FLUXTROL®

Physical Simulation of Soft Magnetic Composite Impeder Performance

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IMAT
ASM'S ANNUAL MEETING
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Background

- Inductive welding is a popular method for making tubes used in a variety of industries
- Induction Tube Welding Process involves:
  - Rolls of steel strip are run through forming mills to create the tube shape with a closing seam
  - An inductor is used to heat the inside edges of this seam
  - The softened tube edges are squeezed together by the closing rolls to form a solid state weld

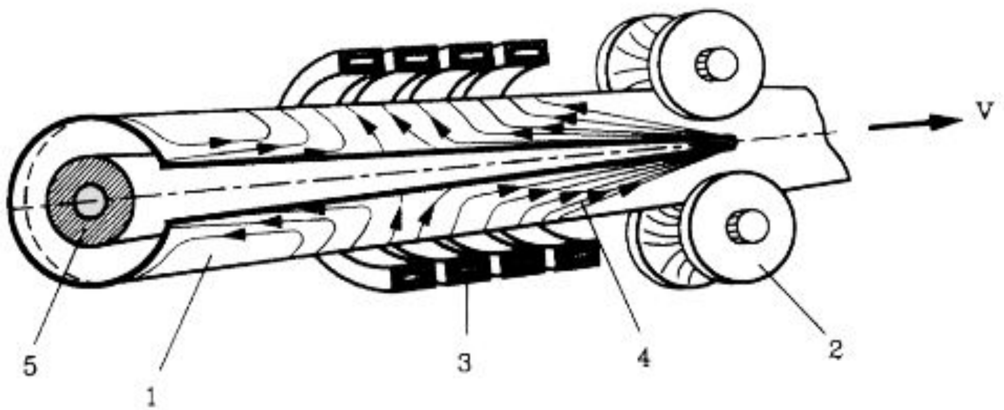


Image taken from UIE book "Induction Heating – Industrial Applications"

