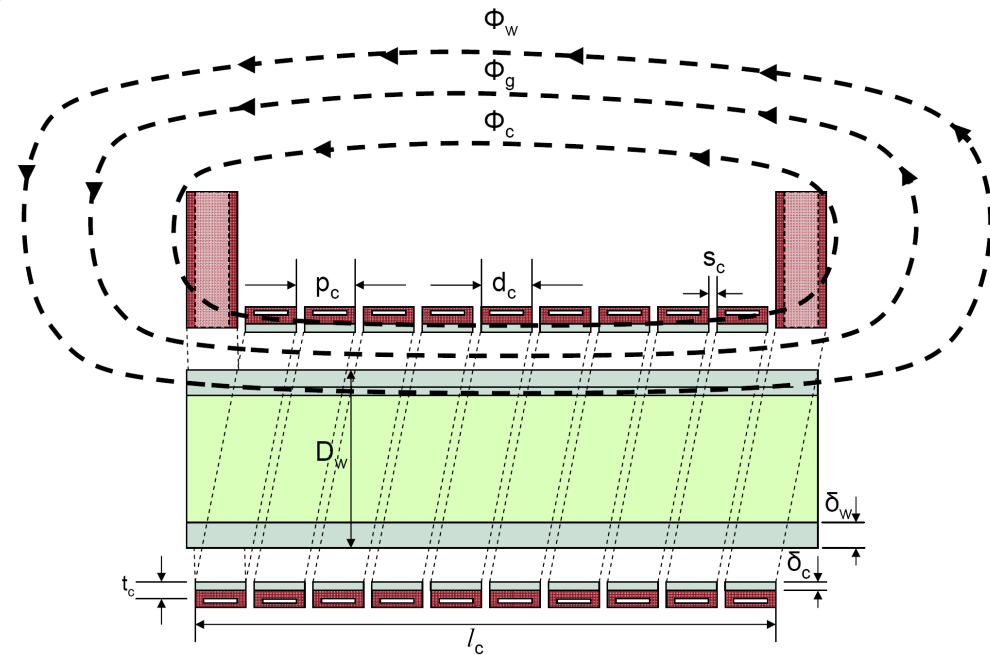
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Heating will vary by the square of the flux density in the air-gap.

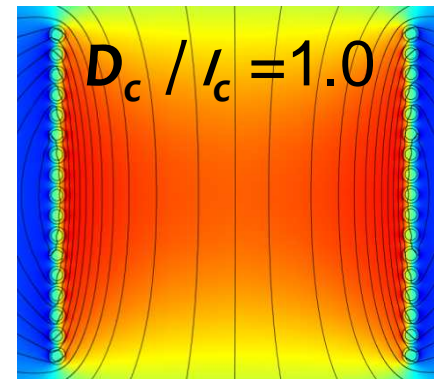
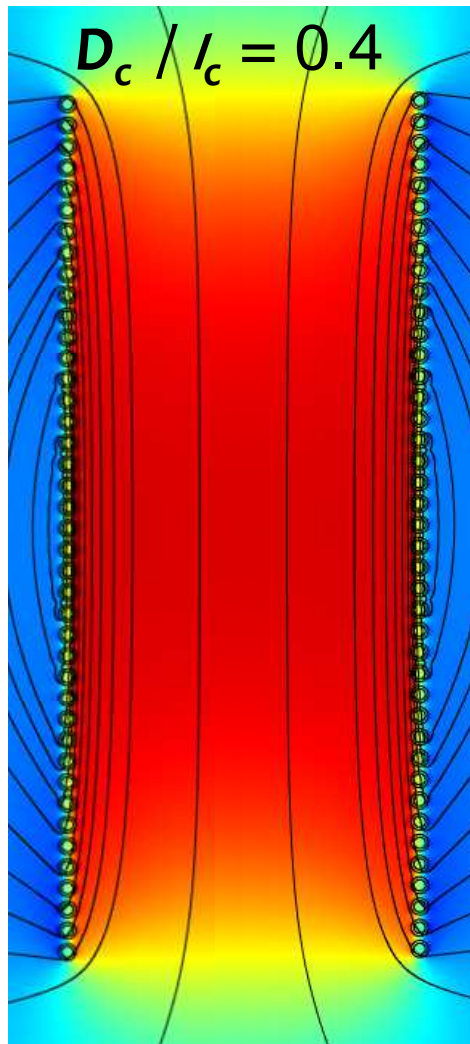
$$P_w = \frac{\sqrt{2}\pi l}{\mu^2} \left( \frac{k_N^* \mu I_c N_c}{l_c} \right)^2 \frac{1}{\sigma_w} \xi_w \varphi(\xi_w)$$

