Modeling Induction Heat Distribution in Carbon Fiber Reinforced Thermoplastics

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Overview

- Introduction
- Model Description
- Results
  - Hairpin coil
  - Oval coil
  - Transverse flux coil
  - Vertical loop coil
  - Comparison of coil styles
- Conclusions

Introduction

- Major welding techniques
- Induction heating characteristics/mechanisms
- Penetration depth

Major Welding Techniques for Thermoplastic Composites

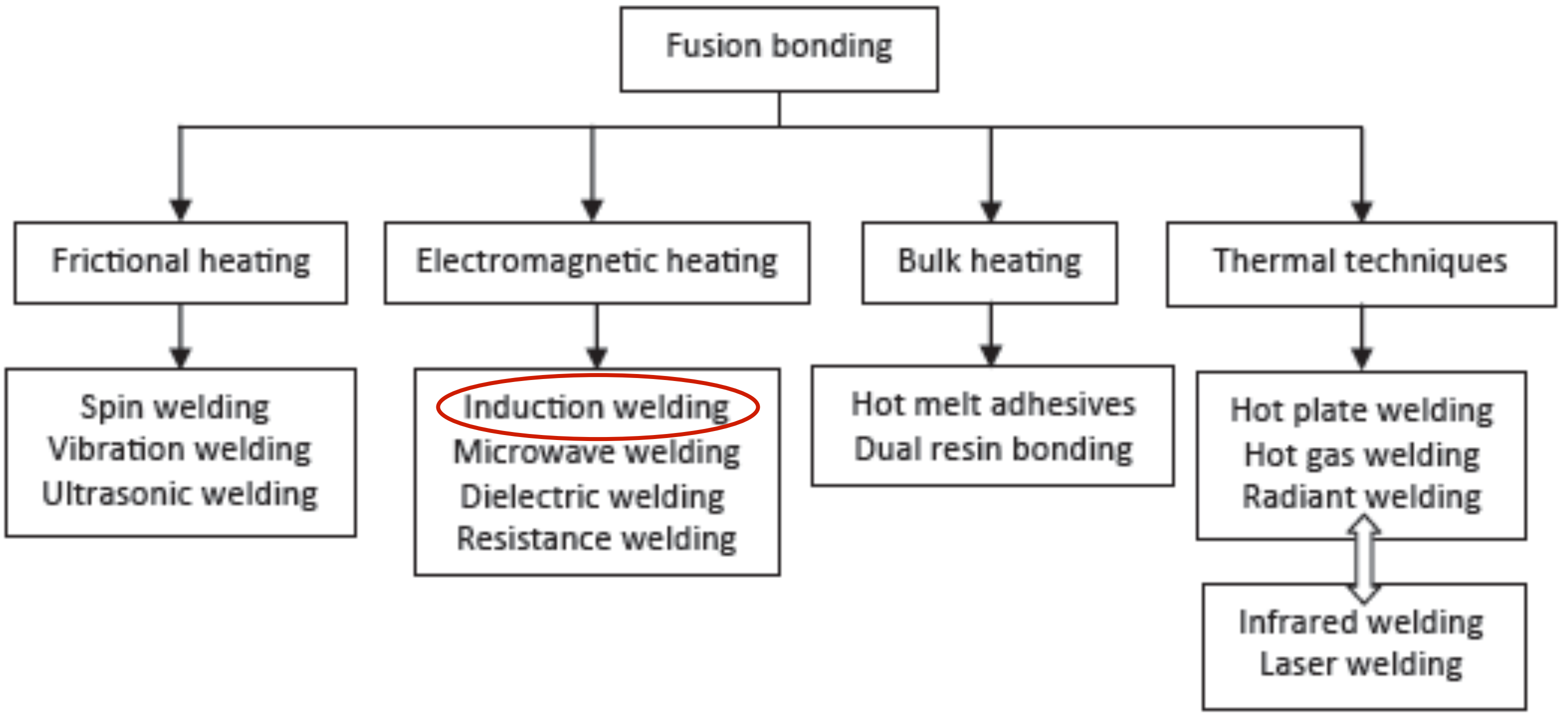


Figure 1. Classification of potential fusion welding techniques for
lastic composites (Ageorges *et al.*, 2001).

Characteristics of the Induction Method

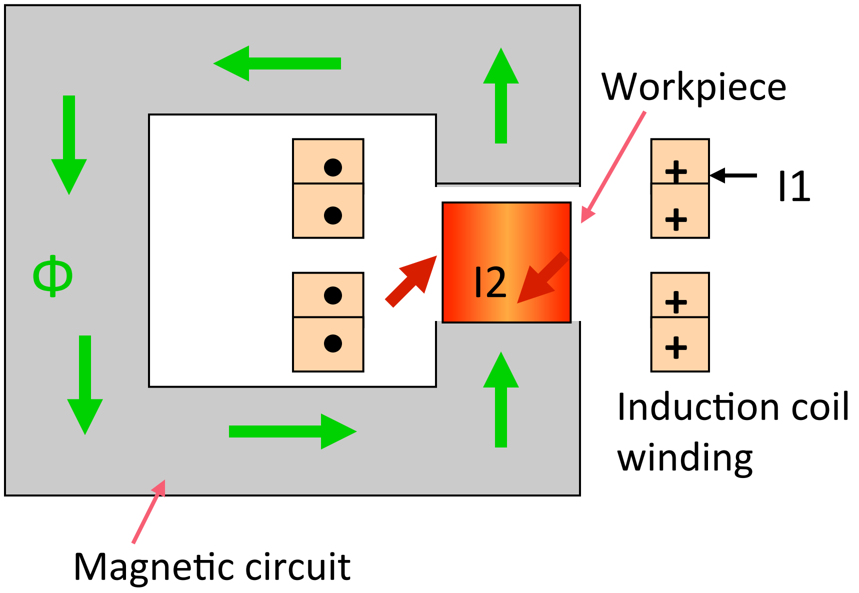
- Contactless
- Generates heat volumetrically
- Heating can be local or global
- Clean, efficient, small footprint
- Difficult to produce uniform temperatures for complex and large geometries -> highly dependent on coil and process design
- This technology must be well understood to utilize its full benefits
- Very favorable for in-line manufacturing

Mechanisms of Heating Thermoplastic Composites by Induction

- The material to be directly heated must be either electrically conductive or magnetic
  - The reinforcement fibers must be conductive (i.e. carbon fiber) to directly heat the composite.
  - For welding, a susceptor can be placed at the weld interface, in which case the reinforcement fibers don't need to be conductive (e.g. fiber glass)
- Conductive materials generate Eddy current losses
- Magnetic materials generate hysteresis losses

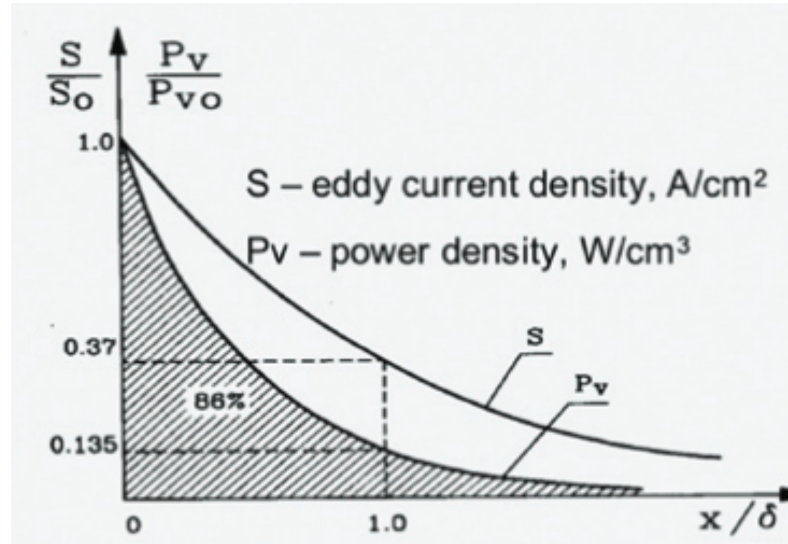
Principle of Induction Heating

- There are three closed loops in any induction device:
  Coil Current (I1) Loop
  Magnetic Flux (Φ) Loop
  Eddy Current (I2) Loop
- Magnetic Flux Loop may be "materialized" as a magnetic core in transformer-type induction system (right) or be invisible (in air or other surrounding media)
- Magnetic Flux Loop is very important because that's where we can install magnetic Flux Controller to improve heating
- **The Current Loop (I2) is extremely important for thermoplastic composite welding. This depends upon a number of factors.**



Penetration Depth

- Definition: the depth from the heating surface that 86% of the power exists; it's the "electrical thickness"
- **When the thickness of materials relative to where currents flow is less than 3δ, current cancellation begins to occur and efficiency drops**



Full relation:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_r\mu_0}}$$

For non-magnetic materials (carbon fibers):

$$\delta = k\sqrt{\rho/f}$$

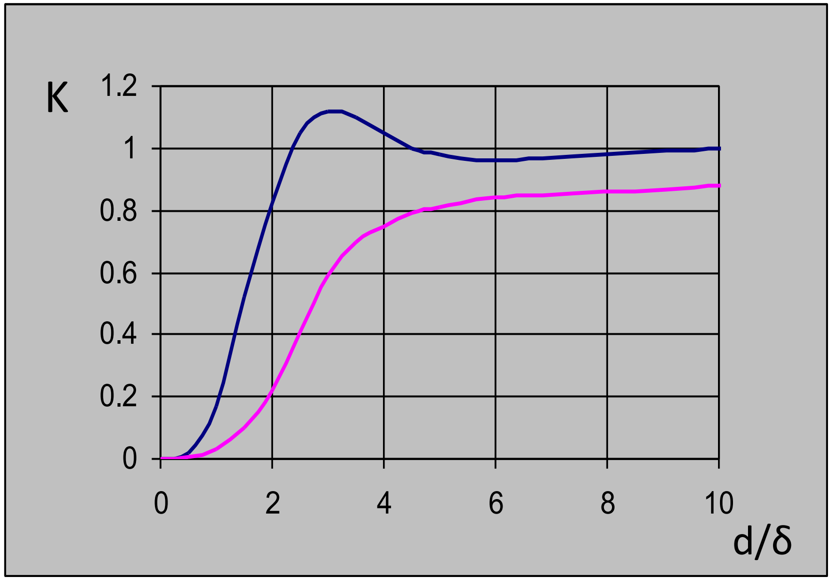
δ is penetration depth in m, ρ is resistivity in Ωm, *f is* frequency in Hz, *k* = 503

Power Transfer Factor for Plate and Cylinder

When part thickness or diameter is small or frequency is low, electrical dimensions are small and K is small also. It is said that the body is transparent for magnetic field (at this frequency). Components of induction system or machine that must not be heated by induction (such as fixtures, fasteners etc.) must be transparent.