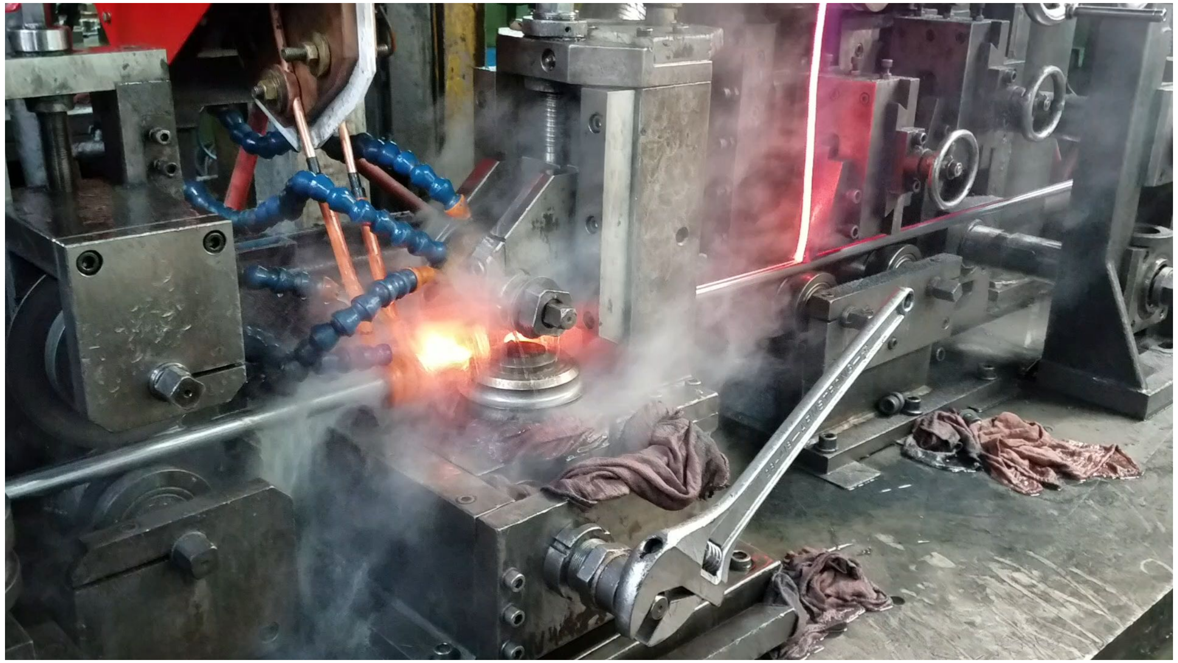
Impeder Background

- Impeders are typically manufactured using a combination of constructive elements and ferrite rods or tubes(ferrites)
- The ferrites have low saturation flux density which is strongly temperature sensitive and becomes more of an issue at lower frequencies
- This new situation creates an opportunity to improve the welding system performance using soft magnetic composite materials (SMCs)
- Fluxtrol impeders have been successfully tested in industrial tube mills and have shown significant performance improvements, matching well with simulation and case study results presented previously at HTS 2019

https://www.efd-induction.com/en/induction-heating-equipment/weldac-tube-welder

Previous Case Study

- Previously presented at HTS 2019, a trial was run at an existing tube mill replacing the Ferrite impeder with Fluxtrol 75
- The process was welding of a 19mm OD steel tube with 3mm thick wall using a 9mm OD through flow impeder
- The line was run for ~20 minutes at the same line speed for both impeders and electrical parameters were recorded
- After this equivalent test, the line speed was turned up to see what the Fluxtrol 75 core could achieve



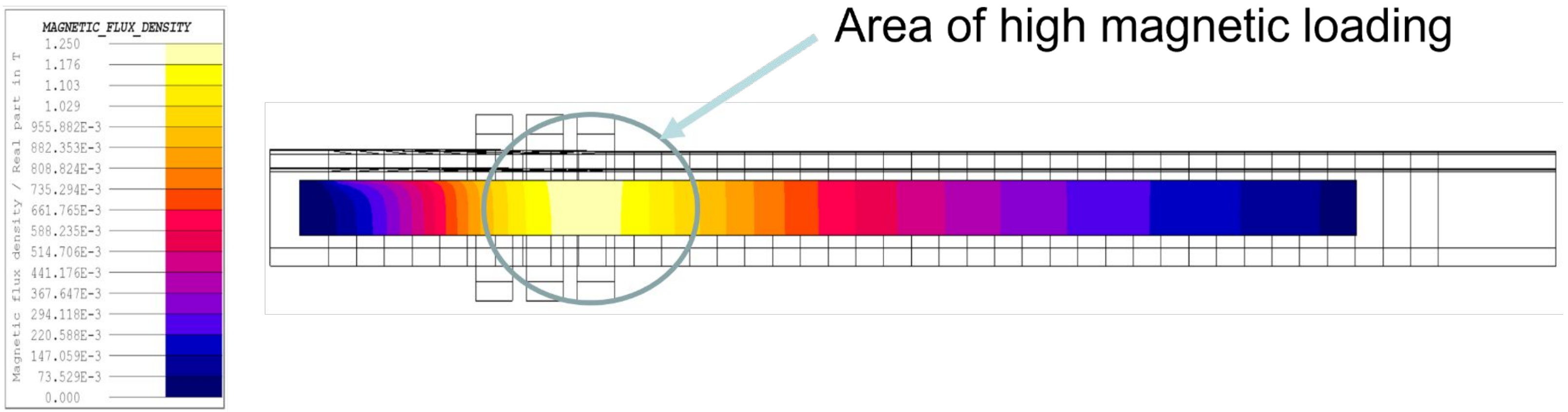
Previous Case Study Results

- Coil current values obtained by multiplying generator current value by transformer ratio and number of turns in the inductor
- At a line speed of ~80 m/min there was a 30% reduction in required coil current and 40% drop in required system power when switching from a ferrite to Fluxtrol 75 impeder
- After the trial was completed, the additional resource in power when using the Fluxtrol 75 impeder allowed for increased line speeds over 95 m/min, removing the induction welding processing bottleneck

