

Improving HF Tube Welding System Performance Using SMC Impeder Cores

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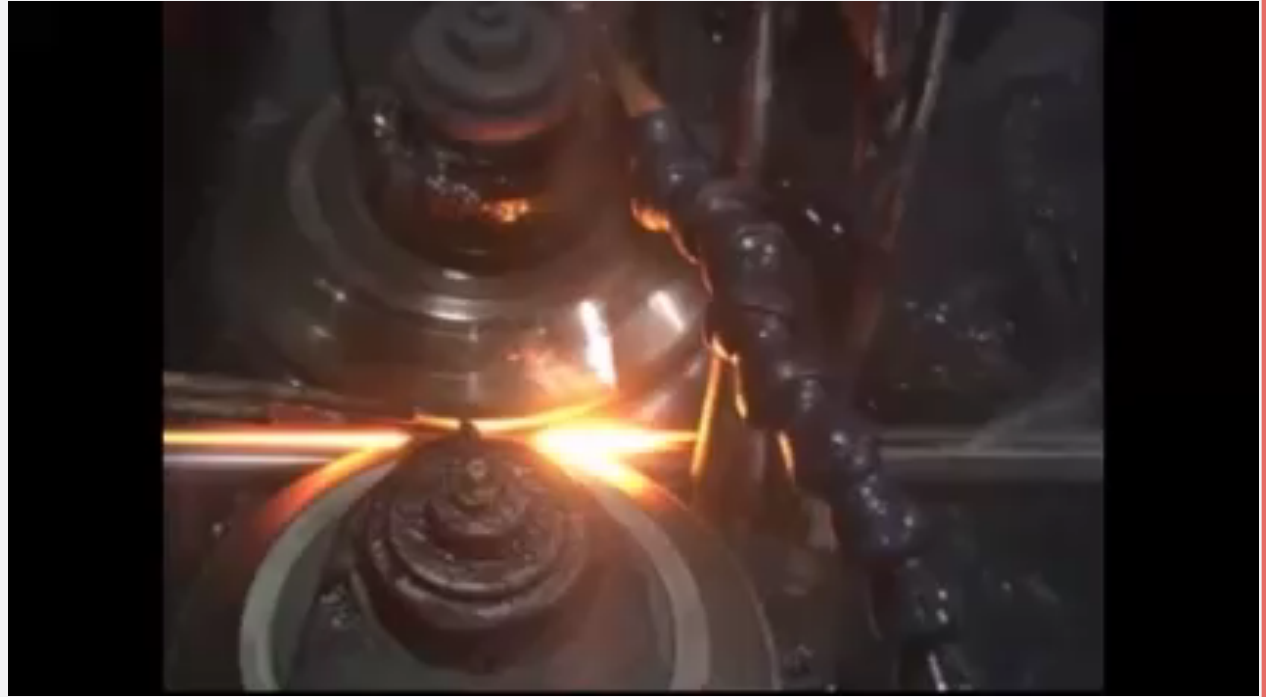
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Overview

- Why This Talk Matters
- The Induction Tube Welding Process
- Impeder Benefits and Material Selection
- Tube Welding Case Studies
- Soft Magnetic Composite Impeder Offline Validation
- Conclusions



Prinz & Co. GmbH Stahlrohr Case Study



- Case setup:

- ~400kHz 50-150kW power supply
- 15mm OD steel tube
- 1.2mm thick wall
- 8.5-9mm OD impeters

	Line Speed (m/min)	Power (kW)
9mm Ferrite	77	58
8.5mm Fluxtrol 50	77	33

- Energy savings for the same line speed was ~40%
- >20 hours impeder life with little to no sign of wear, compared to 4 hours typical for the ferrites
- Energy savings are 25kW or the equivalent of preventing 87 tons of CO₂ per year and saving \$10,000
- Tests were done in Germany and funded by German Government

Gunther, D., Kroll, M., Goldstein, R., Kunke, A., UIE 2024. *Geometry Optimization and Efficiency Increase of HFI Welding Process While Using SMC-impeters*

1) EPA (2022) AVERT, U.S. national weighted average CO₂ marginal emission rate, year 2021 data. U.S. Environmental Protection Agency, Washington, DC.

2) https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_03



Other Cost Benefit Analysis - 5000 hrs/yr

Material	Core Cost	Impeder Cost	Impeder Life	Changeovers/yr	Total Impeder Cost
Ferrite	\$5	\$55	4 hrs	1250	\$68,750
SMC	\$200	\$250	20 hrs	250	\$62,500

Material	Line Cost	Changeover time	Impeder Life	Changeovers/yr	Changeover Time Cost
Ferrite	\$10/min	30 minutes	4 hrs	1250	\$375,000
SMC	\$10/min	30 minutes	20 hrs	250	\$75,000

Material	Scrap Cost	Restart Time	Lbs Scrap/ Changeover	Impeder Life	Changeovers /yr	Changeover Scrap Cost
Ferrite	\$2/lb	1 minute	69	4 hrs	1250	\$173,600
SMC	\$2/lb	1 minute	69	20 hrs	250	\$34,700

Total annual savings are \$455,000, or \$90/hr

Lowers line cost by 15%

\$10 a minute number based upon assumption you can sell tube for \$0.144/lb more than sheet steel

FAHOP Company Case Study

- Case setup:
 - ~400-500kHz 250kW power supply
 - 21-27mm OD steel tube
 - 2.6mm thick wall
 - 13mm OD impeder
- Power required for each impeder material was recorded at various line speeds between 10-60 m/min
- Energy savings for the same line speeds were between 30-50% when using Fluxtrol A

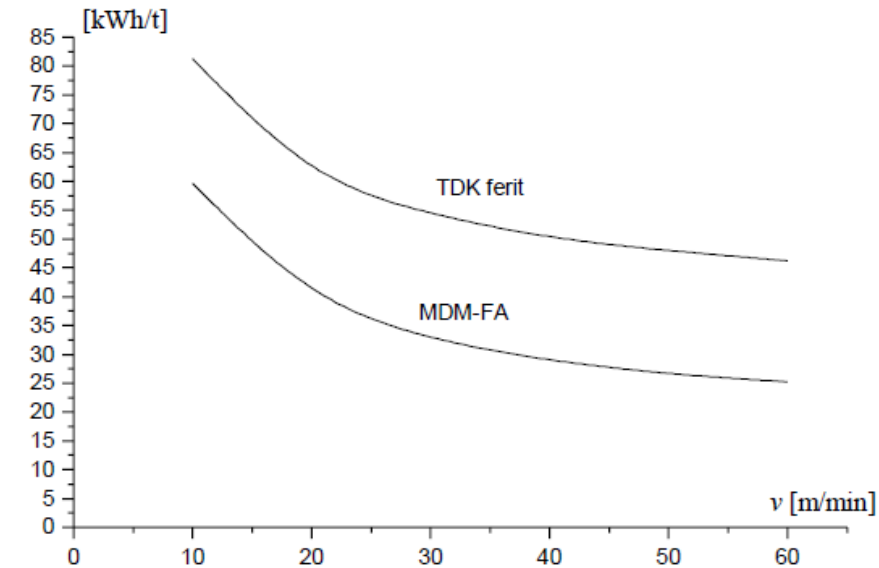


Fig. 6 – Energy consumption per tonne of produced pipe vs. production speed.

Fluxtrol A impeder reported to last approximately 5 times longer in production

Milicevic, Miroslav & Nejovic, Valentina. 2024 Proceedings of the Romanian Academy, Series A. Vol 25. pp 55-64.
Implementation of Optimal HF Welding Procedure of Steel Pipes for High-Quality and Energy-Efficient Welds.

Fahop Study

- Independent analysis done using costs in Serbia
- Fluxtrol had no active participation in the study
- Also compared the results to amorphous lamination impeder from Japan

HIGH ENERGETIC EFFICIENCY OF HF INDUCTIVE WELDING

Table 3 *Presentation the results of comparable criteria for TDK and a new FA impeder and results from [6]*

Criteria Impeder material	$\frac{\text{kWh}}{\text{t}}$	$\frac{\text{kW}}{\text{mm (m/min)}}$	$\frac{\text{kW}}{\text{m/min}}$	Length [mm]
Ferrite - [7]	83.3	3.57	15	400
3% Si-foil	57.11	2.45	10.3	400
Ferrite - TDK	50	1.35	3.52	200
Magn. diel. – FA	27	0.75	1.95	150

Applying the new impeder, energetic savings up to 45 % are achieved in comparison to the ferrite impeder, which justifies the research results. The new impeder also gives savings when compared to some special impiders from [6], so a very useful application is opened with impiders made of magneto dielectrics.

3 CONCLUSION

The main aim of the authors of this paper

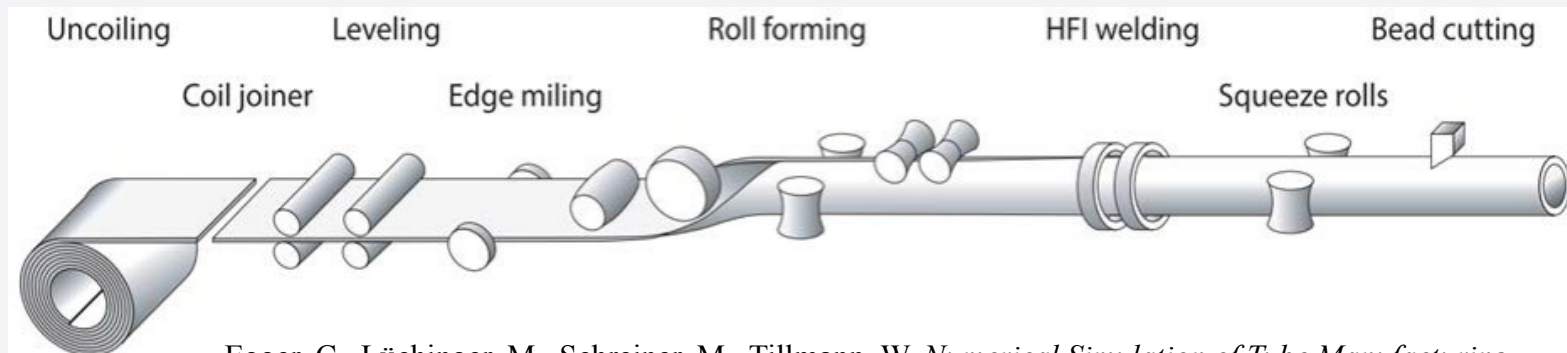
known criteria and the newly introduced criterion, it is determined that the new impeder has better performances regarding to the ferrite impeder.