If size of body or frequency are big, K always tends to threshold value K = 1.

For cylinder there is no maximum of K and electrical efficiency grows with frequency. For plates there is a small maximum when its thickness equals to 3 reference depths (more exactly 3.14δ).



d – plate thickness or cylinder diameter

δ – reference depth

d/δ is "electrical dimension" of the body; it is proportional to root square of frequency

Use of a Susceptor at Weld Interface

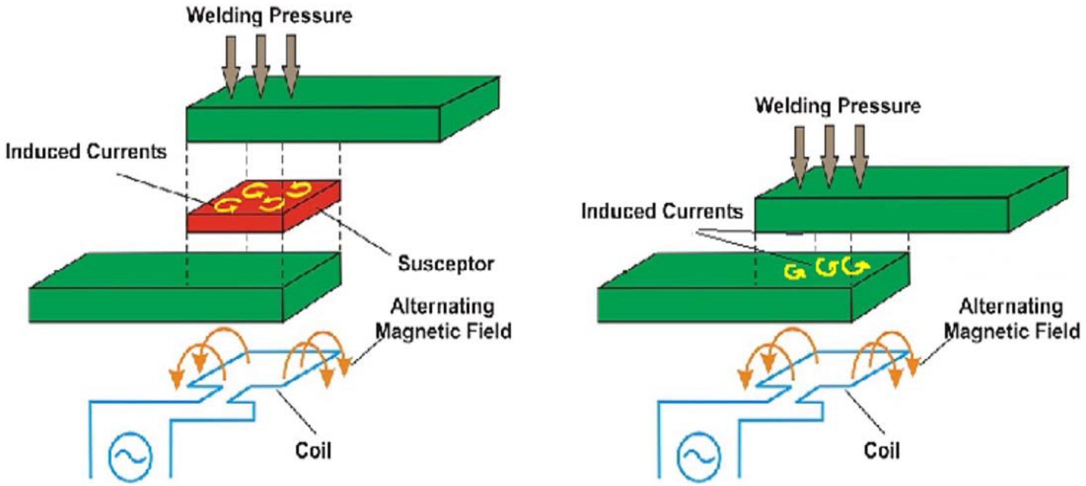


Table 1
Comparison of lap shear strength values

Reference	LSS (MPa)	Laminate type	Weld configuration
Border and Salas [12]	27	Carbon/PEEK	No insert
Cogswell et al. [31]	31	Carbon/PEEK	No insert
Schwartz [5]	38–48	Carbon/PEEK	No insert
Mitschang [27]	30	Carbon/PPS	No insert
van Wijngaarden [32]	25	Carbon/PPS	No insert
Cogswell et al. [31]	36	Carbon/PEEK	PEEK film insert
Border and Salas [12]	44	Carbon/PEEK	PEEK film insert
Todd et al. [7]	33	Carbon/PEEK	PEI/PEEK film
Williams et al. [37]	46	Carbon/PEEK	Woven carbon fibre insert
Nagumo et al. [35]	17–22	Carbon/PEEK	Metal mesh
Hodges et al. [33]	41–48	Carbon/PEEK	Metal mesh and PEEK insert
Whitworth [51]	27	Carbon/PEKK	PEKK film insert
van Wijngaarden [32]	18	Carbon/PPS	Expanded metal foil
Suwanwatana et al. [46]	20	Glass/PPS	Nickel/PSU film insert
van Wijngaarden [32]	10	Glass/PPS	Expanded metal foil

Ref. 8: Ahmed T.J et al

Model Description

FEA program Flux 2D is used for case analyses
-materials and geometry used are described

Equivalent material properties used in the Simulations

Material	Orientation	Volume fraction*	K (W/mk)	Keq (W/mk)	Cp (J/kgK)	Cpeq (J/kgK)	d (g/cm3)	deq (g/cm3)	ρ (Ωm)*
PPS	Parallel	0.54	0.29	5	1000.70	906.3	1.35	1.54	5.0E-04
T300 carbon fiber		0.46	10.5		795.50		1.76		
Composite	Perpendicular	1	-	0.5	-	906.3	-	1.54	3

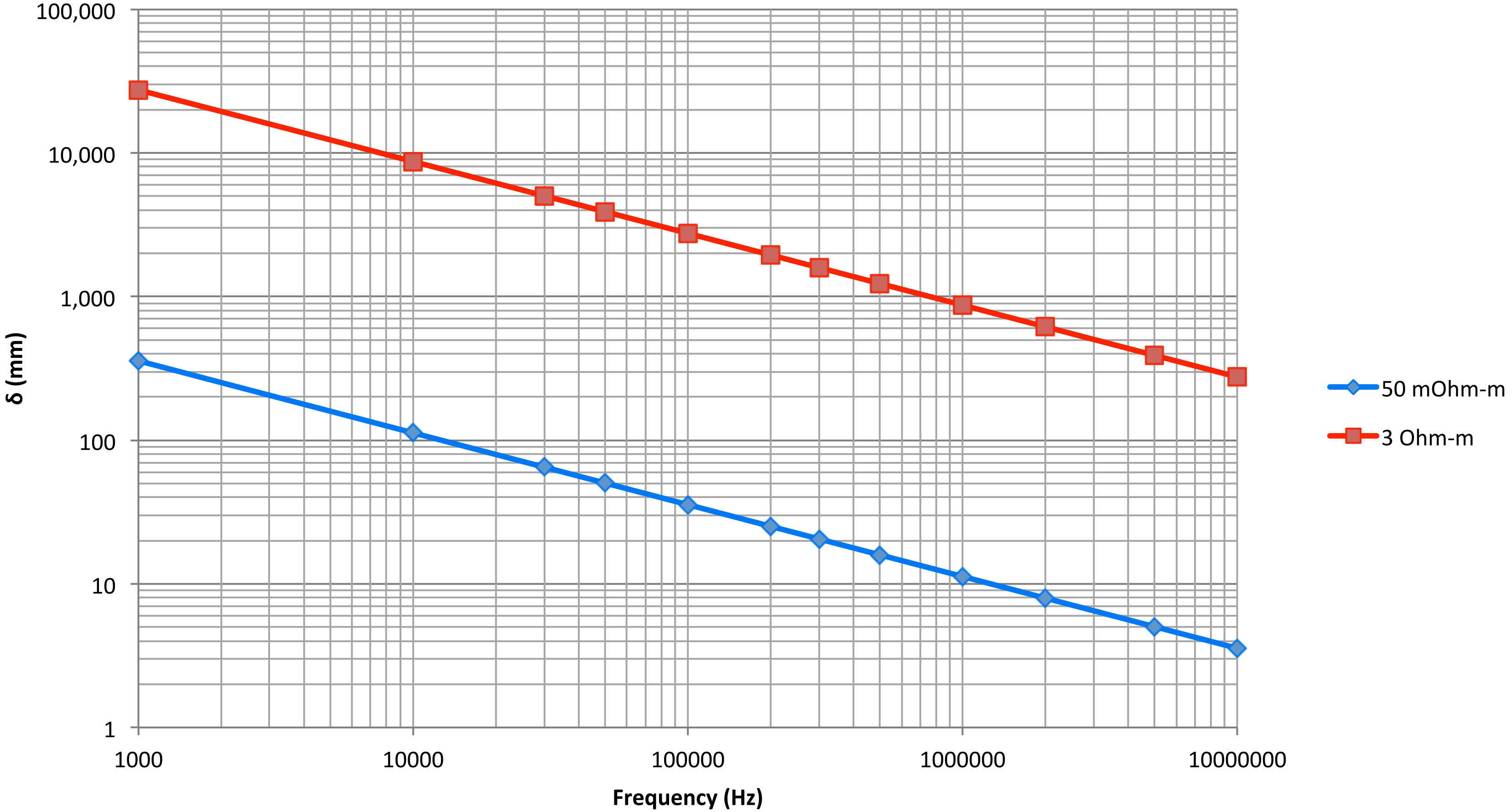
*Values from Ref 4: Fink et al.

Difference in δ of 77 times!