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

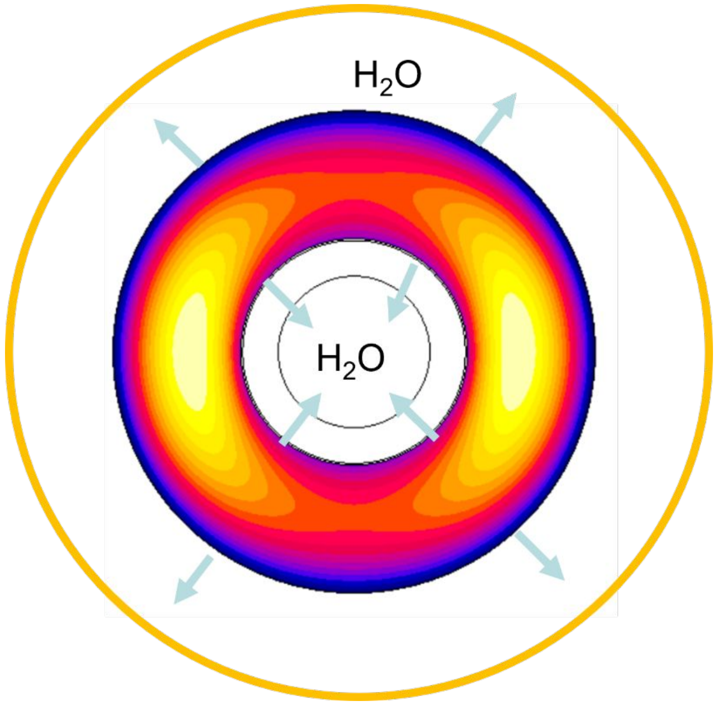
Impeder Conditions

- Based upon previous successful trials, we have done modelling to predict the effect of using Fluxtrol materials as the impeder core in tube welding systems
- The models also show what conditions Fluxtrol materials will be exposed to
- Due to higher saturation flux density, Fluxtrol materials have the potential to significantly improve the welding system parameters in applications where the ferrites are saturated
  - The concern is that due to higher losses of Fluxtrol materials compared to ferrites, can the impeders be cooled to survive these harsh conditions?
- Below an example of a 3D model can be seen, showing magnetic flux density distribution in an impeder made of Fluxtrol A under extremely high loading



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
  - $P = hA\Delta T$
- Investigations to date show that in impeders with reasonable water flow, local heat removal is the more challenging parameter



Experimental Validation

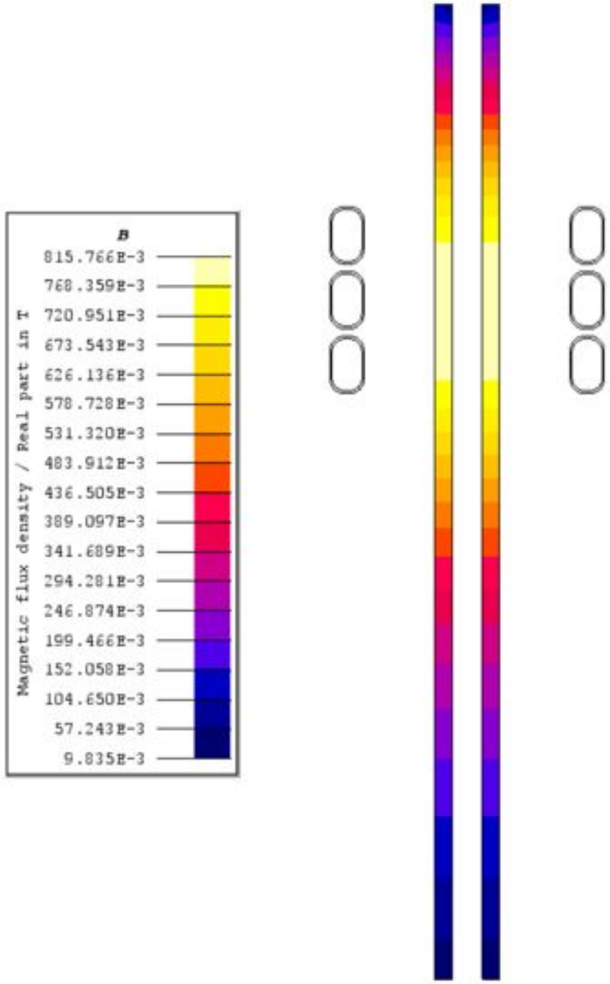
- While calculations based on the most current figures show that with proper design we can satisfactorily cool the Fluxtrol impeders in nearly all cases with water, we want practical data and the ability to test new impeders in-house before implementation at the customer site
- These tests will allow us to understand if our calculations are correct, as well as provide guidelines for use in the field, including required water flowrates through the assembled impeder for a given process frequency
- and estimated magnetic loading