If the annual savings are calculated for the referent tube with diameter of 21.6 mm, the clear financial saving is approx. \$ 350,000. The achieved saving of energy of 45 % makes possible the increase of production, that is, the production rate of the steel tubes up to 90 % what justifies the efforts of researchers.



The Induction Tube Welding Process

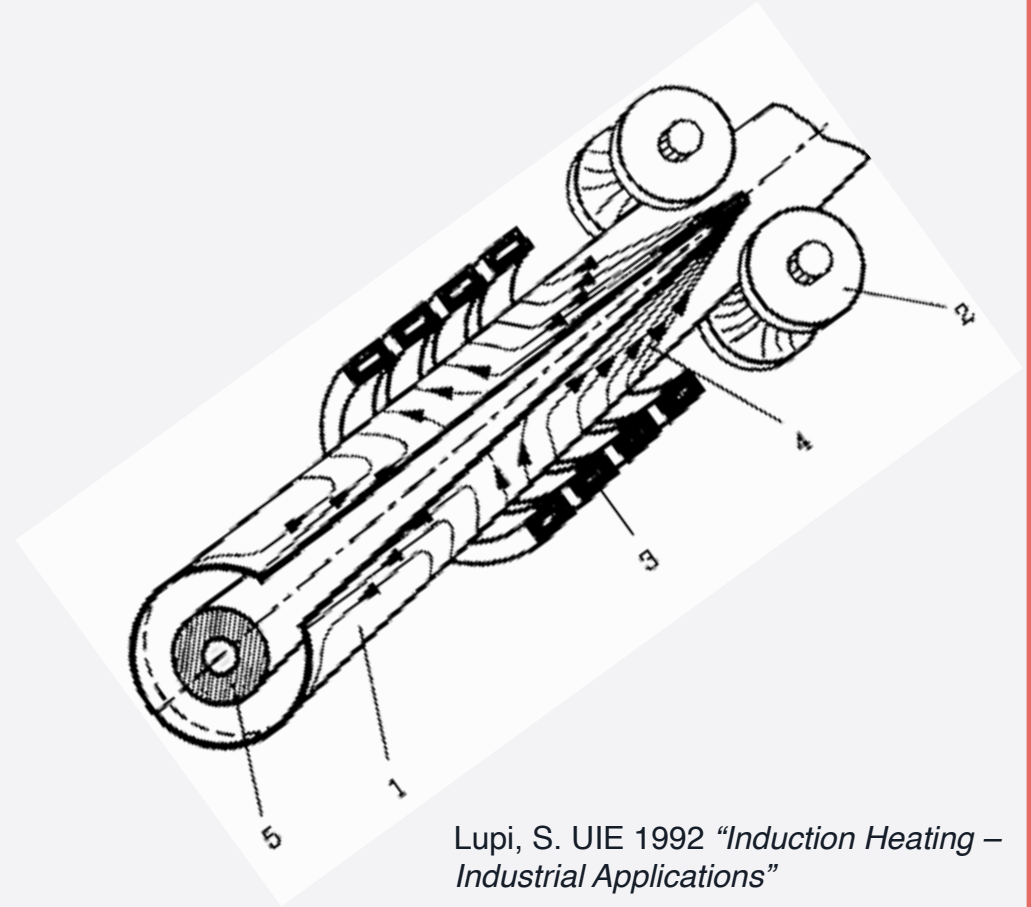
- Inductive welding has been around for a long time—
 - First patents on the process were in the 1940's
 - Known high frequency industrial production in the 1950's
- The Induction Tube Welding Process involves:
 - A steel strip run through forming rolls
 - Forms a tubular shape with an open seam
 - An inductor which is used to heat the inside edges of this seam
 - The hot edges are squeezed together to form a tube



Egger, C., Lüchinger, M., Schreiner, M., Tillmann, W. *Numerical Simulation of Tube Manufacturing Consisting of Roll Forming and High-Frequency Induction Welding*. Materials 2022, 15, 1270.

The Induction Tube Welding Process

- Current is induced in the tube body
- When the currents hit the open seam, there are 3 options for current flow
 - Towards the welding point
 - Back along the seam edges
 - Along the ID of the tube





Inductive Tube Welding Market Trends

- The availability of higher, more efficient power at choice of frequencies
- Improved material handling
- More Advanced Process Monitoring and Control – Industry 4.0
- Improved Material Cutting
- Limiting factor in the performance of many small tube installations is now the impeder

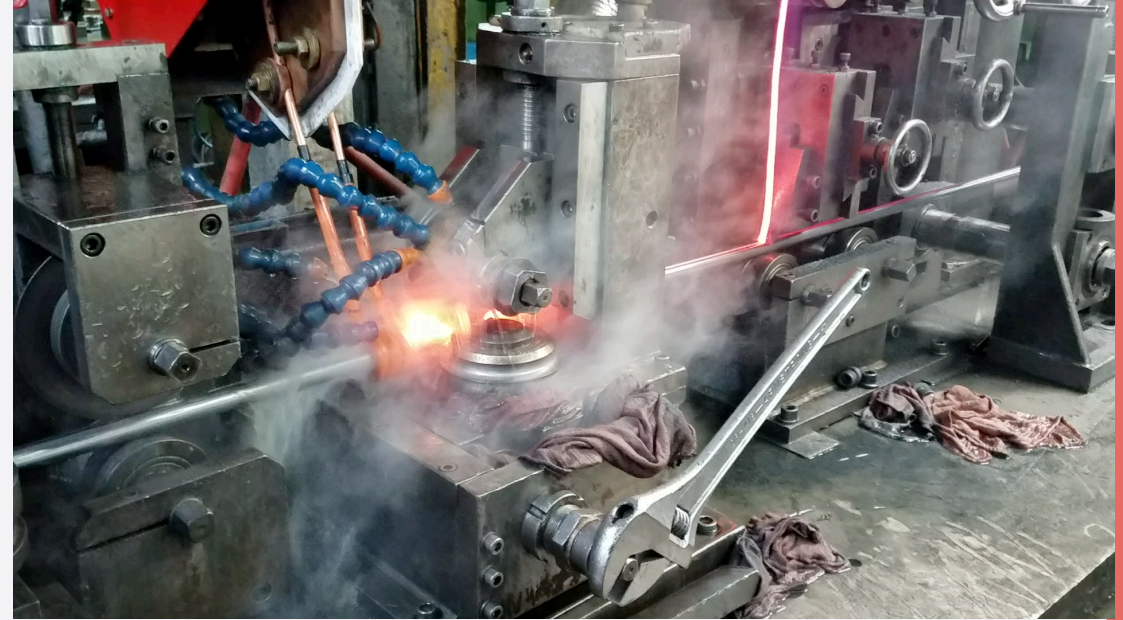
What is an impeder?

- An assembly that contains a soft magnetic material that “impedes” the current flow on the inside of the pipe
- Typically manufactured using ferrite materials
- Fixtured within the forming tube



Through Flow Impeder Trial

- A trial was run at an existing tube mill replacing the Ferrite impeder with Fluxtrol 75
 - Very short lifetime of ferrites
 - Not able to meet production targets
- The line was run for ~20 minutes at the same line speed for both impeders and electrical parameters were recorded
- Induction system set-up the same in both cases – only impeder change



<https://fluxtrol.com/ASM-HTS-2019-improving-inductive-welding-system-performance-with-soft-magnetic-composites>



Results of the Trial

- Coil current values obtained by multiplying generator current value by transformer ratio and number of turns in the inductor

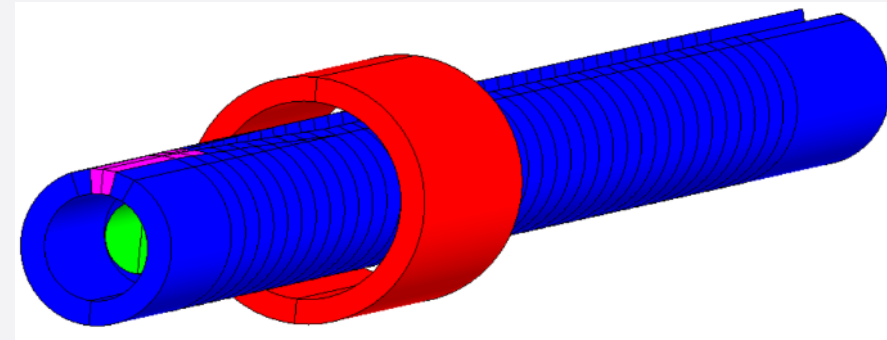
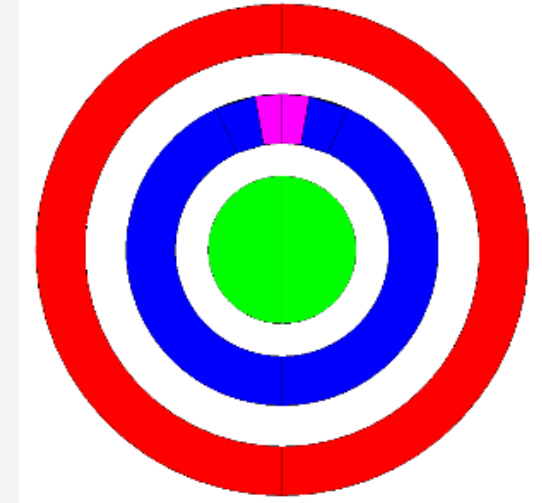
Magnetic Controllers	Coil Current (# Ampere turns)	Power (kW)	Line Speed (m/ min)
Fluxtrol 75	5000	200	82
Ferrite Impeder	7300	325	82
Fluxtrol 75 Highest Speed	5400	220	96