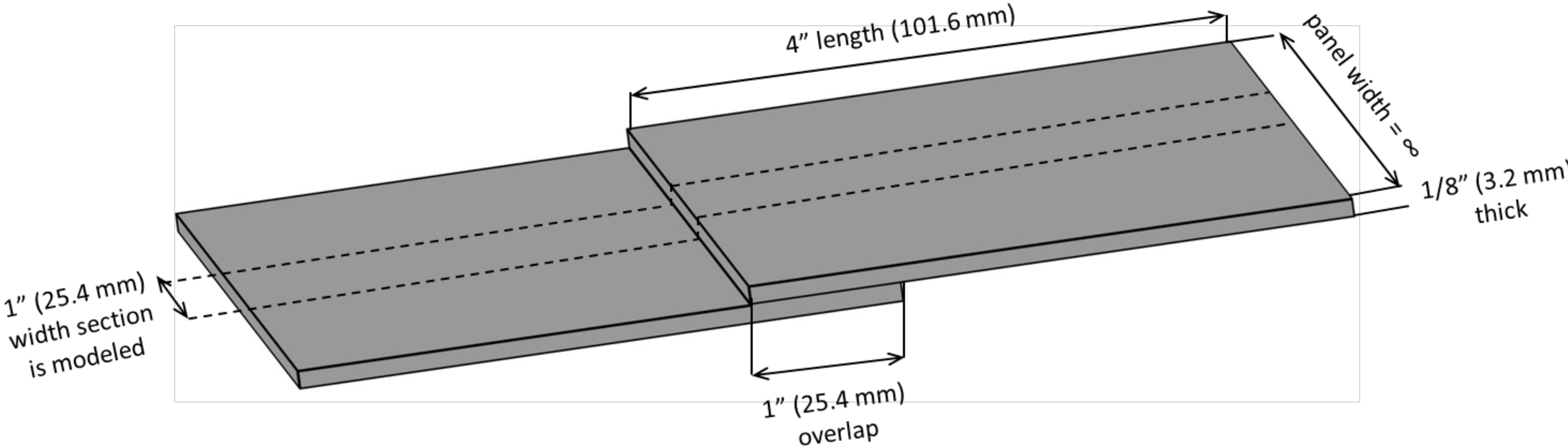
Heating behavior is highly dependent on material properties, which can vary drastically in CFRTs due to varying lay up schedules and pre-preg types.

For simplicity of this study, a woven fabric reinforcement is selected (5-harness satin carbon fiber fabric reinforced polyphenylensulfide, 46% fiber by volume).

Reference Depth vs Frequency



Dimensions of Lap Joint Used in FEA Simulations



- Other surrounding components such as pressure applicators are not considered.
- Pressure application components can have significant thermal effects.
- Three-dimensional edge effects from the return current are not considered.
- Ideal electrical contact between two plates is assumed

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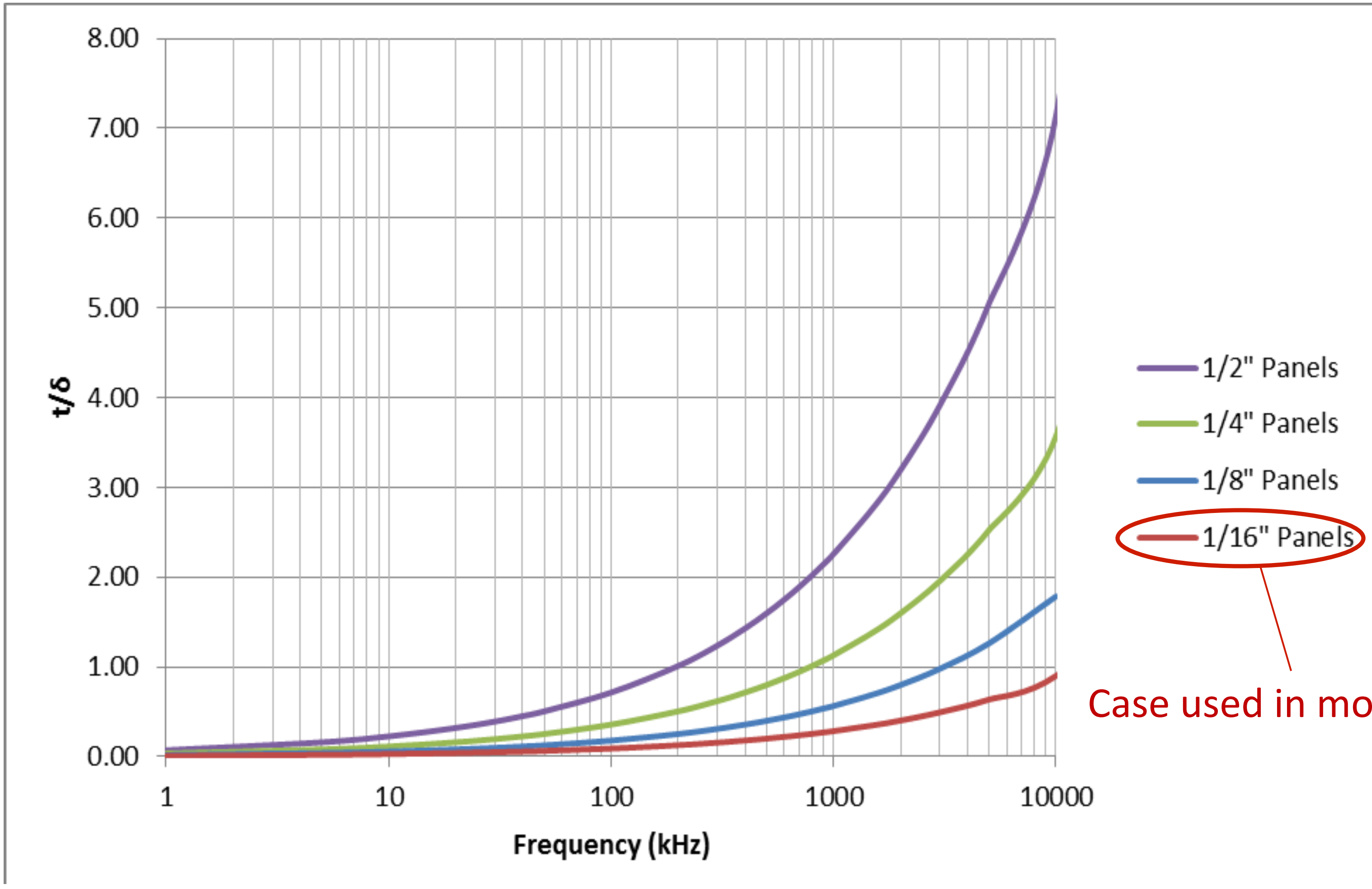
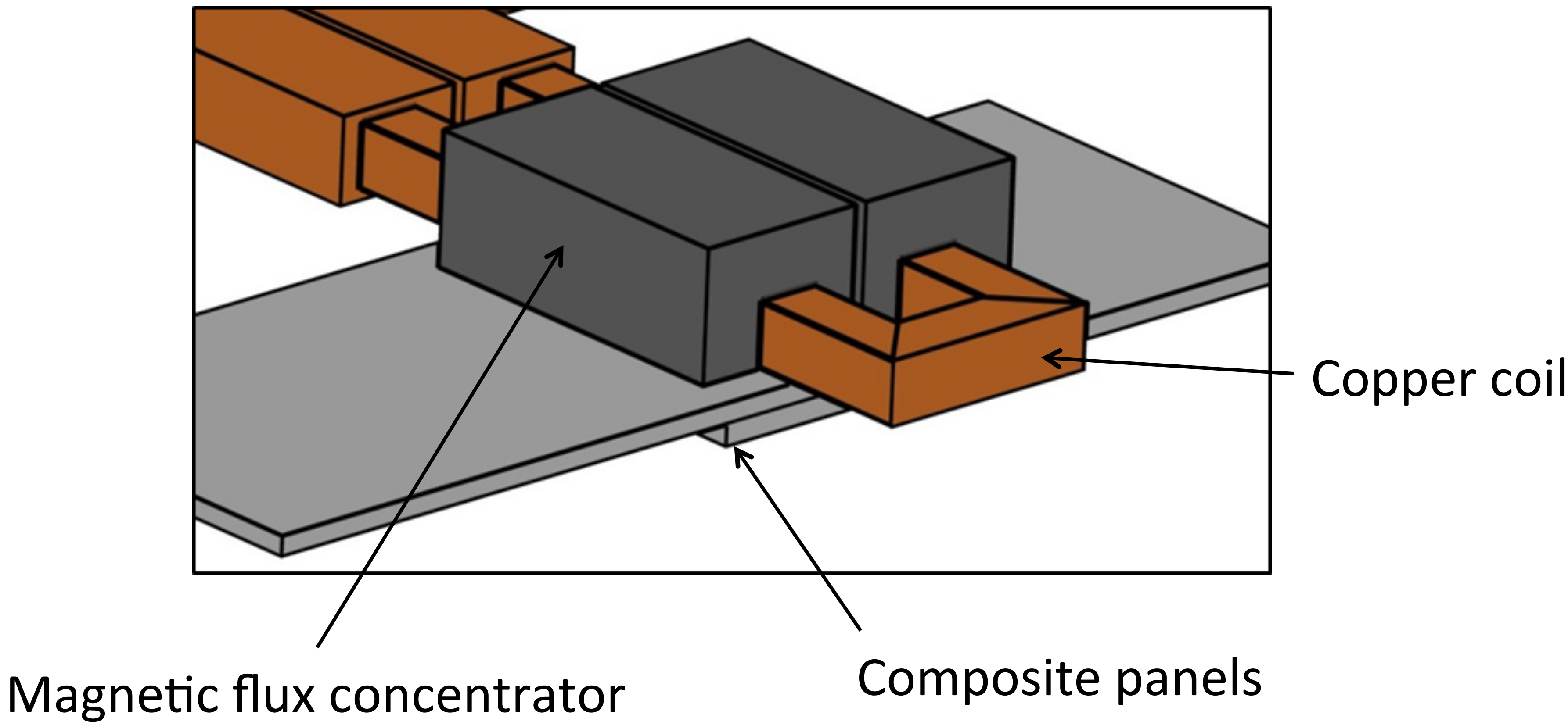
Ratio of thickness to penetration depth vs frequency for various thicknesses of CFRT panels