Experimental Setup

- The test stand can be seen in the image to the right, which mimics the magnetic flux density the impeder would experience in a real welding installation
- Losses for the impeder are calculated using the recorded change in water temperature and flowrate and are compared to simulated losses
- Voltage and current from the coil are measured using a voltage probe and Rogowski belt, and these values are used to model the magnetic loading of the impeder
- After running each SMC impeder at increasing power settings, an upper operational range for each material can be constructed

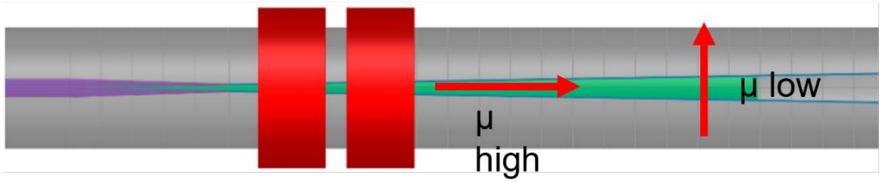
Simulation of Experimental Setup

- By using the measured electrical parameters for each trial, as well as the magnetic properties for each SMC, a simulation of the setup was created to calculate the expected loading of the impeder to estimate losses
- The distribution of magnetic flux in the test rig is designed to mimic the distribution of magnetic flux in a typical tube welding installation
- The modeled losses can then be compared to the measured losses

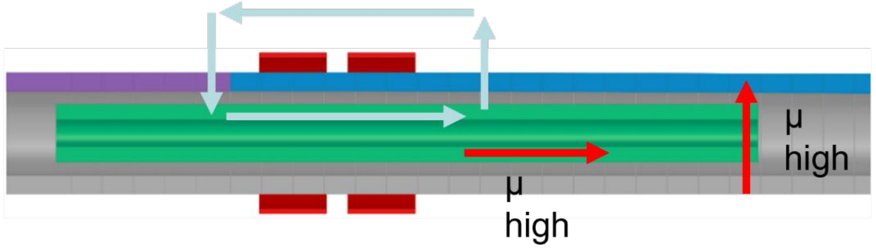


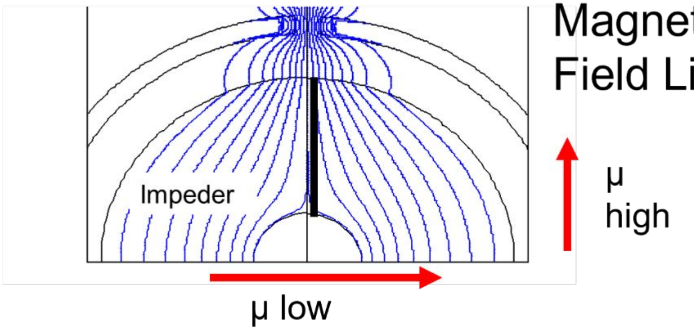
Difference Between Rig and Reality

- In real welding installations, the magnetic flux penetrates through the slot between the edges of the strip
- The field is in line with the particles, which are parallel to the seam between the two halves
  - High permeability
  - Low losses
- In our test rig, there is no shielding of the unfavorable direction for magnetic flux at the entrance and exit of flux from the core on the sides (away from seam)
  - Lower permeability
  - Higher losses