Over 30% lower current and almost 40% lower power for the same production speed

<https://fluxtrol.com/ASM-HTS-2019-improving-inductive-welding-system-performance-with-soft-magnetic-composites>

Through Flow Impeder Trial Details

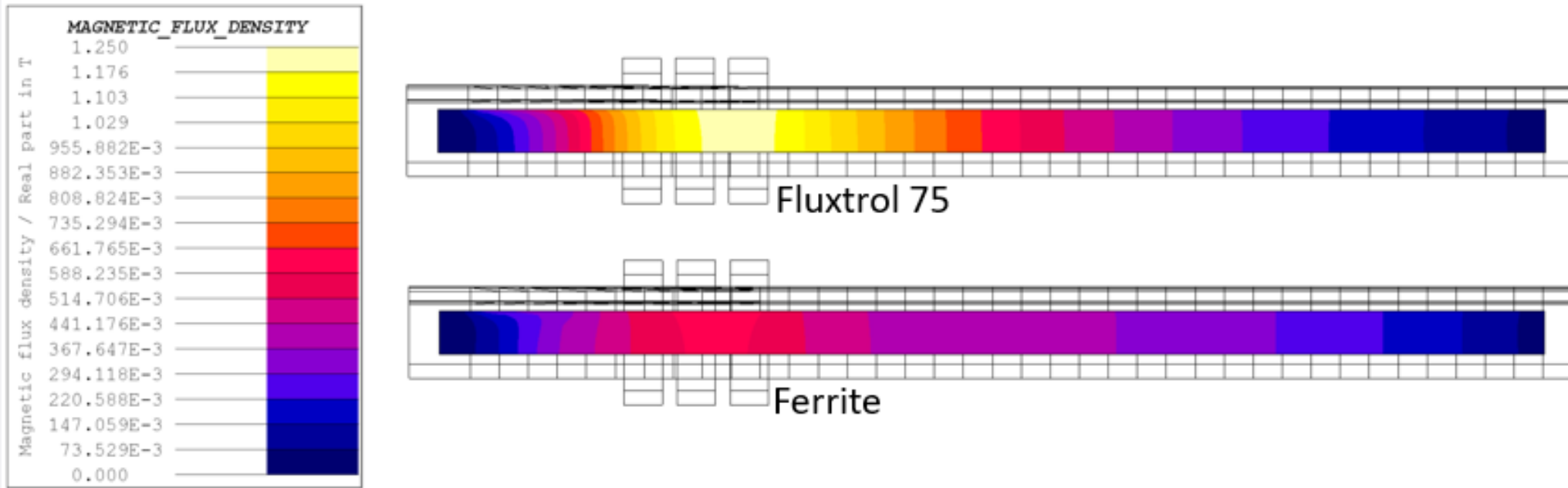
- Steel Tube:
 - 19 mm OD with 3 mm wall thickness
 - 2° weld vee angle
- Inductor:
 - Shown Conceptually Here as Single Turn
 - 24 mm ID, 41 mm length
 - 64mm from the end of the coil to the apex
- Impeder:
 - 9 mm OD
 - 230 mm length



<https://fluxtrol.com/ASM-HTS-2019-improving-inductive-welding-system-performance-with-soft-magnetic-composites>

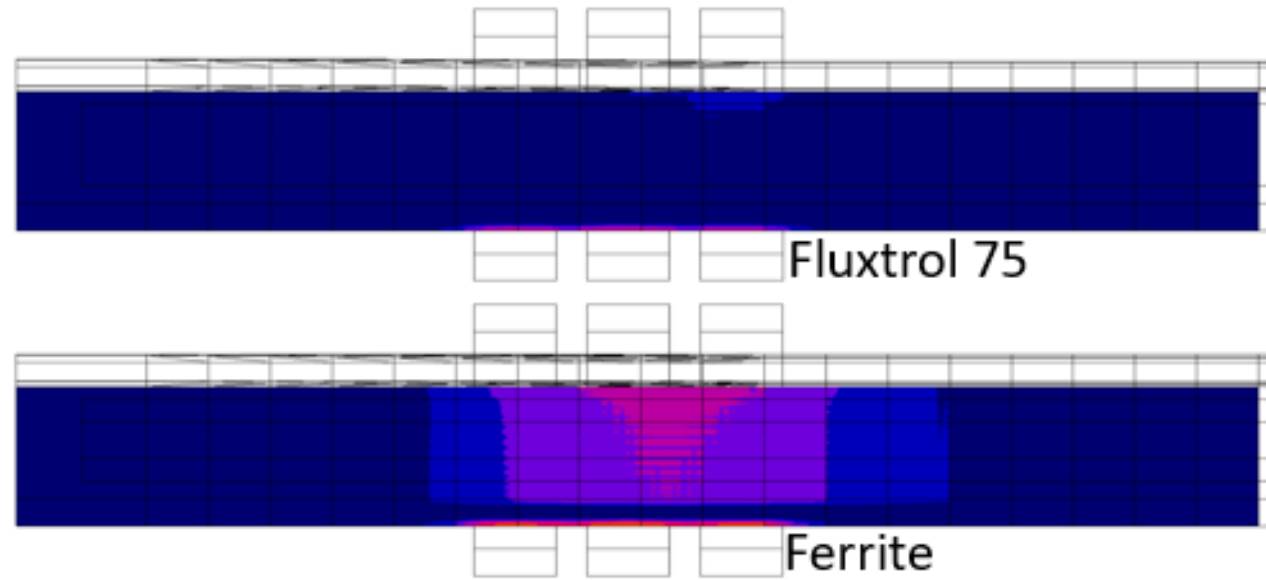
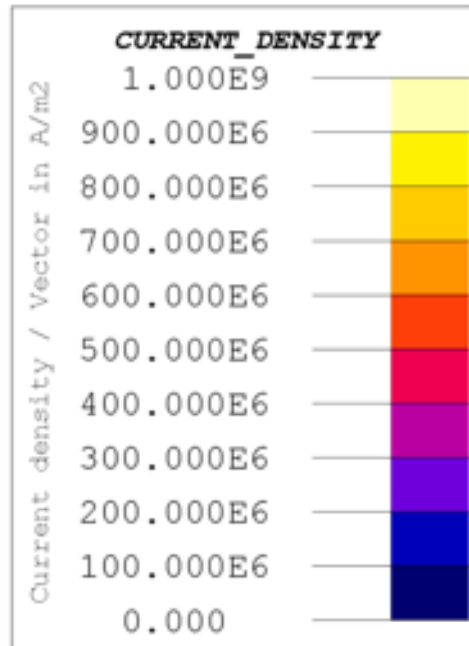
Magnetic Flux Density Distribution in Impeder Core

- Fluxtrol 75 is below its saturation flux density of 1.4T
- The Ferrite is heavily saturated (Bs 0.4-0.5 T), as can be seen by the wide zone carrying max flux extending past the inductor



<https://fluxtrol.com/ASM-HTS-2019-improving-inductive-welding-system-performance-with-soft-magnetic-composites>

Current Density on the ID



- Once the ferrite reaches saturation, current begins to flow more freely around the ID of the tube
- This additional current is how we can explain the higher current and power required using the ferrite impeder as compared to the Fluxtrol 75 impeder

<https://fluxtrol.com/ASM-HTS-2019-improving-inductive-welding-system-performance-with-soft-magnetic-composites>



Flow Through Impeder Energy Savings

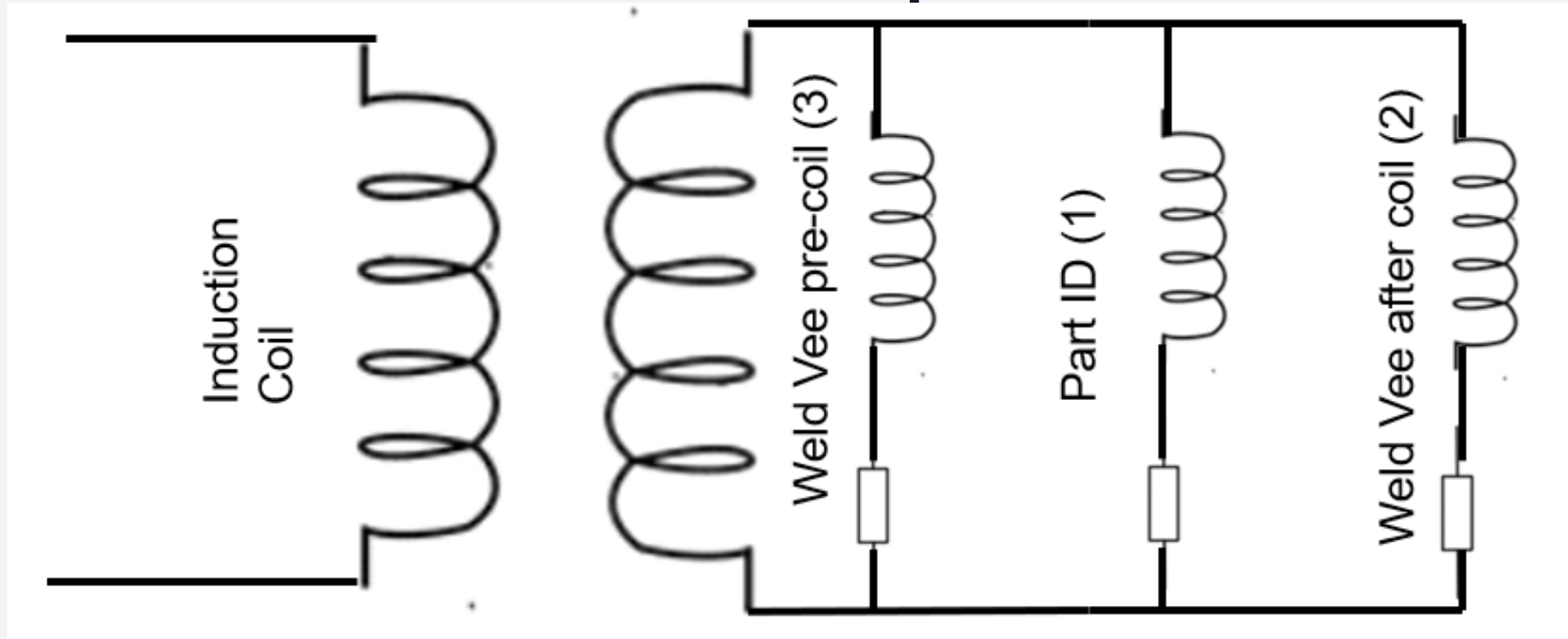
- This study shows over 100 kW lower power required for 20% higher line speed
 - **45% lower kWhr/ton of tubing produced!**
- Using the same assumptions as the previous case:
 - Running at the same line speed prevents 437 tons of CO2 and saves \$50,000 in electricity costs
 - Running at the higher line speed prevents 479 tons of CO2 and saves \$55,000
- **Same volume of product produced in 730 less hours**