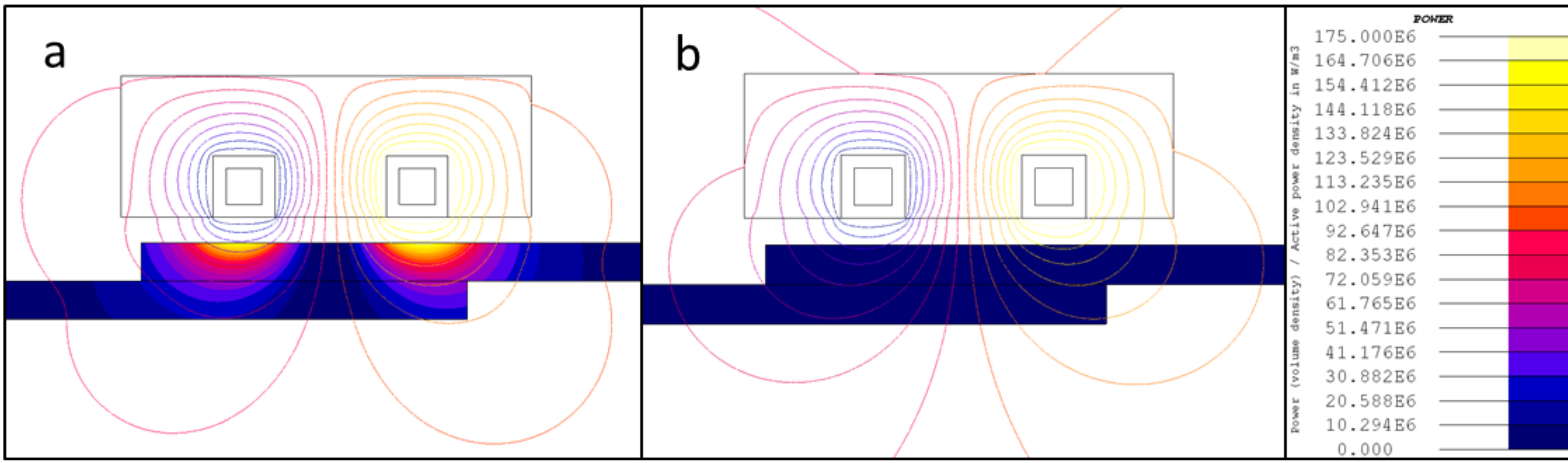
Results

- Electromagnetic and thermal models are presented for various coil designs
- The cases are to provide a comparative review and are not optimized for any certain goal

Hairpin Style Coil



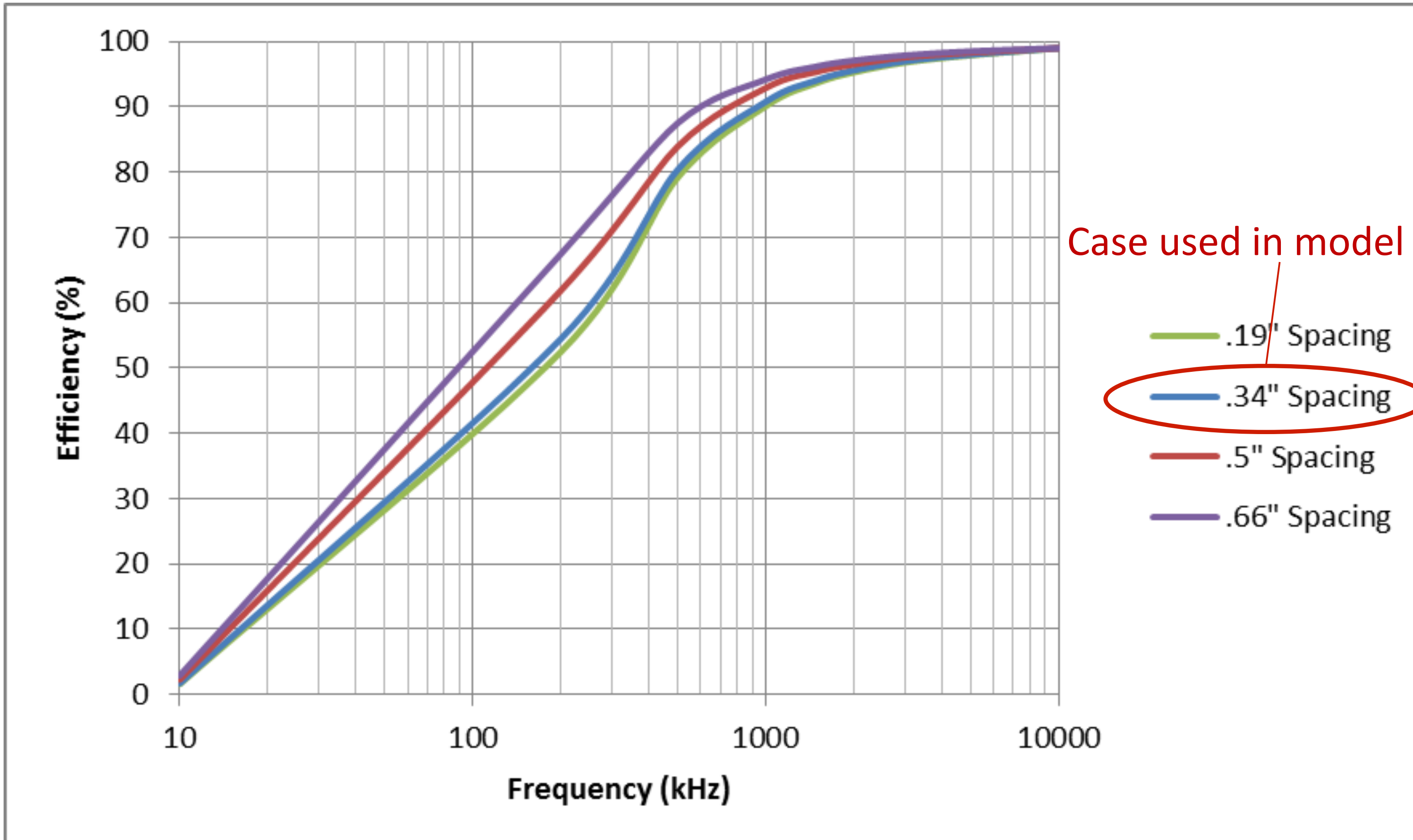
Power density and magnetic field lines for Opposing Material Directions (2 MHz)



a) Resistivity parallel to fibers (5e-4 Ωm), δ = 8 mm

b) Resistivity perpendicular to fibers (3 Ωm), δ = 616 mm

Electrical efficiency vs frequency for one-sided hairpin coil at various turn spacing



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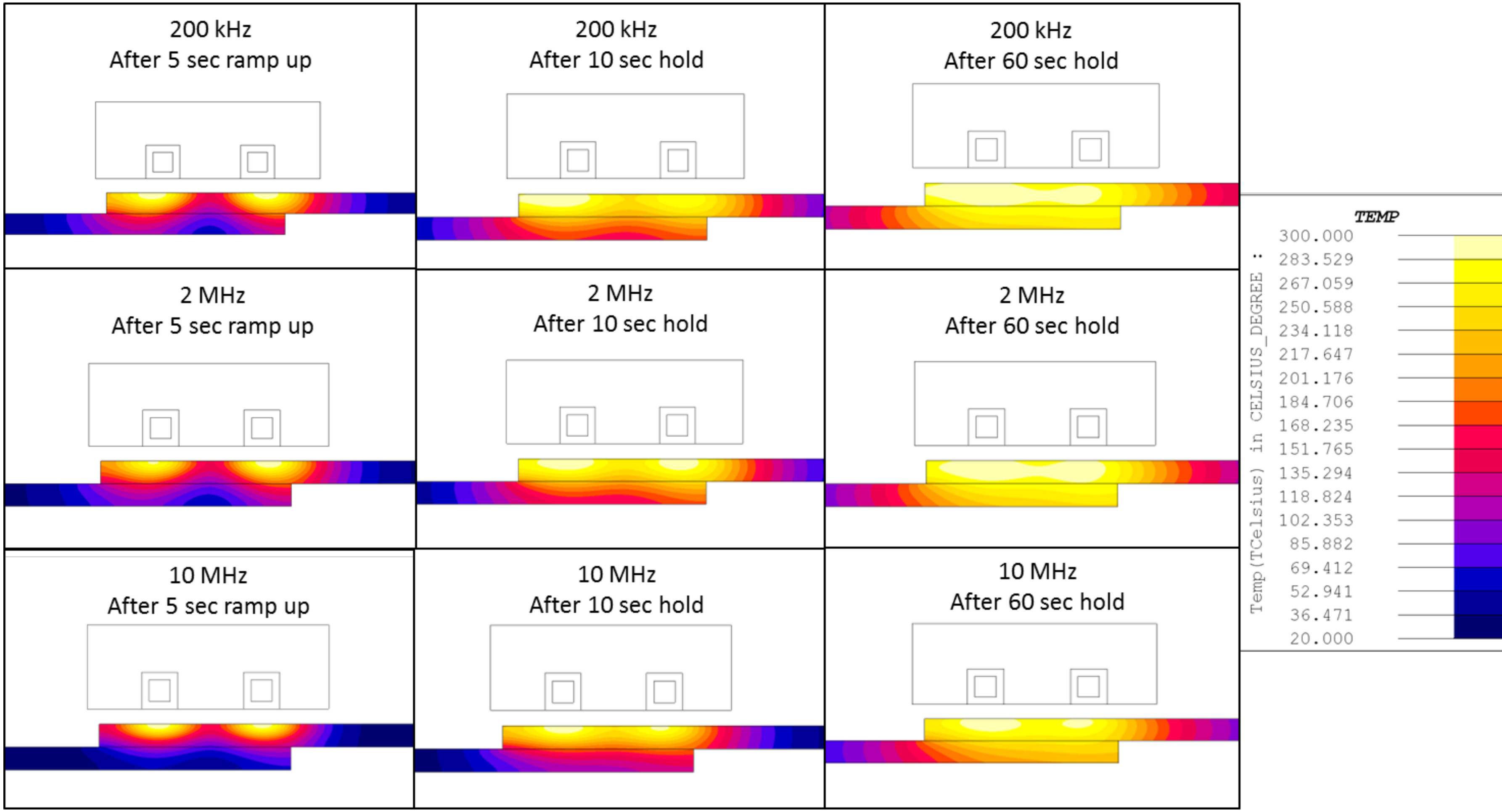
The further apart the turns, the higher the efficiency in mid-frequency range (until turns are outside of heat zone)