Flux Circuit



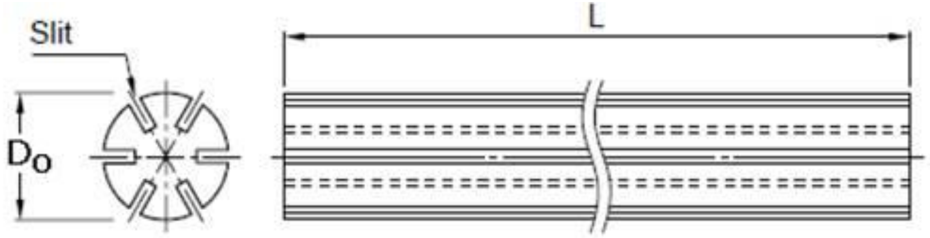


Magnetic Field Lines

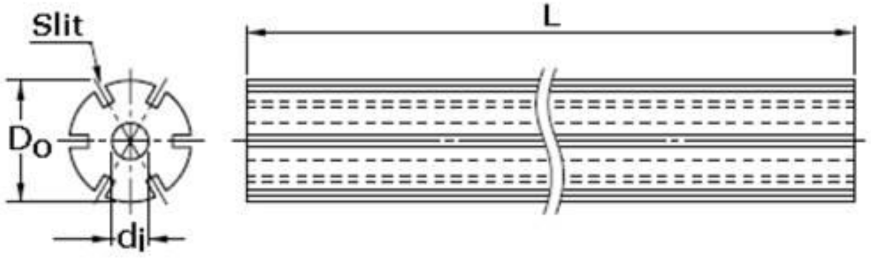
Trial Impeder Geometries

- Standard Impeder geometries were chosen to make use of readily available impeder casings

- The shapes of the ferrites to be replaced in these casings include:
  - Flow through impeder
    - Core OD 10mm
    - Length 200mm
    - 6 Flutes



  - Return Flow impeders
    - Multiple ODs and IDs
      - Core OD 12mm, ID 6mm
      - Core OD 14mm, ID 7mm
      - Core OD 19mm, ID 9mm
    - Length 200mm
    - 8 Flutes



Experimental Trials

- The following trials were run for 1 hour using 14mm Impeders made from various materials, cooling water with an inlet temperature of 15°C and 40 PSI pressure

Trial	f (kHz)	Max Flux Density (T)	Flowrate (GPM)	ΔT (°C)	Measured Losses (kW)	Estimated Losses (kW)	Loss Ratio
A	300	0.61	2.1	9.1	3.8	3.2	1.19
559H	306	0.55	2.4	2.9	1.4	1.5	0.93
559 Org	300	0.64	2.3	3.8	1.7	2.3	0.74

- Losses were calculated using the difference in inlet and outlet water temperature and the flowrate, and was estimated using magnetic flux densities from Flux 2D and new Fluxtrol loss data
- Overall delta T in the cooling water was acceptable in all cases as expected based upon the water flow rate
- Work is being done to reduce error in the experimental setup, as the current error in measured vs. estimated losses is unsatisfactory