- 1A CO₂ emissions factor of 6.99*10⁻⁴ tons/kWh
- 2 shifts, 7 days or ~5000 hr/year of production
- 2\$0.08 per kWh

	Line Speed (m/min)	Power (kW)
10mm Ferrite	82	325
10mm Fluxtrol 75	82	200
10mm Fluxtrol 75	96	220

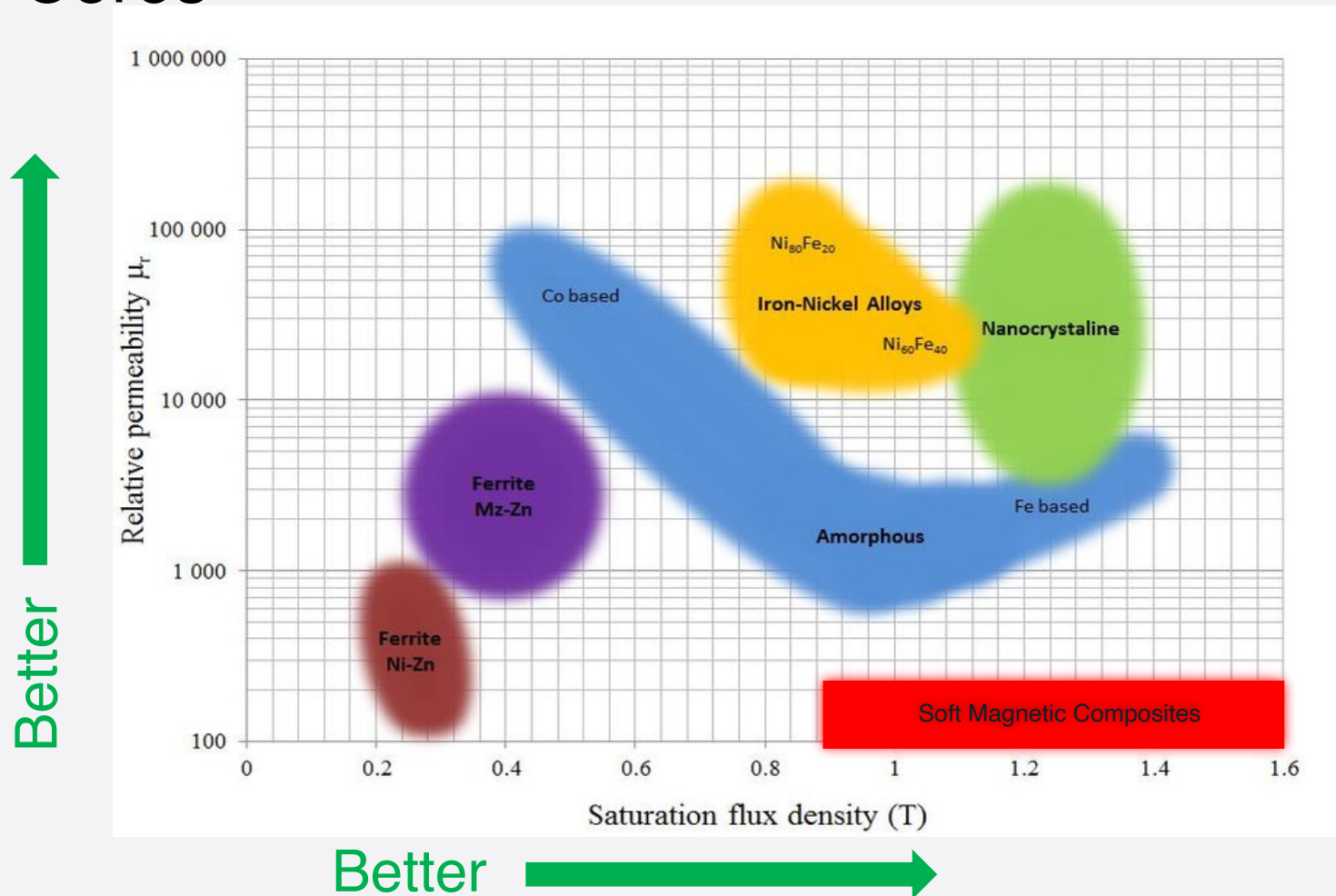
1) EPA (2022) AVERT, U.S. national weighted average CO2 marginal emission rate, year 2021 data. U.S. Environmental Protection Agency, Washington, DC

Circuit Model Concept



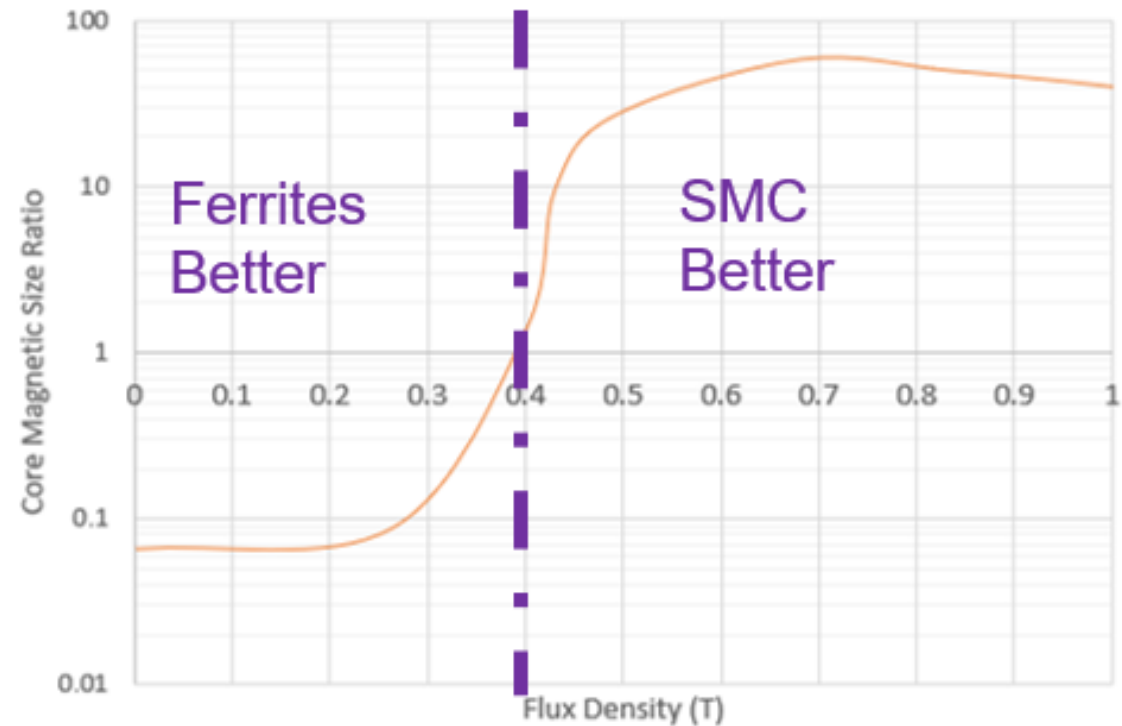
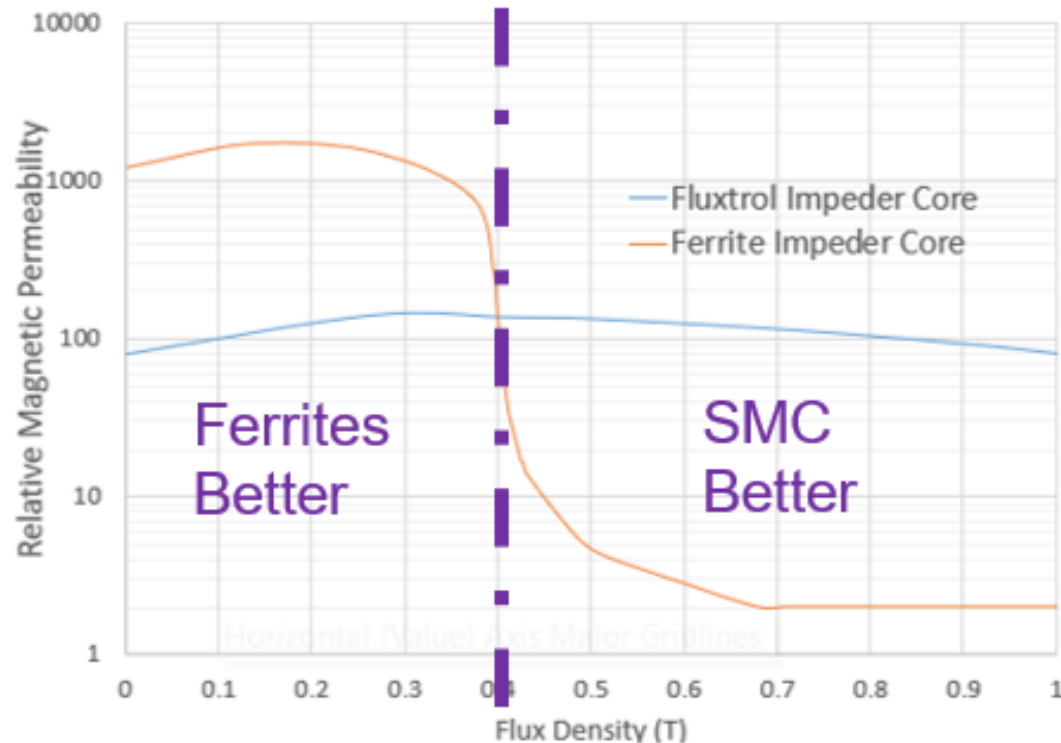
- The product of magnetic permeability of the core and the cross-sectional area of the core are $\approx$ directly proportional to inductance for the part ID path
 - The higher the value of the product
 - The greater the inductance of the Part ID current path
 - The lower the percentage of current that will flow on the part ID
 - The larger percentage of the current on the tube edge