Temperature at end of 5 second ramp up, 10 second hold, and 60 second hold at 200 kHz, 2 MHz, and 10 MHz

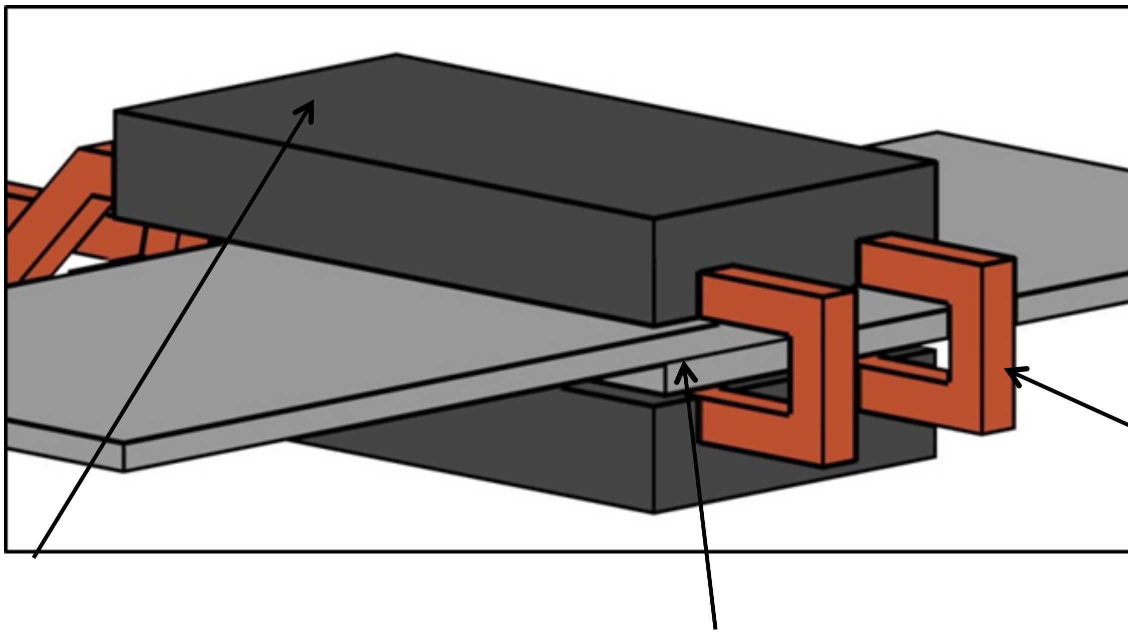


300 °C is target (melting point of PPS ≈280 °C)

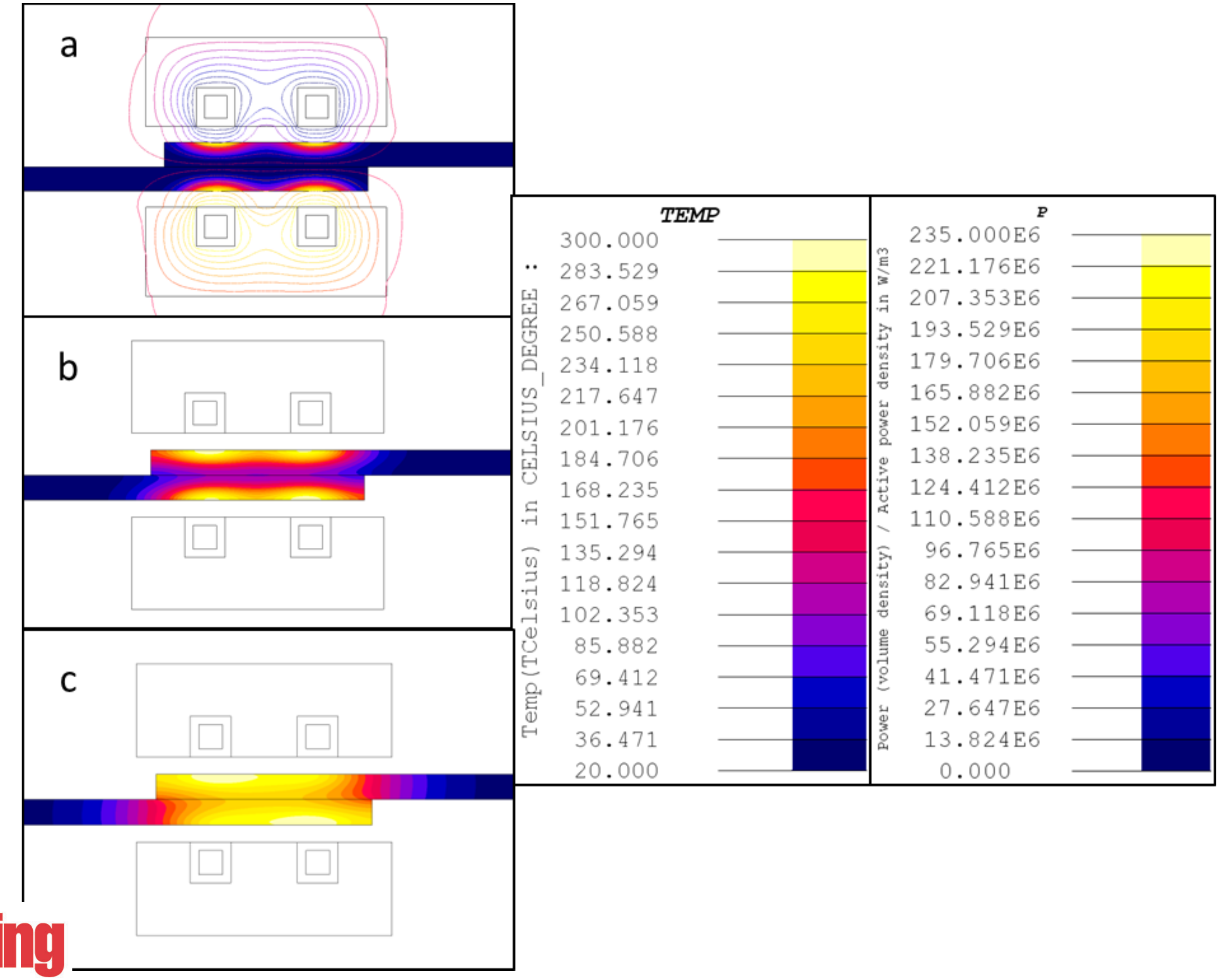
1-sided vs 2-sided Heating

- There is an inverse relation of electrical efficiency and temperature uniformity in thickness for one-sided heating using a hairpin (most common in literature) or pancake style coil
- Two-sided heating is more difficult to implement due to accessibility reasons, but for targeting uniform temperature at the joint interface in a short amount of time and keeping power demand low, two sided heating is desired
- Remainder of designs investigated utilize 2-sided heating