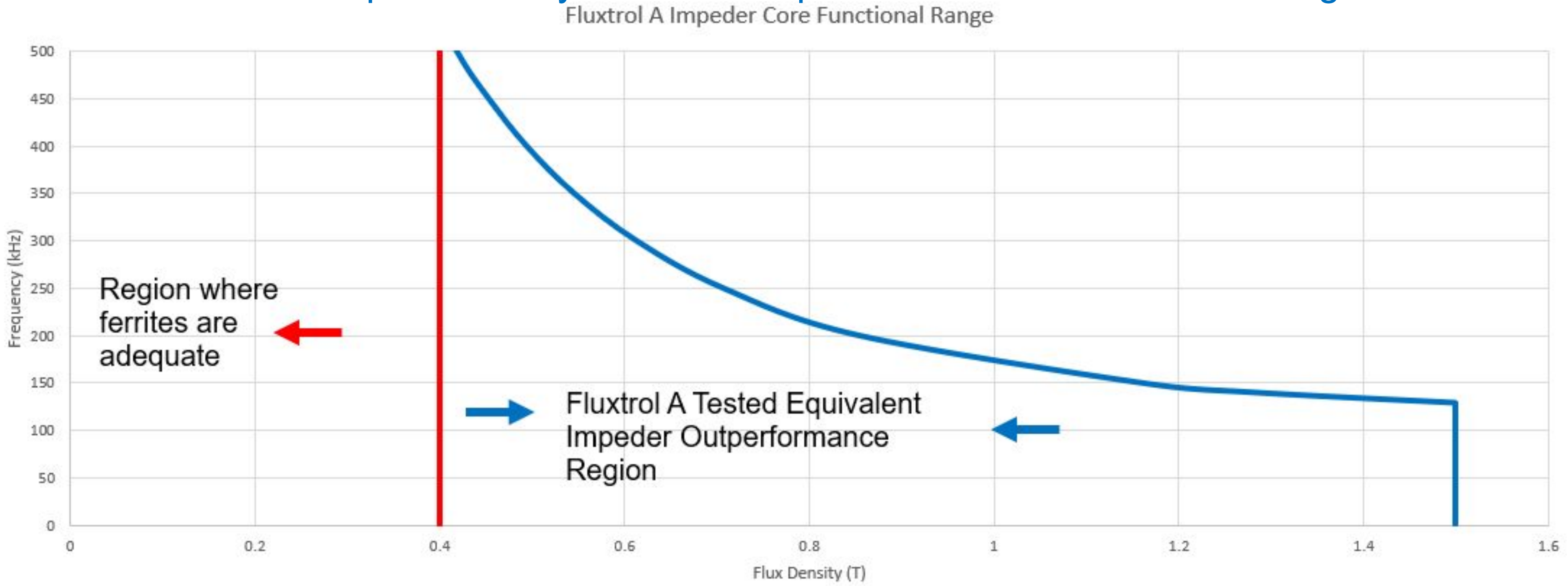
Creation of Operational Ranges

- Each combination of frequency and magnetic loading leads to losses in each soft magnetic composite material according to the published loss equation
- To the right an example of equivalent losses to those created in the test stand can be seen for Fluxtrol A across a range of frequencies and loading
- By inducing the greatest losses in the material using the test stand an operational range can be constructed for the frequency and loading which leads to the same losses

Loss Equation for Fluxtrol A $Pv = aB^{2(1-B/b)}f + cB^2f^2$ a=1.55, b=1.8, c=0.004		
f (kHz)	**Max Flux Density (T)**	**Losses (W/cm^3)**
500	0.42	379
400	0.49	379
300	**0.61**	**379**
200	0.85	379
150	1.16	379
129	1.50	379