Magnetic Properties of Soft Magnetic Materials Used as Magnetic Cores



M. Kaçki, M. S. Rylko, J. G. Hayes and C. R. Sullivan, "Magnetic material selection for EMI filters," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, 2017, pp. 2350-2356, doi: 10.1109/ECCE.2017.8096456.

Fluxtrol A vs Ferrite Core Comparison



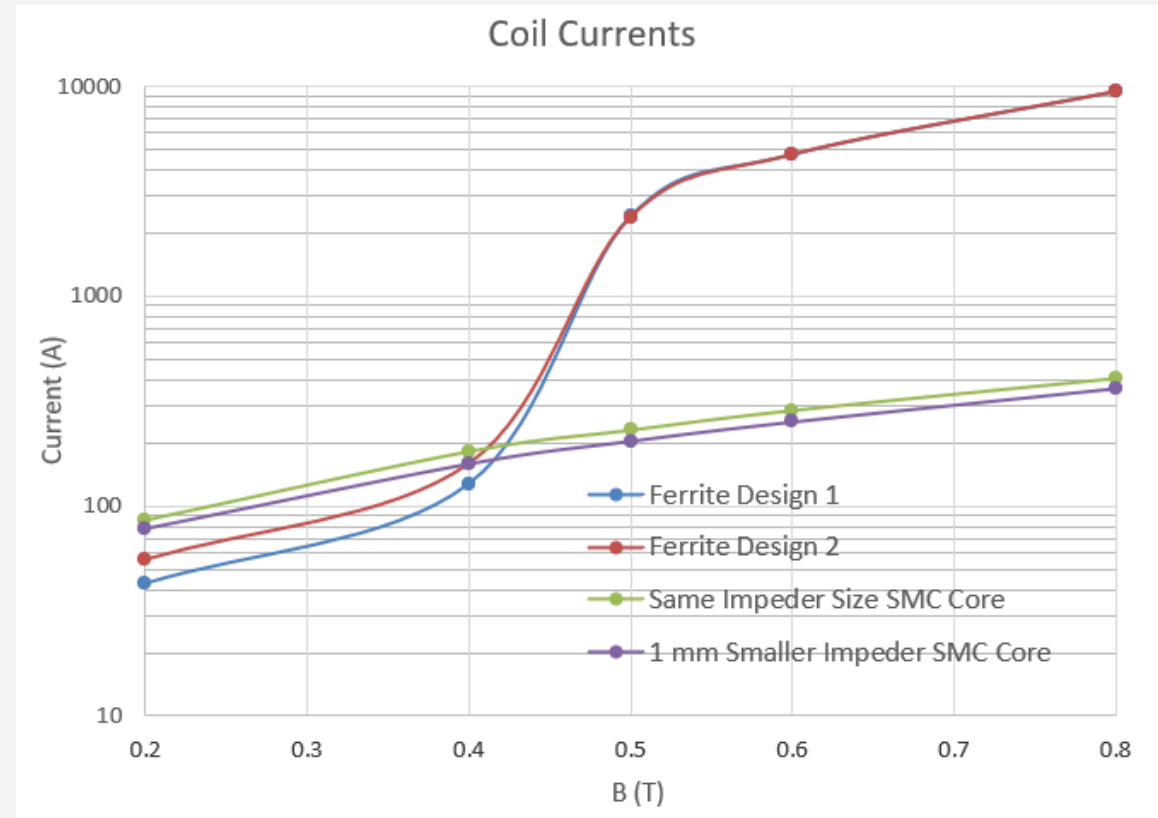
- To the left of the line, typical ferrites used for impederes will outperform the Fluxtrol A material
 - However, Fluxtrol A will still be approximately 100 X better than air
- To the right of the line, Fluxtrol A will outperform ferrites
 - At the level of 0.7 Tesla and above, Ferrite will only be approximately 2 X better than air, while Fluxtrol A remains approximately 100 X better

Case Study – Return Flow Impeder

- Inside of the ID of the impeder core, there is a brass tube
- A steel rod passes through the inside of the brass tube
 - **Very little space is available for the impeder core**
- Main failure mode of the impeder core was mechanical, so 2 different SMC cores were considered
 - Fits in same casing as current ferrite impeders
 - Fits in 1 mm smaller casing than current ferrite impeders
- Calculations made for this case without a tube in place – only induction coil and impeder elements

Current vs Bcore

- Lower currents are required for ferrites at low flux densities
- At high flux densities, much higher currents are required for ferrites



- Losses in the induction coil and power supplying circuitry components are proportional to the coil current squared.
- In production testing, the core was 3 mm smaller diameter (2 mm smaller impeder diameter) and still showed almost 20% energy savings



Region of High Process Efficiency

- If the impeder can carry the majority of magnetic load of the ID path, the system is running near the maximum theoretical efficiency
 - Region of High Process Efficiency
- In small tubes, space is limited for the cores, limiting the total magnetic capacity (**Bs X Area**)
- With proper design, SMC's can carry over double the 0.4T saturation flux density of typical ferrites under tube welding conditions

$$\text{Regime of High Process Efficiency} \propto B_{\text{impeder}}^2$$

$$\left(\frac{B_{\text{SMC}}}{B_{\text{Ferrite}}} \right)^2 = \left(\frac{0.8}{0.4} \right)^2 = 4 \times \text{Regime of High Process Efficiency}$$



SMC vs Ferrite Impeders

Advantages of SMC

- Higher Saturation Flux Density
 - Performance Improvement
- Temperature/time stability of magnetic properties
 - Improved stability of production (ferrite properties very sensitive to temperature and stresses)

Disadvantages of SMC

- Cost of impeder
- Lower permeability at low fields
- Higher losses than ferrites
 - Requires better cooling
 - May not work in gas cooled systems

Opportunities for SMC Impeders

- Small diameter, heavy-walled steel tubes
- Small tube applications where welder is the bottleneck and impeder is in saturation
- Applications where impeders frequently fail due to mechanical impact with line
- Applications with metallic components inside of the impeder
- Applications with very short impeder life



Kent Corporation Case Study

- Case setup:
 - ~400kHz 300kW power supply
 - 12.7mm OD steel tube
 - 1.25mm thick wall
 - 8.5-9mm OD impellers
- Energy savings for the same line speed was ~20%
- All metallurgical and structural tests passed





Kent Corporation Case Study Energy Savings

- Even though the tube size and wall thickness is smaller than the previous two studies, energy savings is 13kW or the equivalent of preventing 45 tons of CO² per year and saving \$5,200 in electricity
- Taking the time saved to produce the same amount of product, over 50 tons of CO² could be prevented and \$5,700 saved with increased production speeds

	Line Speed (m/min)	Power (kW)
9mm Ferrite	82	69
8.5mm Fluxtrol A	82	56
8.5mm Fluxtrol A	93	62



Note – Impeder
OD listed, not core
size

- Impeder ran with no need to adjust power settings for over a full shift before being changed out – typical ferrite impeder life much shorter
- No arc's and sparks
- Bottleneck was manual unload of tubes

Barriers to Adoption

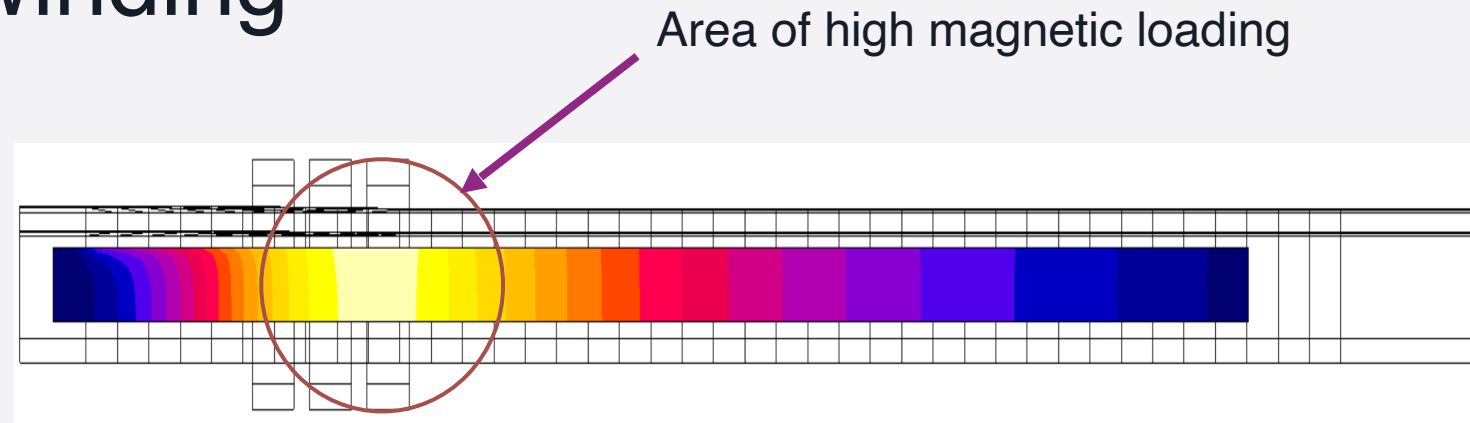
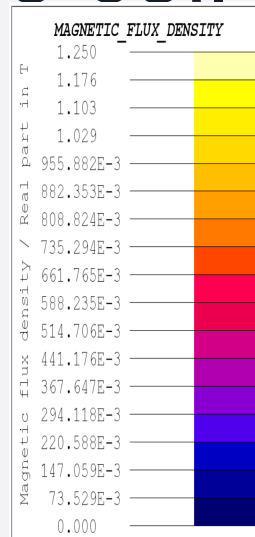
- Tests on a tube mill are very expensive
 - 150 to 1000' ft/min line speeds typical
- Validation of new process can be very expensive
- Ferrites are proven technology and the current industry standard for decades
- SMC cores are 10 – 50 times more expensive to purchase on an individual unit basis
 - Annual Costs of Impeders Only are often similar, production savings tend to be much higher
- SMC losses are higher, so good cooling is required
 - Need to be mindful of water circuit design