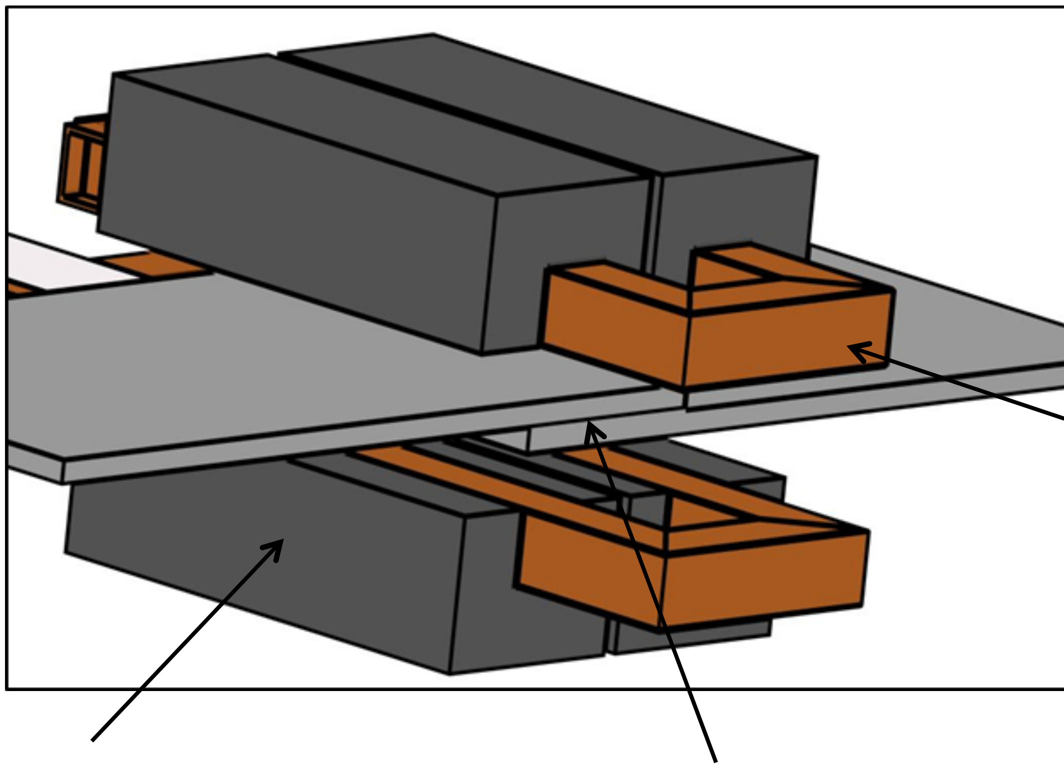
Two Turn Oval Style Coil



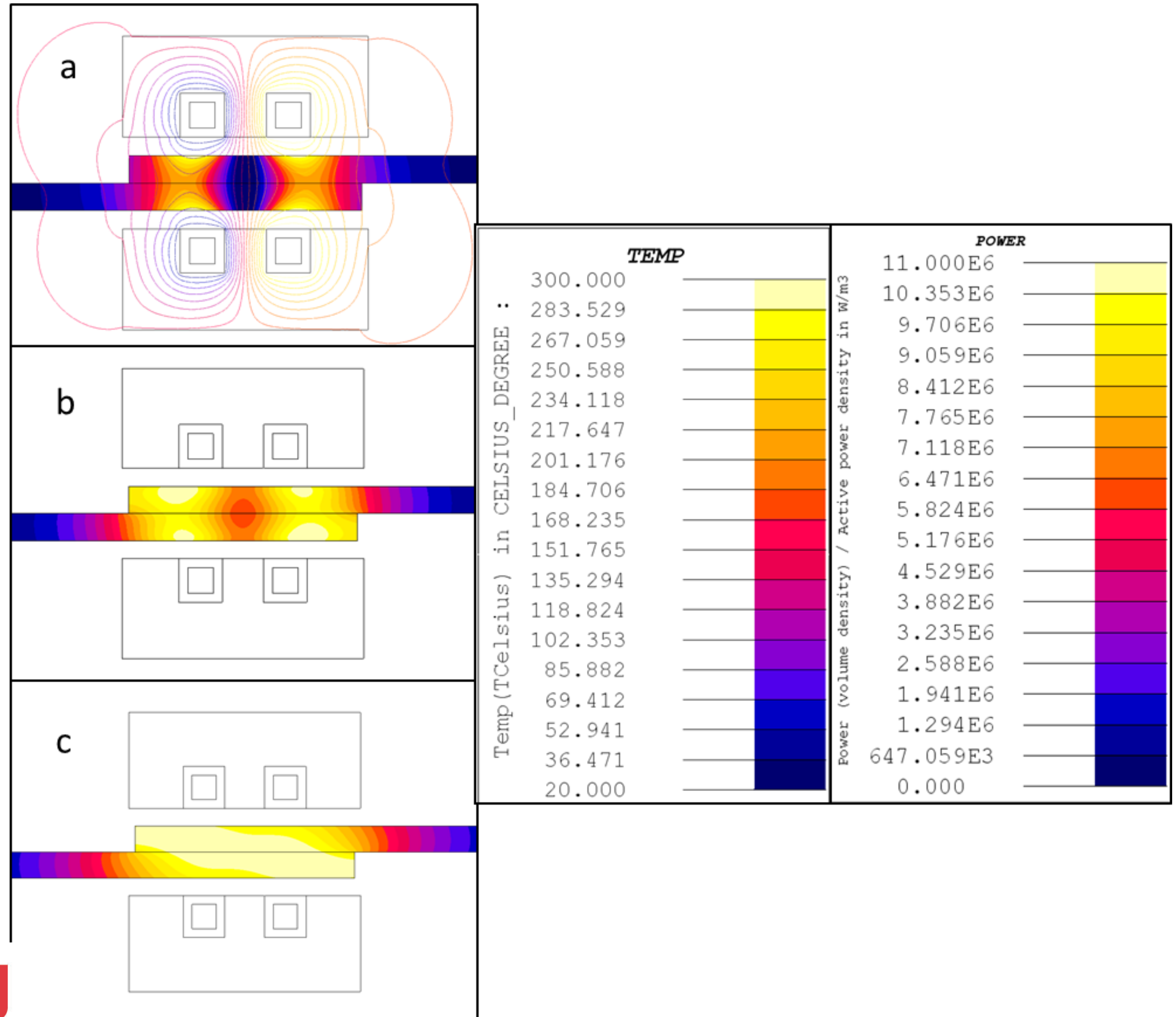
Power density (a), and temperature at end of 5 second ramp up (b) and 10 second hold (c) at 2 MHz