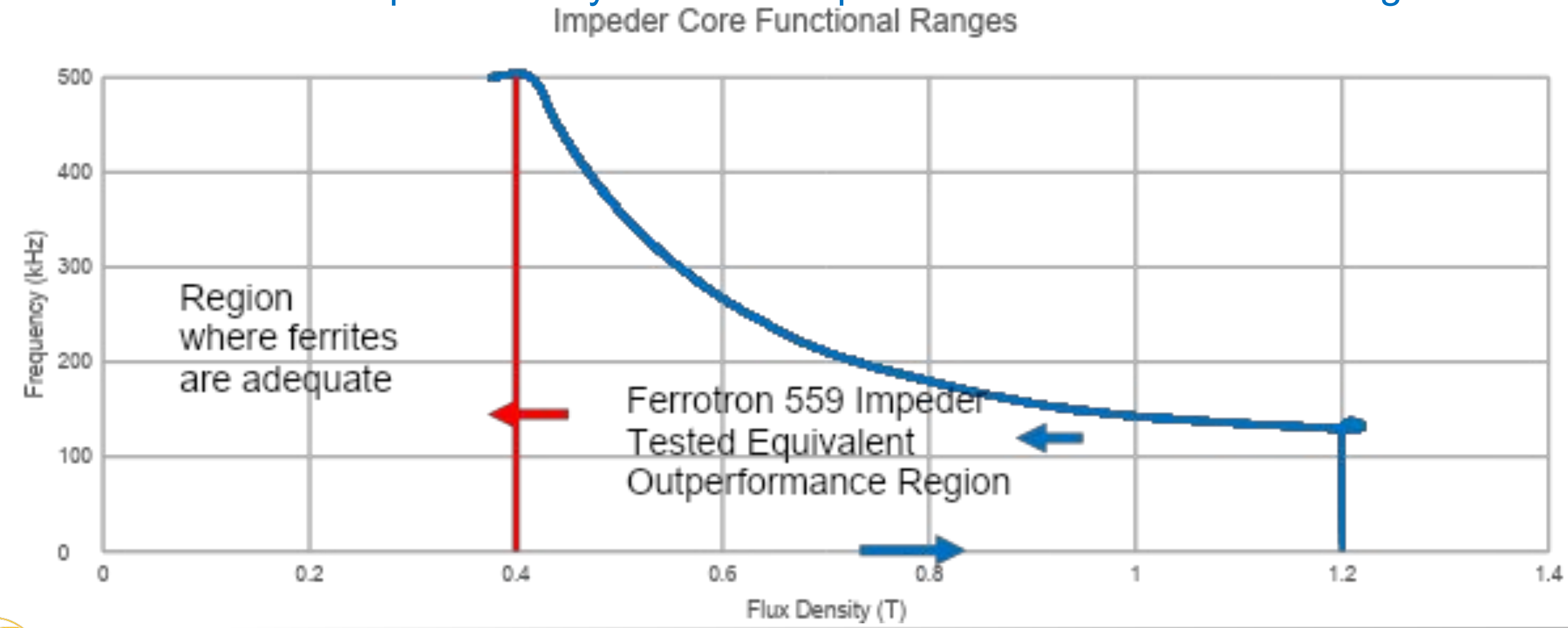
Fluxtrol A Impeder Operational Range

- Shown here is a graph detailing the performance characteristics of Ferrite and Fluxtrol A impeder cores when placed within standard impeder casings and supplied with sufficient cooling water pressure (40PSI)
- Regions to the left of each line are the functional ranges for each core, and regions to the right, non-functional ranges due to either magnetic saturation or overheating
- The Fluxtrol Impeder Outperformance Region relates to opportunities for improved welding system performance
  - Red Line is Operational Limit for a ferrite with a saturation flux density of 0.4T
  - Blue Line is Experimentally Validated Equivalent Conditions on Test Rig