Impeder Core Validation Approach

- 2D/3D models for Impeder Cross-Section Design and Cooling Requirements
- Laboratory Testing for Welding Impeder Physical Simulation
 - Offline survivability testing
- Field Testing Support with Industrial Partners Once Design Is Proven

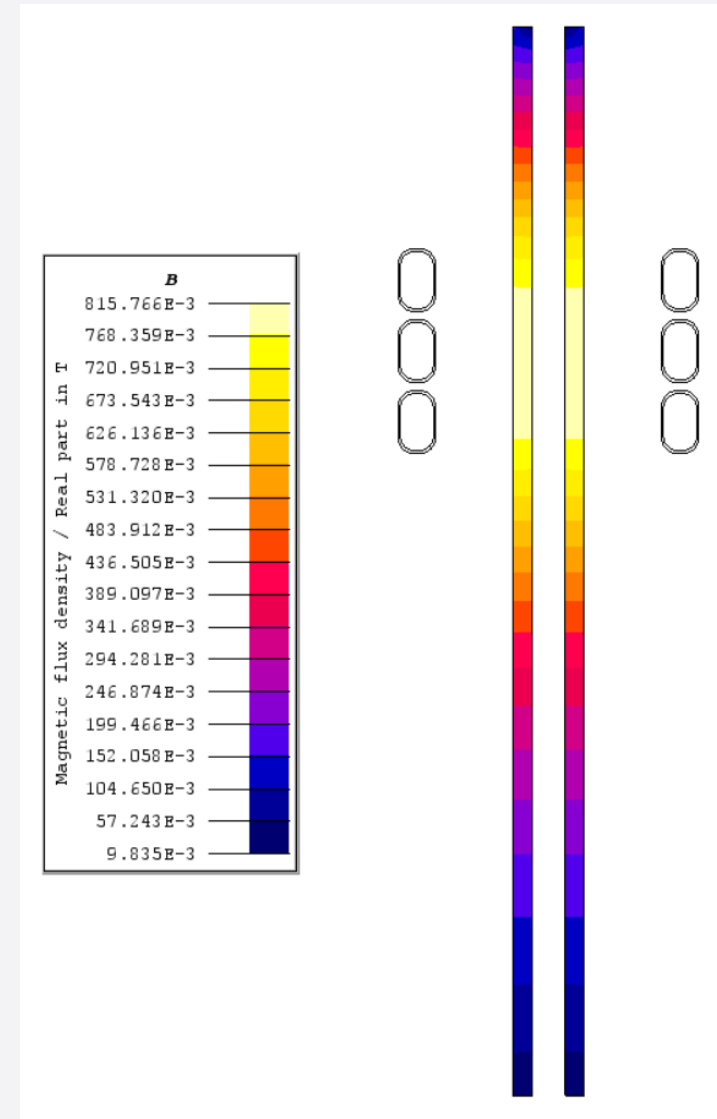
Impeder Conditions

- Prior to saturation, there is a significant gradient in the magnetic flux density in the core axially
 - Radially the gradient is small
- This Area of High Magnetic Loading is located under the coil winding



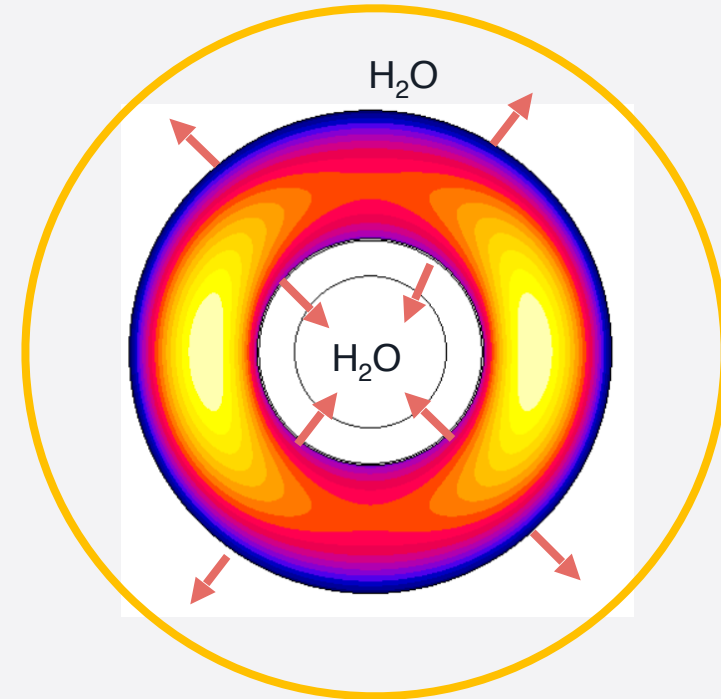
Design of Experimental Setup

- If we remove the steel tube, the distribution of magnetic flux density looks very similar
- With magnetic losses being the main concern for SMC's, we built coils similar to tube welding coils and install the impellers directly in the coils
- We apply high frequency power to the coil and install impellers in the test stand



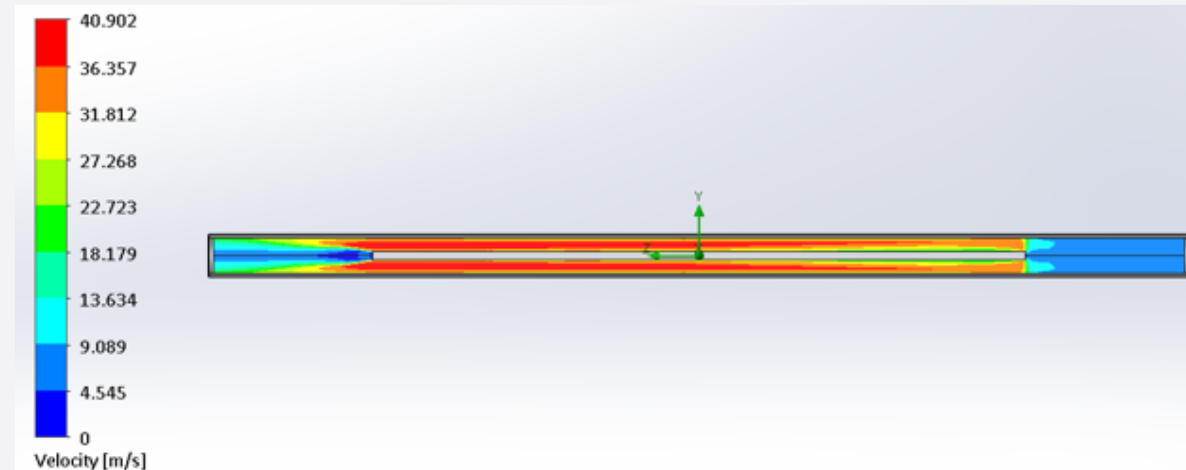
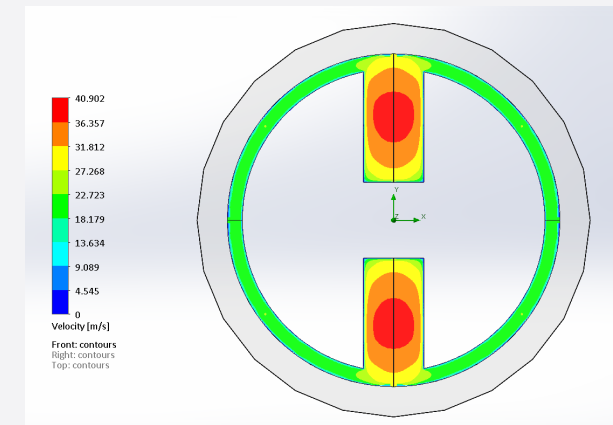
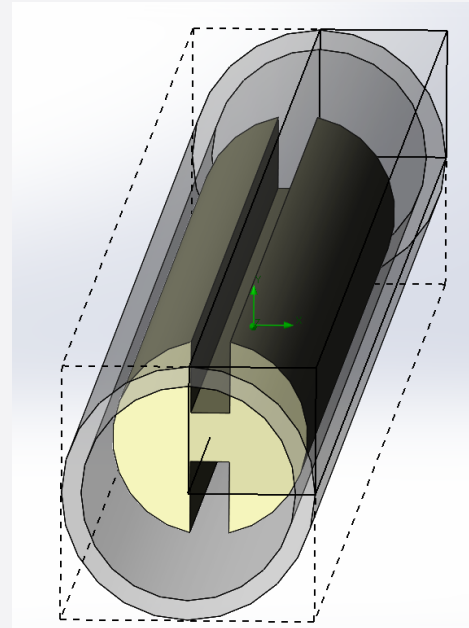
Cooling Calculations