Modified short coil correction factor

'Air-Gap' Flux Density

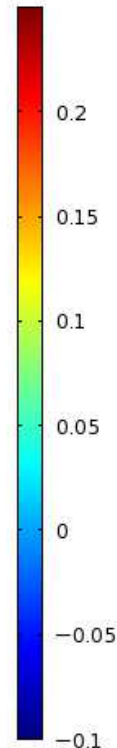


# 'Long' vs. 'Short' Coil Peak Flux Density



Tesla

▲ 0.2442



▼ -0.0596

Infinite coil:  $B_\infty = \mu_0 H_\infty = \mu_0 N_c I_c / l_c$

Real coil:  $B_z = k_N B_\infty = k_N \mu_0 N_c I_c / l_c$

$k_N$  = 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.



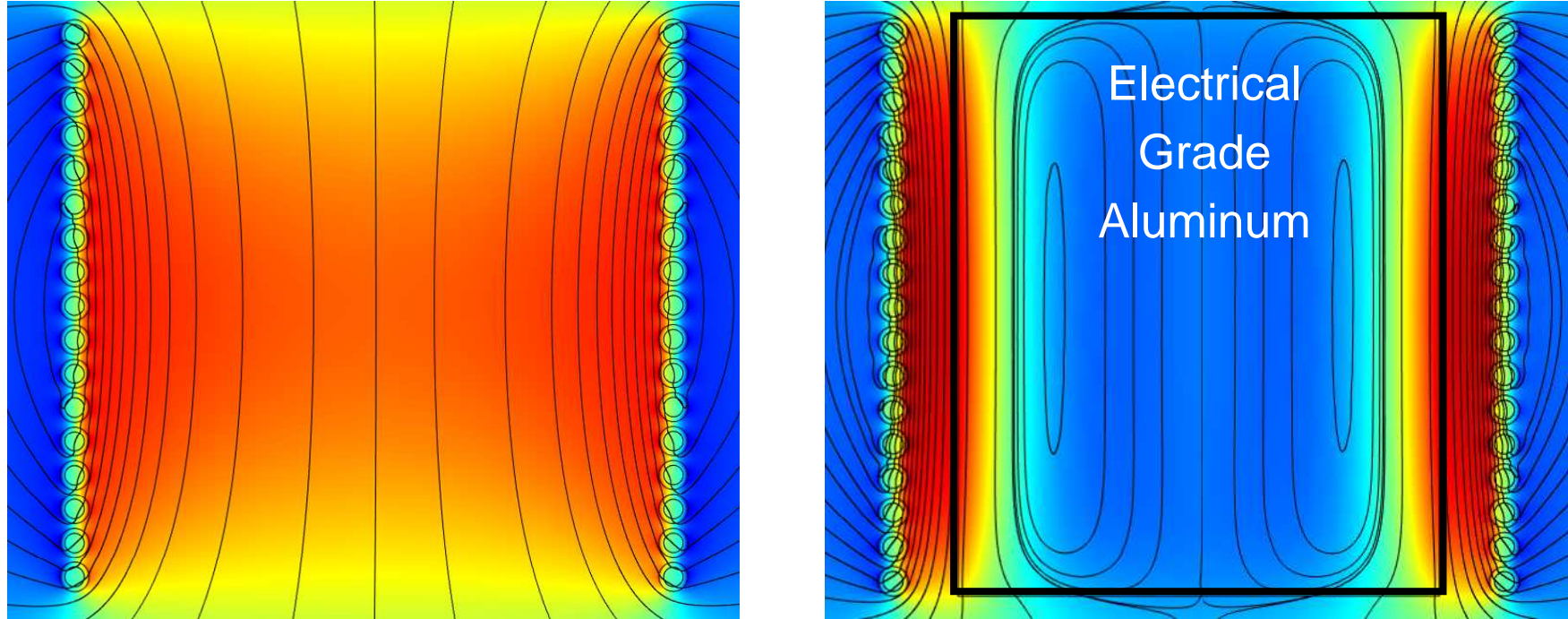
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# Short Coil with Air Core and Work Piece

$$D_c / l_c = 1.0, 50 \text{ Hz}, 1000\text{A RMS}$$



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

$$B_z = k_N^* B_\infty = k_N^* \mu_0 H_\infty = k_N^* \mu_0 N_c I_c / l_c$$



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# Modified Short Coil Correction Factors