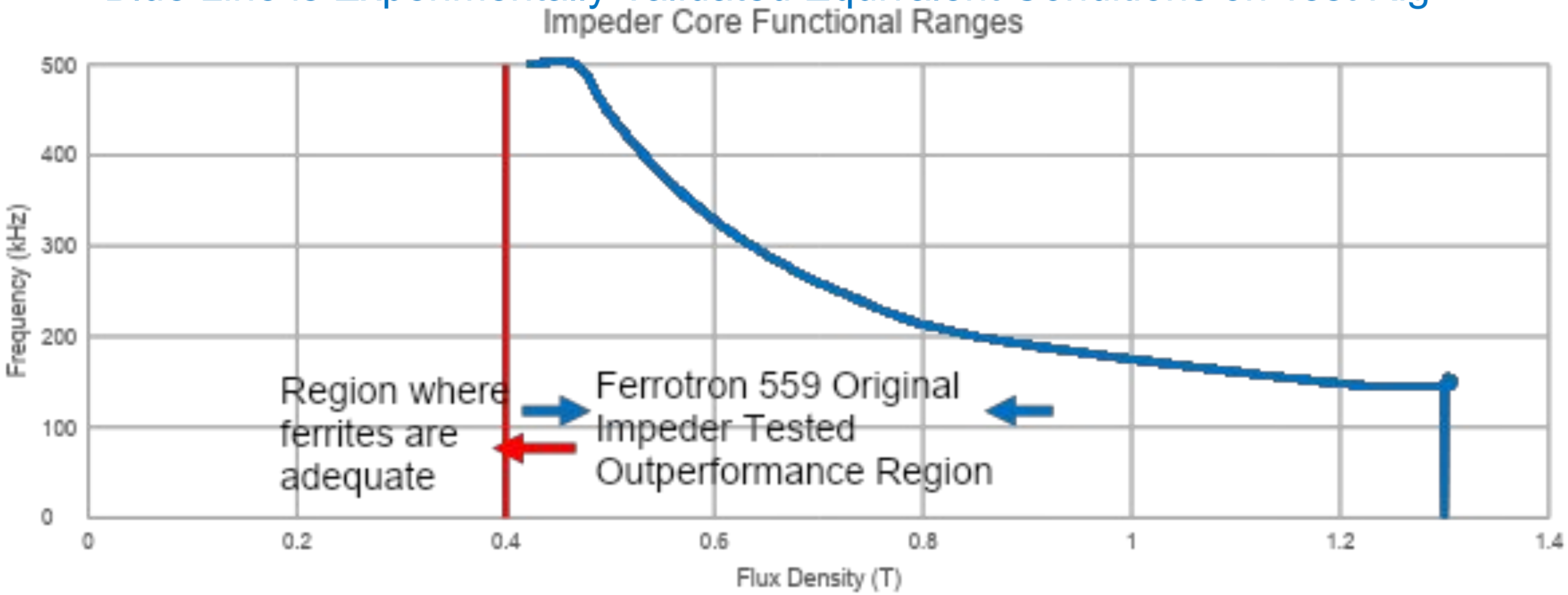
Ferrotron 559 Impeder Operational Range

- Shown here is a graph detailing the performance characteristics of Ferrite and Ferrotron 559 impeder cores when placed within standard impeder casings and supplied with sufficient cooling water pressure (40PSI)
- Regions to the left of each line are the functional ranges for each core, and regions to the right, non-functional ranges due to either magnetic saturation or overheating
- The Fluxtrol Impeder Outperformance Region relates to opportunities for improved welding system performance
  - Red Line is Operational Limit for a ferrite with a saturation flux density of 0.4T
  - Blue Line is Experimentally Validated Equivalent Conditions on Test Rig



Ferrotron 559 Original Impeder Operational Range

- Shown here is a graph detailing the performance characteristics of Ferrite and Ferrotron 559 Original impeder cores when placed within standard impeder casings and supplied with sufficient cooling water pressure (40PSI)
- Regions to the left of each line are the functional ranges for each core, and regions to the right, non-functional ranges due to either magnetic saturation or overheating
- The Fluxtrol Impeder Outperformance Region relates to opportunities for improved welding system performance
  - Red Line is Operational Limit for a ferrite with a saturation flux density of 0.4T
  - Blue Line is Experimentally Validated Equivalent Conditions on Test Rig



Theoretical vs. Experimentally Validated Operational Ranges

- These previously shown operational ranges are based on the maximum loadings for each SMC impeder core that have been proven to survive on the test stand
- The theoretical operation for each material is expected to cover a greater range of frequencies and magnetic loading
- Work is planned to expand on the trials already preformed and expand the experimentally validated ranges

Further Trials

- In order to fully develop the operational ranges for all these materials, an extensive list of trials is planned using the test rig in the Fluxtrol Lab
- Other materials were deemed potentially useful for use in induction tube welding systems including Fluxtrol 50 and Fluxtrol 75

Material	Impeder Size
Fluxtrol A	10mm,12mm,14mm,19mm
Fluxtrol 50	10mm,12mm,14mm,19mm
Fluxtrol 75	10mm,12mm,14mm,19mm
Ferrotron 559H	10mm,12mm,14mm,19mm
Ferrotron 559 Original	10mm,12mm,14mm,19mm

- The goal is to find the maximum survivable setting for each material and size in order to best define the operational range for each material, and optimize the geometries to maximize impeder and tube mill performance
- Additionally, work is being done in parallel to run more trials on industrial tube mills

Conclusions

- An experimental test stand has been developed in the Fluxtrol laboratory for physical simulation of industrial tube welding conditions
- Tests with 3 grades of SMC showed that the materials could survive at 300 kHz at flux densities exceeding the saturation flux density of ferrites commonly used for tube welding impeder cores
  - Potential for increased productivity and efficiency
- Using published loss data, the equivalent loading was calculated at various frequencies showing the experimentally validated operational window for the SMC materials
- For tube welding cases where the ferrite is saturated, there is room for improvement when switching to an SMC impeder provided there is proper cooling and system controls

THANK YOU!

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