- Cooling involves both total heat removal and local heat removal
- Total heat removal is dependent upon total coolant flow
 - $P = mC_p\Delta T$
- Local heat removal is dependent upon velocity of water flow, shape of impeder and thermal conductivity of material
 - $P = hA\Delta T$



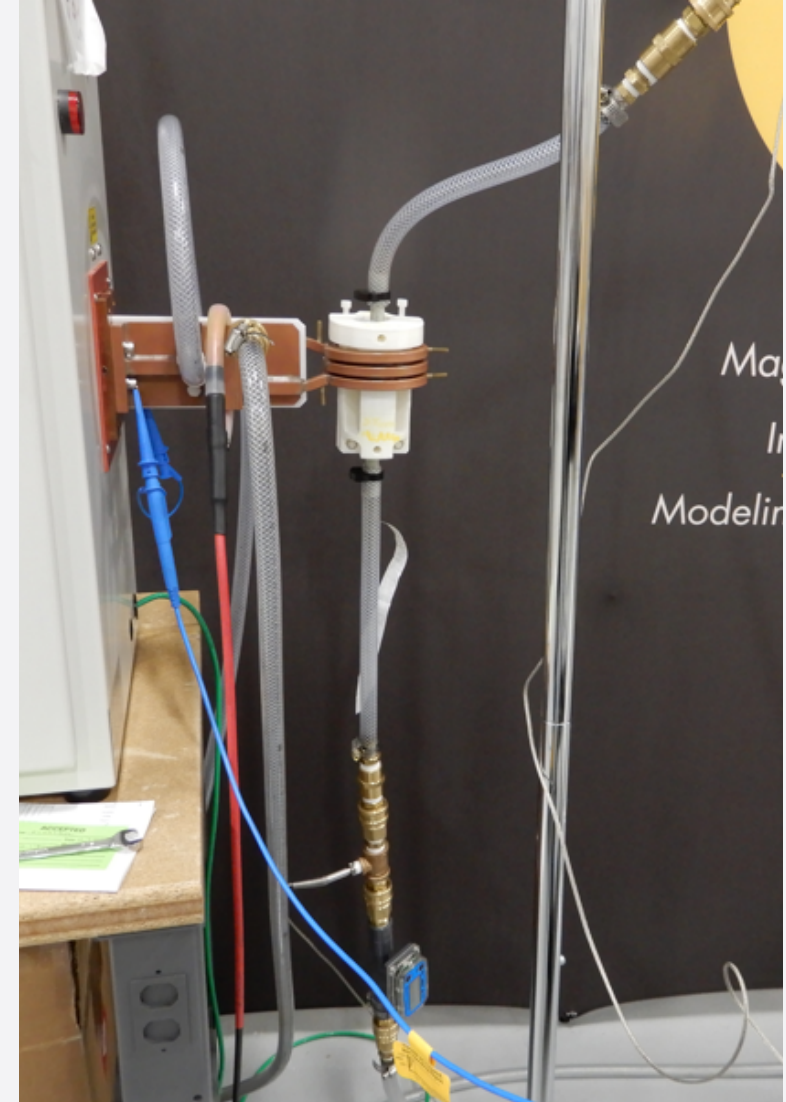
CFD Models Understand Water Flow

- Verify sufficient volume of flow for global cooling with available pressure
- Verify local cooling capability
- Understand impacts of various fittings and flow paths
 - Especially important for return flow impellers



Test Installation

- Measure coil voltage and current and compare to EM Models for the associated flux density tested
- Measure water flow and inlet and outlet temperature
- Make calorimetric calculations for losses in the impeder
- Compare these value to our calculated values
- Run core for extended durations to prove durability at conditions more challenging than they will experience in the field