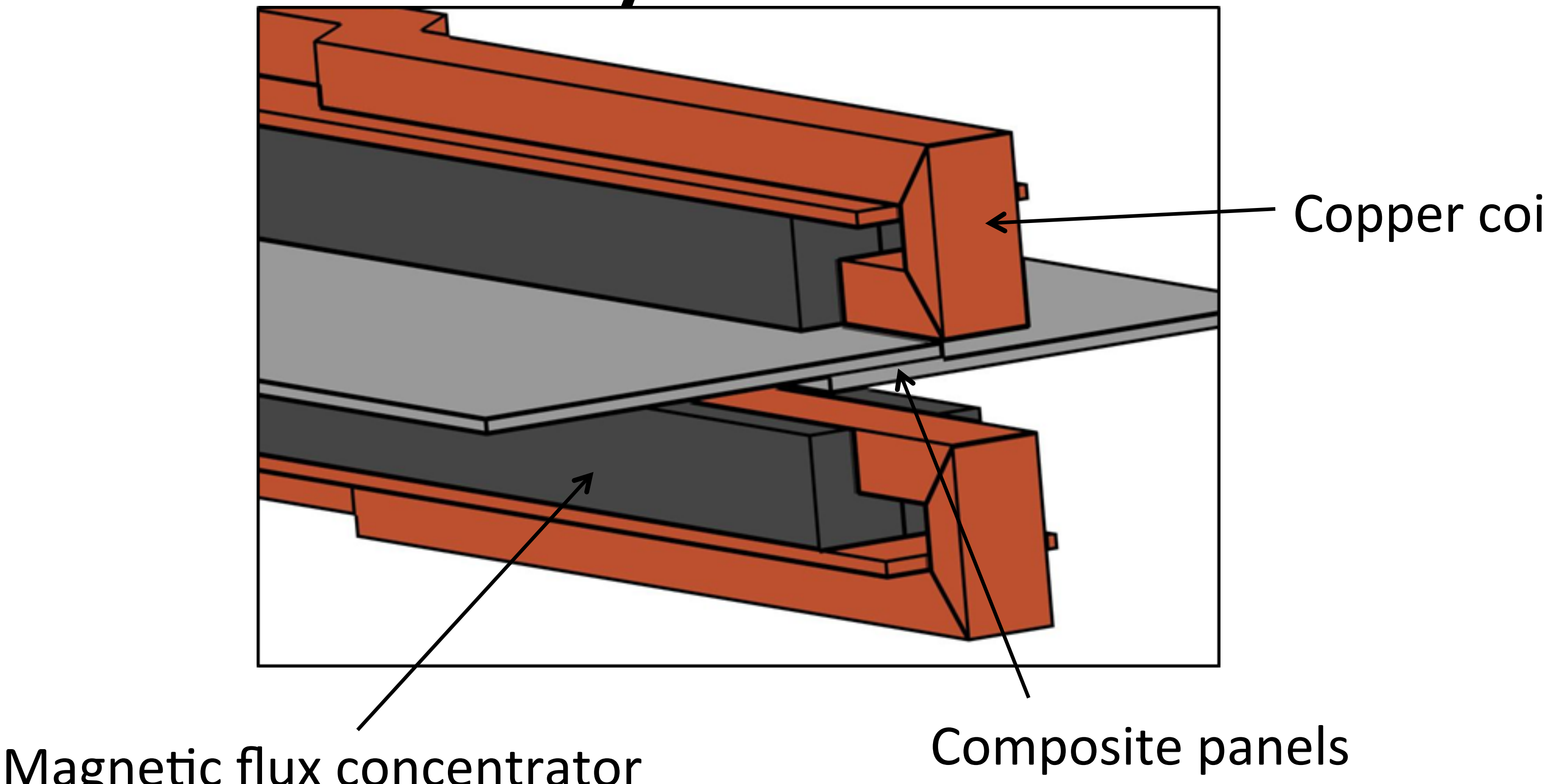
Transverse Flux Style Coil



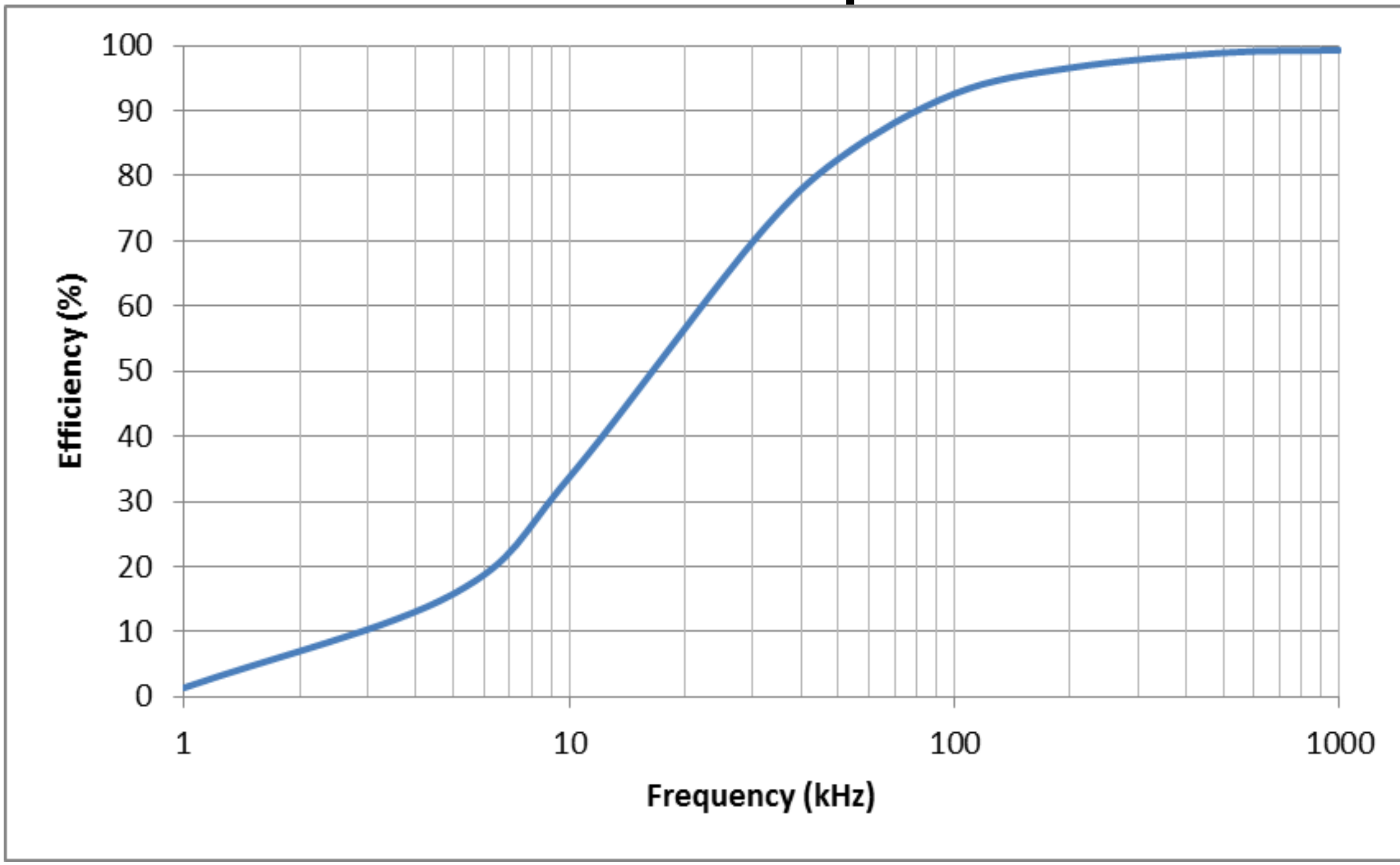
Power density (a) and temperature at end of 5 second ramp up (b), and 10 second hold (c) at 2MHz



Two Sided Vertical Loop Style Coil



Electrical efficiency vs frequency for Vertical Loop Coil



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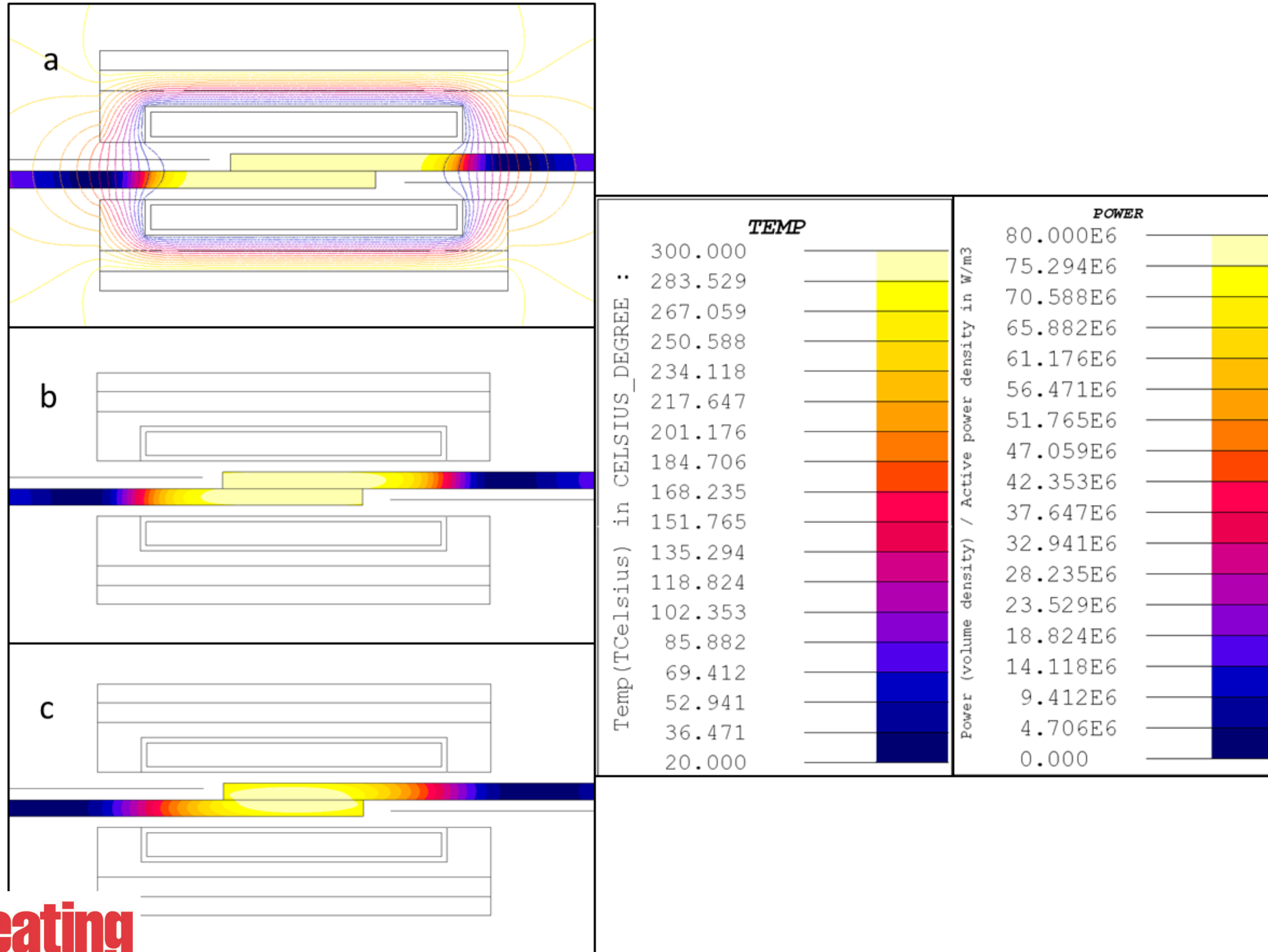
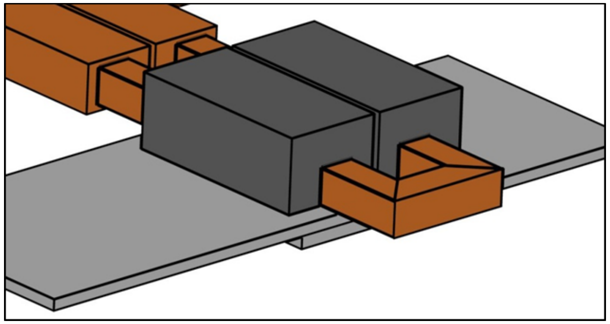
High efficiency is achieved at lower frequencies than other coil styles

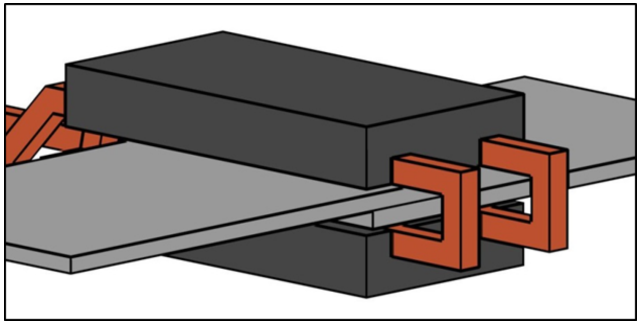
Power density (a), and temperature at end of 5 second ramp up (b) and 10 second hold (c) at 300 kHz