**Vaughan and Williamson (1945):**

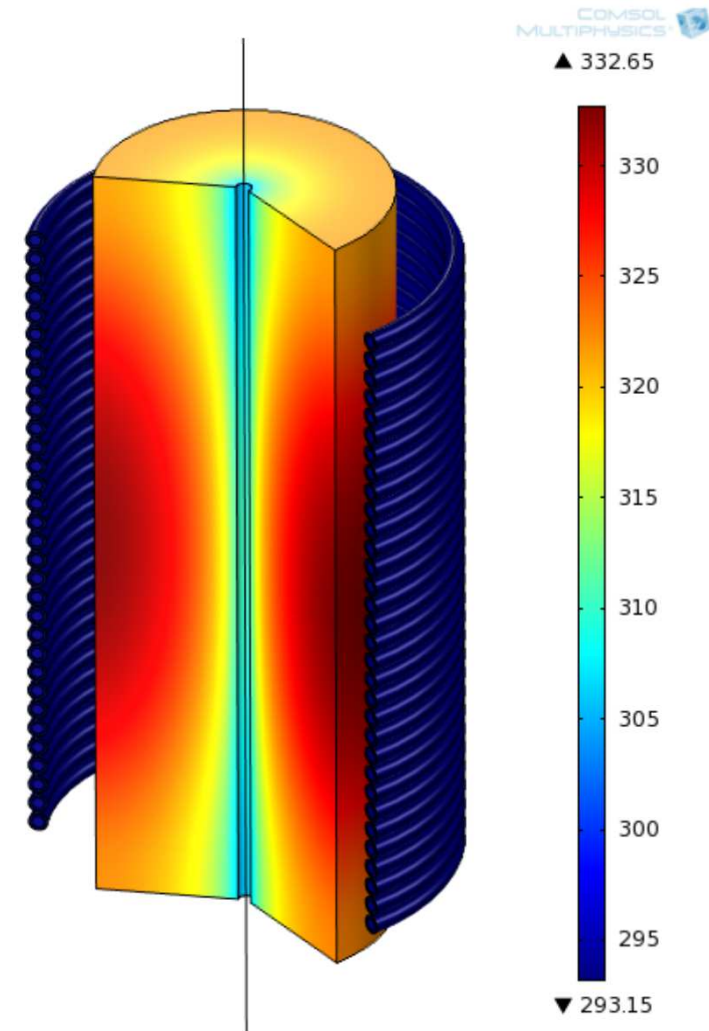
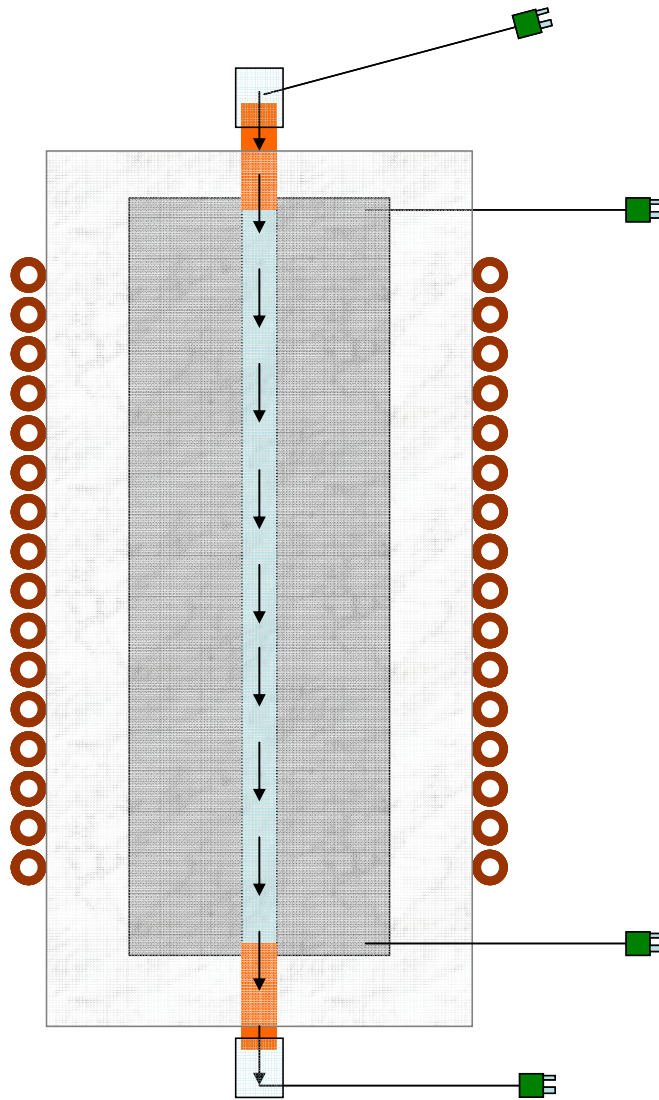
$$k_N^* = k_N \left( 1 - \left( \frac{D_w}{D_c} \right)^2 \right) + \left( \frac{D_w}{D_c} \right)^2$$