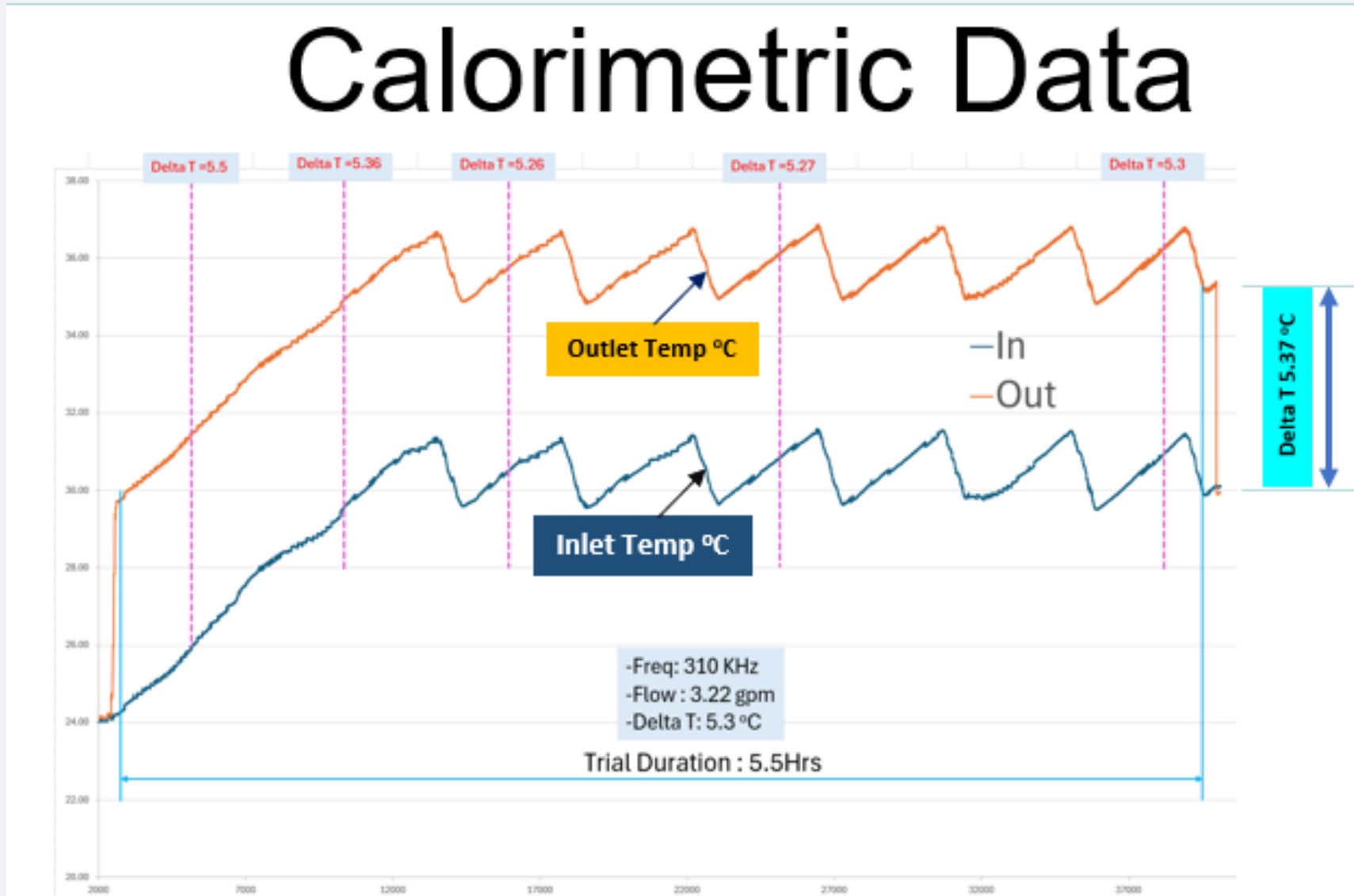


10 mm Solid Fluted SMC Core Trial

Calorimetric Data

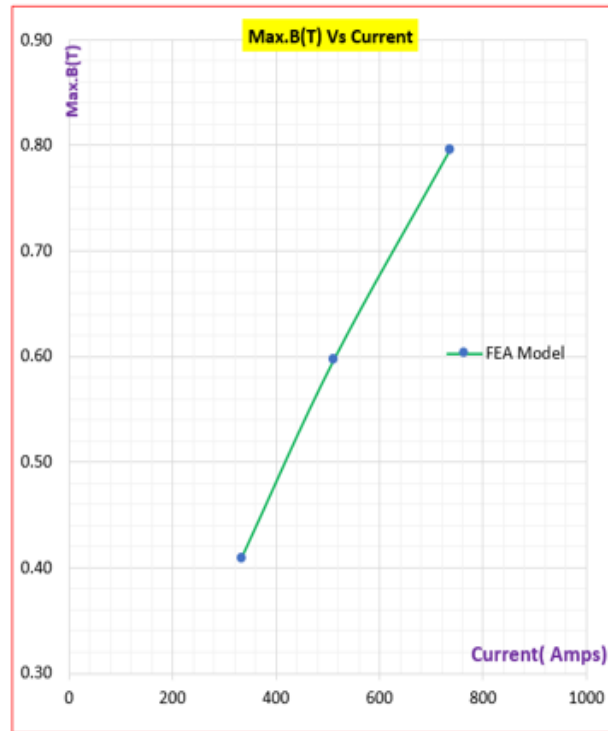
Return
water 96
F

Supply
water 86
F

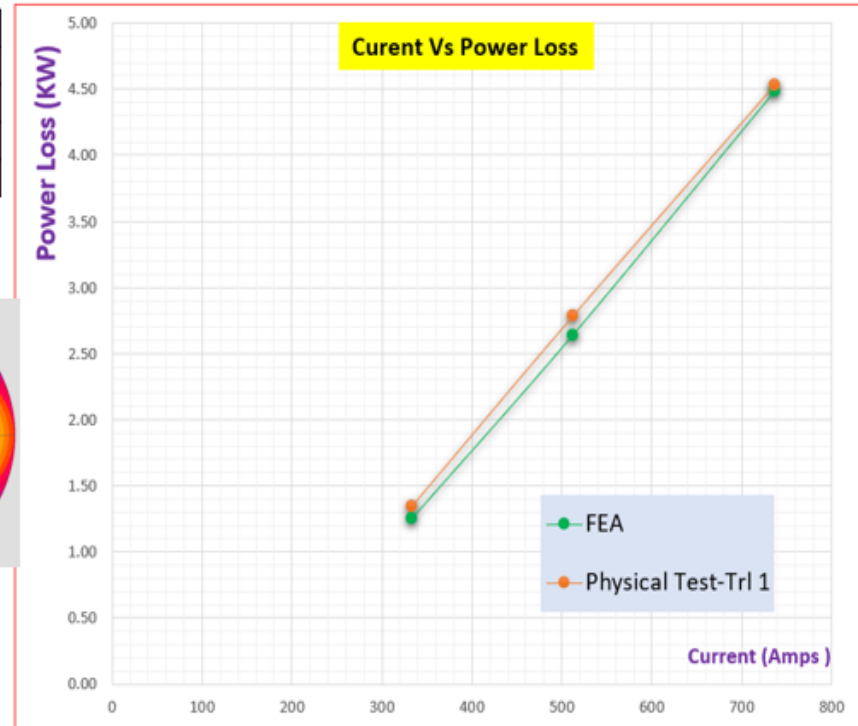
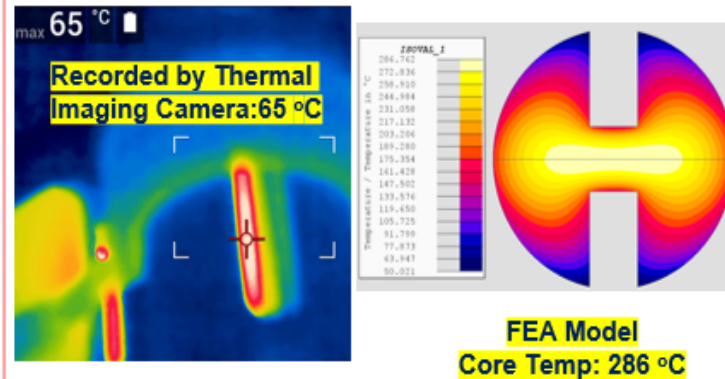


Comparison of Tests and Experiments

FEA Model					Experimental(Physical Test data)				
FEA I/O data					Power(KW)	Mass Flow Rate(m)	Temp.Diff(Delta T)	Specific Heat (C _p) of water	Current
Impeder OD	F(KHz)	I _{rms}	U _{rms}	Max B (T)	P _v * V (Integral Power)	(Kg/Sec)	°C	KJ/kg °C	Amps
10 mm	310	333	68	0.409	1.25	0.202	1.6	4.18	333
10 mm	310	512	102	0.597	2.64	0.202	3.3	4.18	512
10 mm	310	737	143	0.796	4.48	0.202	5.4	4.18	737

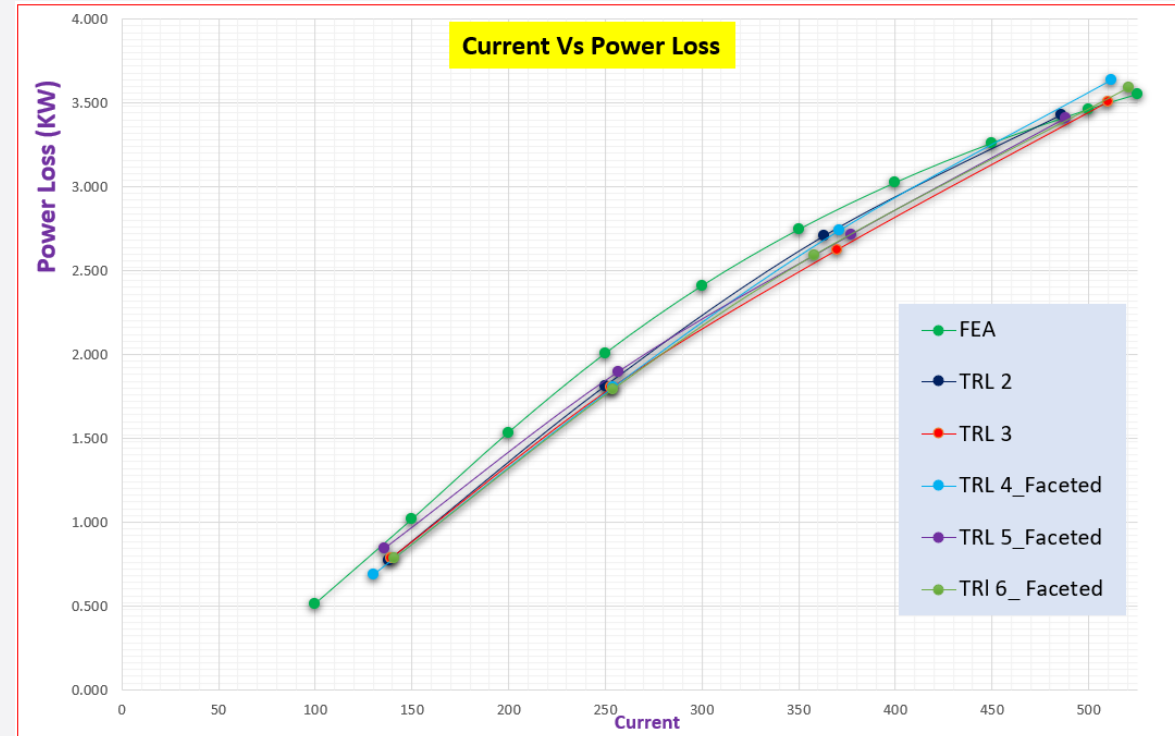
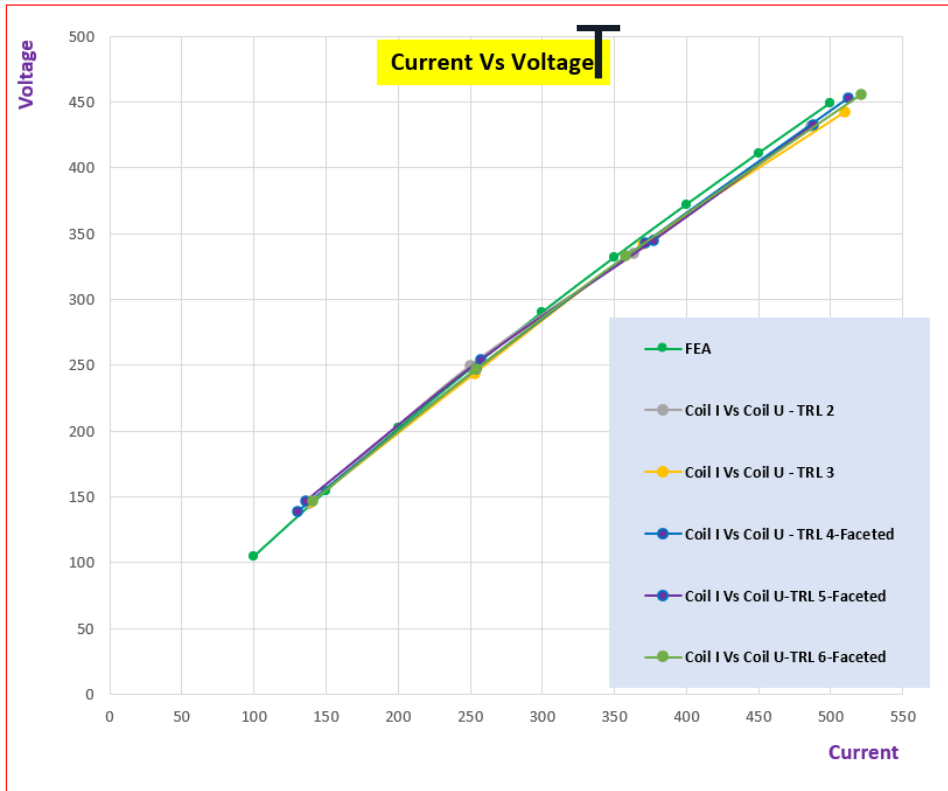


Power Loss Deviation % : Trl # 1			
Current Amps	Physical Test(KW)	FEA (KW)	Dev. % From FEA.
333	1.35	1.253	7.6%
512	2.78	2.639	5.4%
737	4.53	4.484	1.0%



Impeder Core 10mm Hollow: @ 200 KHz

Maximum Flux Density Tested ≈ 1.2



- Experimental data are well correlated with simulation result and highly repeatable.
- Power loss deviation is less than 5%.

Power Loss Deviation % at Max PS			
TRL #		FEA	Dev. %
Trl # 2	3.43	3.4	1.5%
Trl # 3	3.51	3.5	0.3%
Trl # 4	3.63	3.51	3.4 %
Trl # 5	3.41	3.42	0.3%
Trl # 6	3.6	3.54	1.7%

Summary

- Many small tube welding installations are limited by the impeder
- SMC's have the potential to greatly improve the performance of these installations
 - **Savings are \$100's of thousands annually per line**
 - **Increased impeder and coil lifetime**
 - **Production rate improvements**
 - 20 – 50% energy savings/carbon reduction
- SMC's have higher magnetic losses, so it important to appropriately design the impeder core and cooling circuit
- A workflow for verifying impeder capabilities offline based upon computer models and physical simulation



Acknowledgements

- Multiple Fluxtrol team members participated in the modeling, design, manufacturing and testing of the impeder cores
- For welding tests carried out at Prinz & Co. GmbH Stahlrohre, impeder cores and the impeder system were manufactured by TWTools. The project was financially supported by the German Federal Ministry for Economic Affairs and Climate Protection under the funding code ZF402804FH9.
 - Grant participants Technical University of Chemnitz (Prof. M. Kroll et al), University of Hanover ETP (Dr. Nikanorov, et al), Polytron GmbH and TWTools