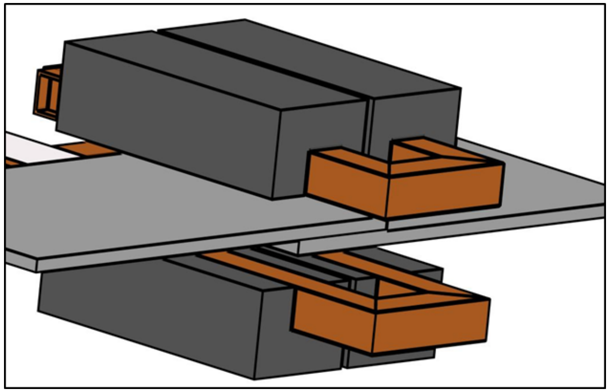
Comparison of Major Coil Styles



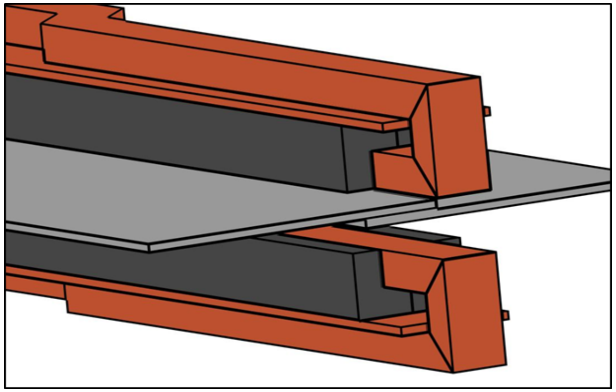
Hairpin



Oval



Transverse Flux



Vertical Loop

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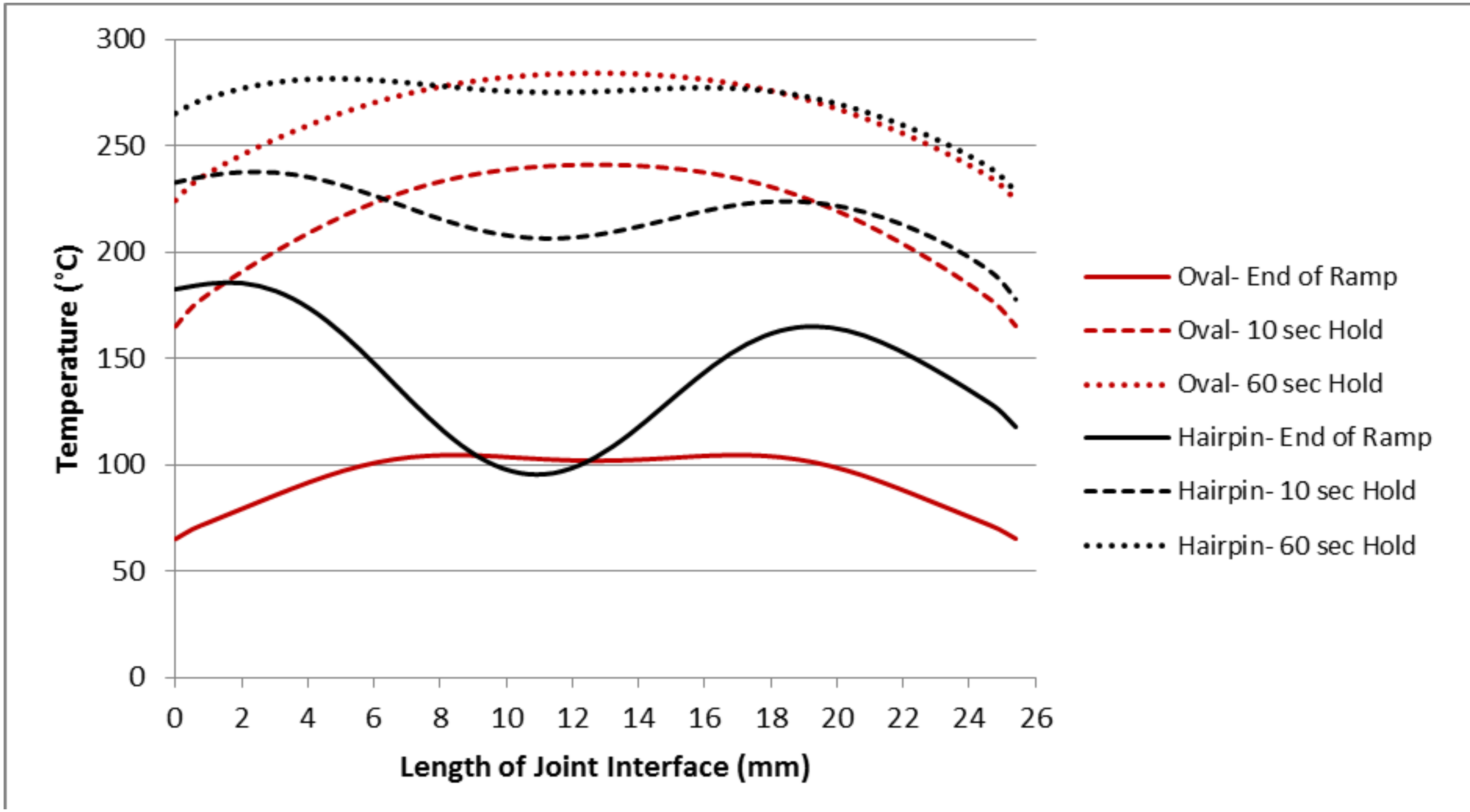
Temperature along weld joint interface for hairpin and oval coils after 5 second ramp up, 10 second hold, and 60 second hold



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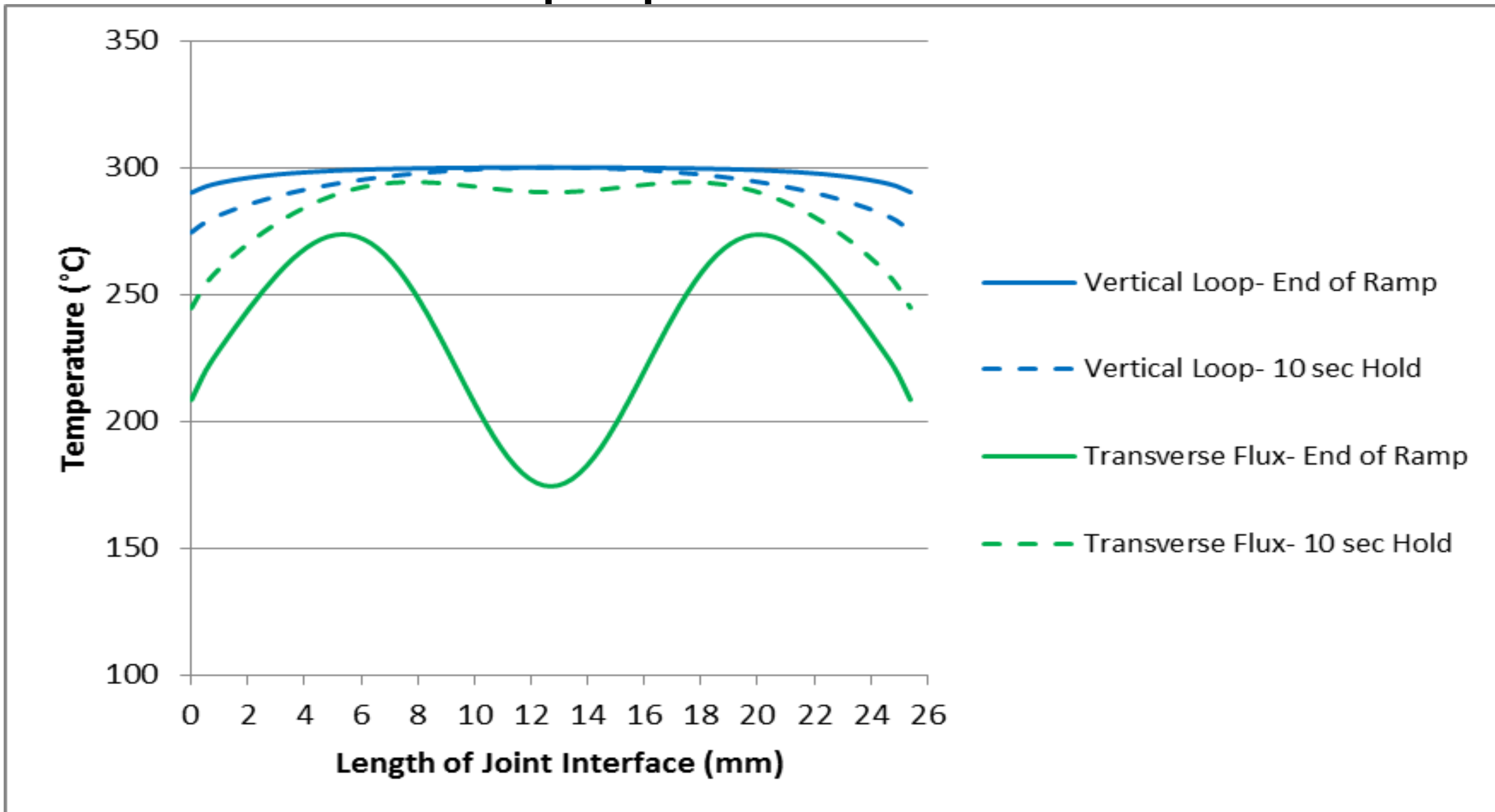
Temperature distributions can be improved with coil optimization and external material selection

Temperature along weld joint interface for transverse flux and vertical loop coils after 5 second ramp up and 10 second hold



Temperature distributions can be improved with coil optimization and external material selection

Electrical Parameter Comparison

Coil	Concentrator	Frequency (kHz)	Total P/in (W)	Part P/in (W)	Efficiency (%)	Coil U/in (V_{rms})	Coil Current (A_{rms})	Apparent P/in (kVA)	Max Temp (C)	Max Temp at Joint (C)	Heat Time (sec)
Hairpin	yes	2000	193.7	184.6	95.3	22.3	48.4	1.1	300	185	5
Hairpin	no	2000	242.4	229.6	94.7	19.6	110	2.2	300	203	5
Hairpin	yes	200	399.6	210.2	52.6	21	403.8	8.5	300	195	5
Hairpin	yes	10000	125.9	124.3	98.7	32.2	18.3	0.6	300	125	5
Solenoid	yes	2000	215.7	168.4	78.1	63.6	78.5	5.0	300	102	5
Transverse Flux	yes	2000	304.5	290.7	95.5	36.3	40.1	1.5	300	273	5
2-Sided Vertical Loop	yes	300	804.7	790.6	98.2	18.8	189	3.6	300	300	5
2-Sided Vertical Loop	no	300	1494.1	812.2	54.4	20.1	1870	37.6	300	300	5

The vertical loop coil shows the highest power demand since a wide uniformity zone is rapidly generated. The power demand can be decreased with further optimization of the coil design.

Conclusions

- Heat uniformity and electrical efficiency is highly dependent on coil style and frequency.
- Coil/process design should be material and orientation specific.
- One sided heating is easiest to implement, but requires longer heating times and higher surface temperatures to reach good thermal uniformity at the joint.
- The vertical loop coil has the highest efficiency and reaches uniformity the quickest, but has a higher power demand.
- If heat time is not critical, any of the coil styles could be optimized to produce decent uniformity at the joint.
- The models assume an infinitely long system, but non-uniformities due to the ends of the panels would also need to be worked out.

Next Steps

- 3-dimensional simulation
- Material property characterization
- Experimental development
- More complex materials pursued (e.g. quasi-isotropic)
- Possible industry partnership