**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



Magnetic field measurements  
Axial/Transverse  
From 0.1 $\mu$ T-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)

Electrical conductivity accuracy of **+/- 0.5%**

Standards +/- 0.01% IACS



# 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, (mm) at 50 Hz and 20°C from Equation (6)	48.4	56.2	53.4
$\xi_w$ from Equation (8)	13.43	12.47	12.79
$\varphi(\xi_w)$ from Equation (9)	3.948	5.388	5.252
Coil 1	0.823	0.862	0.859
Coil 2	1-1	1-2	
Coil 3		2-2	
			3-3





# Coils Used



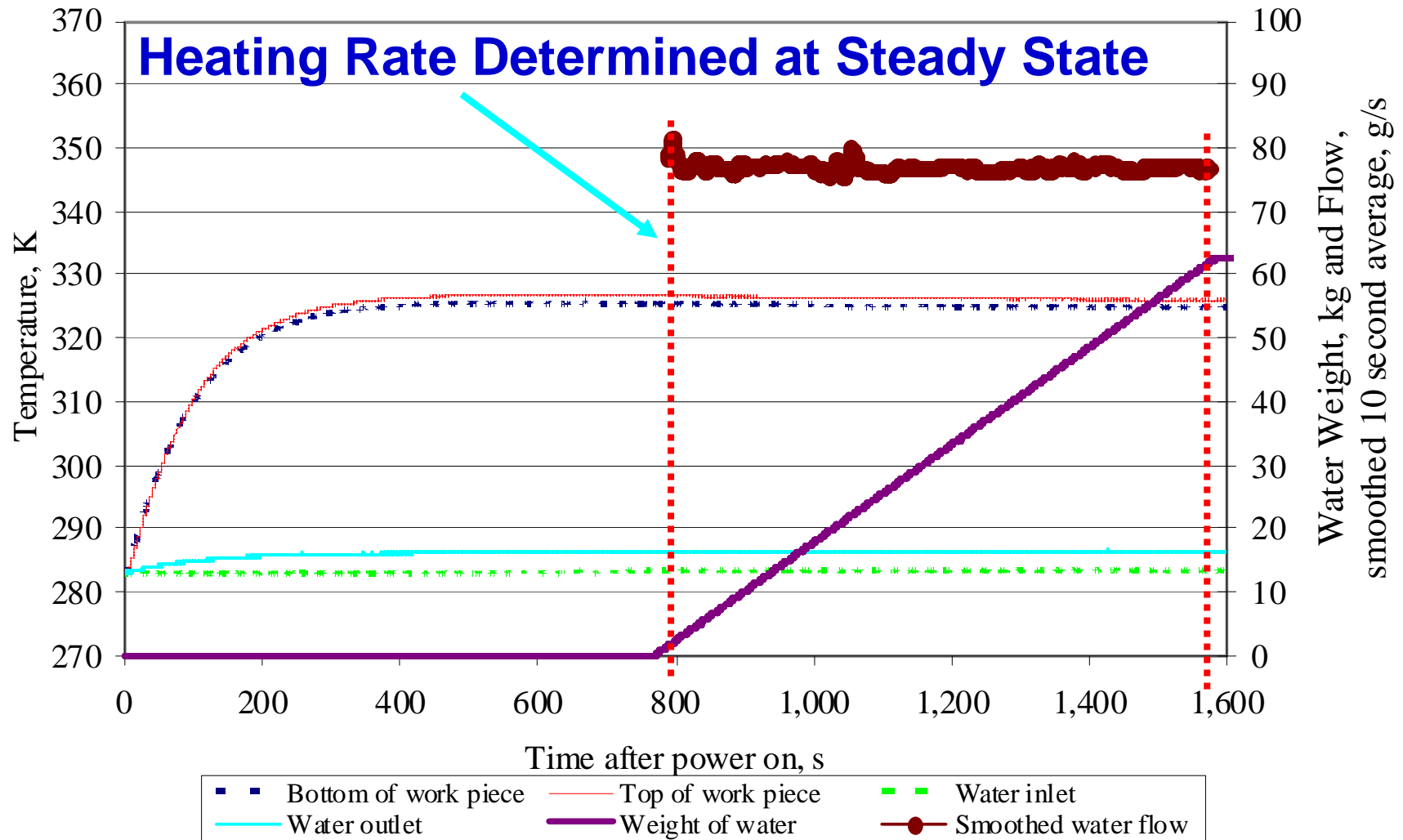
**Coil 3**



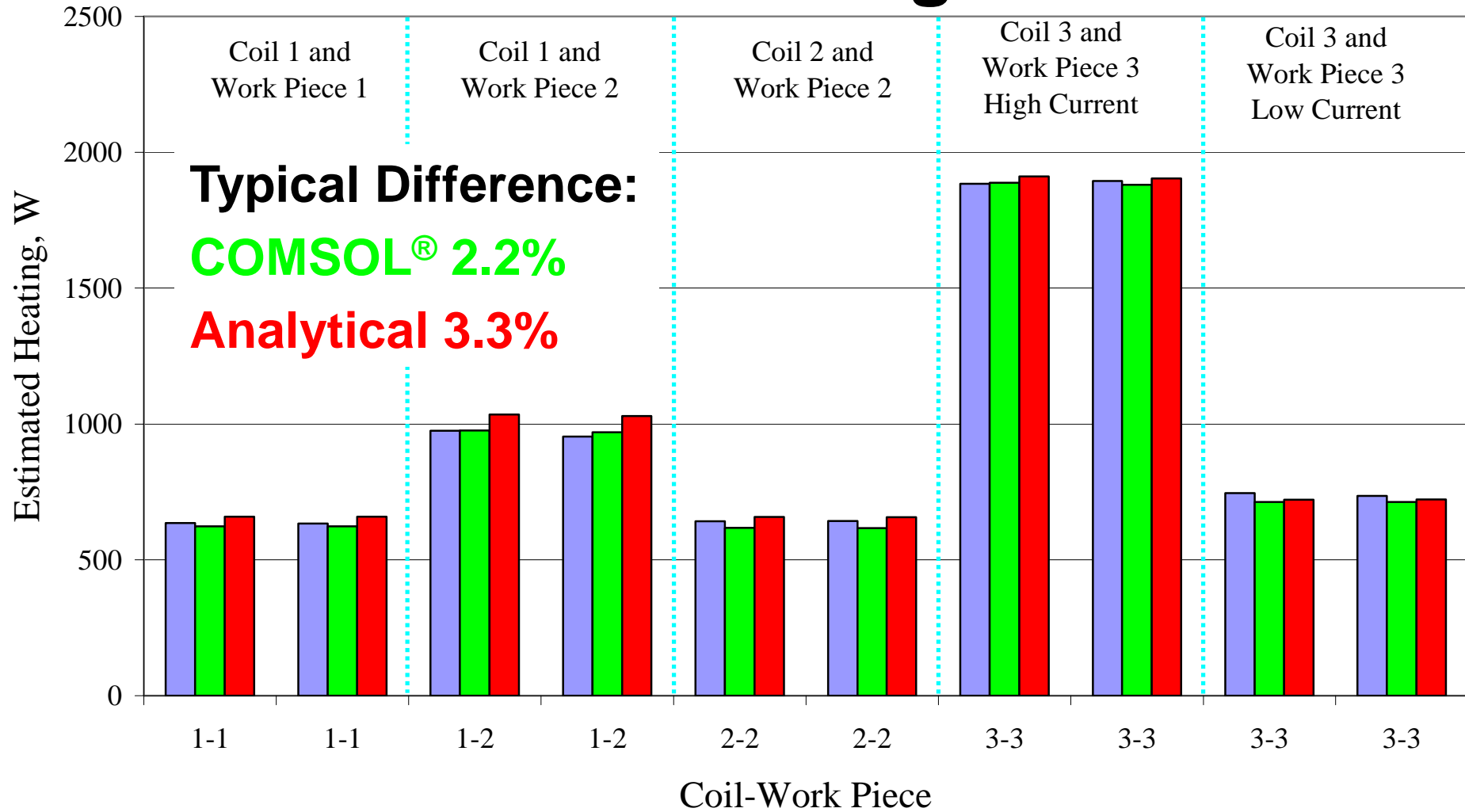
Coils	Short Coil 1	Short Coil 2	Long Coil 3
Average Diameter, mm	132	155	132
Height, mm	106	108	218
Diameter to Height ratio	1.24	1.44	0.60
Number of Turns	16	16	32
Short Coil Correction Factor from Equation (2)	0.641	0.607	0.786
Electrically Determined IACS conductivity, %	80	80	80
Penetration Depth $\delta_c$ (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



■ Calorific ■ COMSOL ■ Analytical



# 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



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# 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  $\sim 2\%$  based on  $\sqrt{\text{error}}$  the in the induced power.





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**contact: [mark.kennedy@material.ntnu.no](mailto:mark.kennedy@material.ntnu.no)**



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