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AC Losses and Surprising Magnet Heating in Reciprocating Active Magnetic Regenerative Refrigerators

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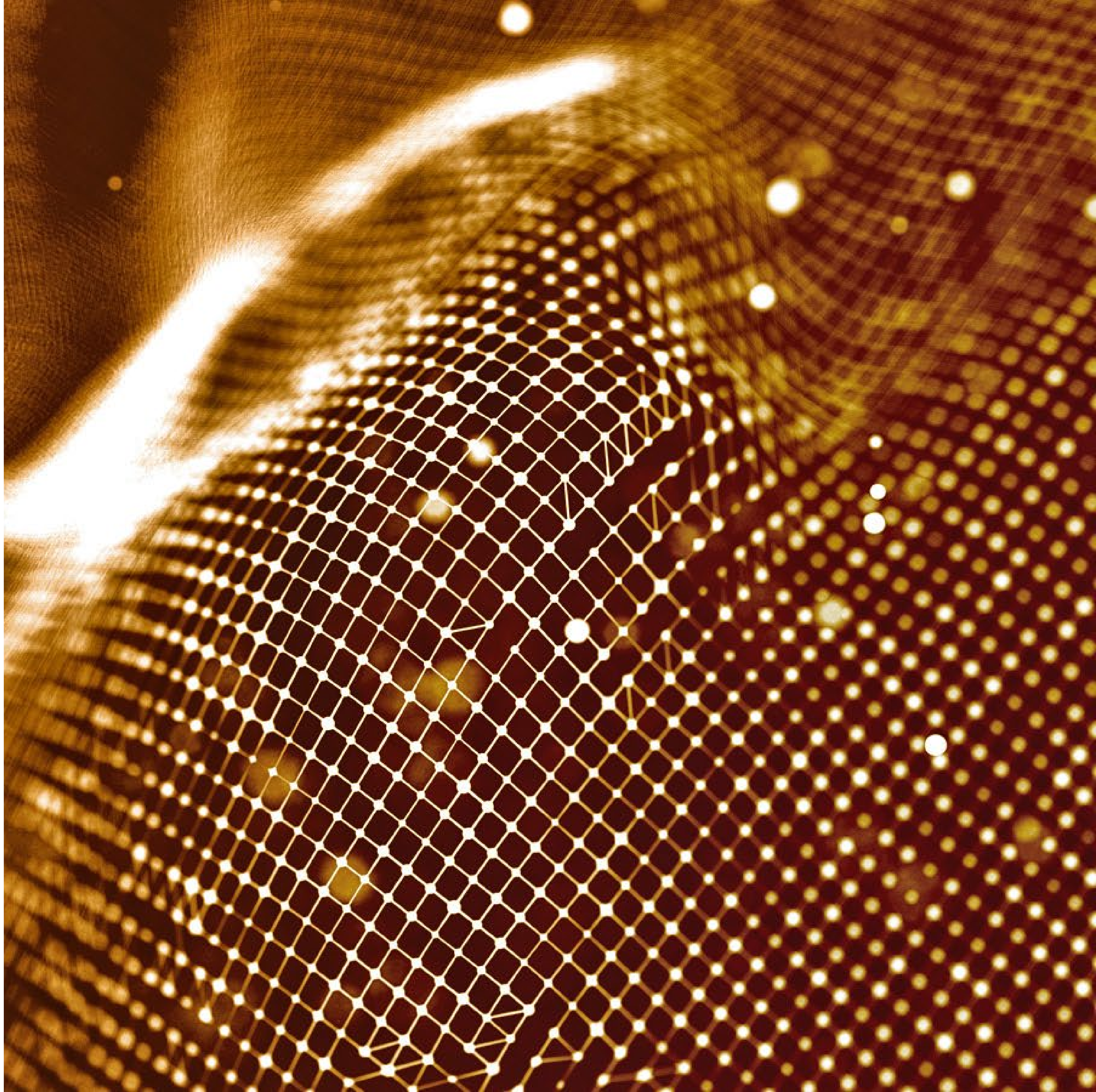

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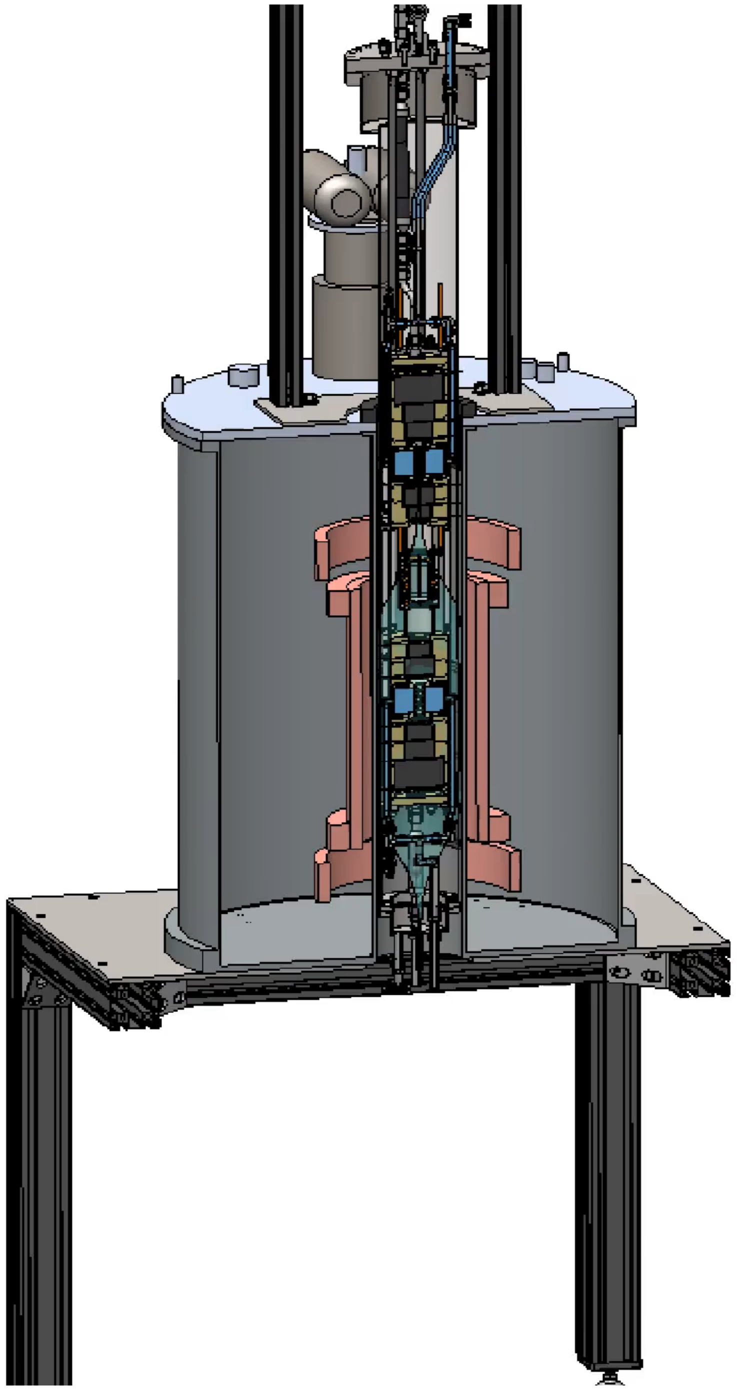
Outline

- Magnetocaloric effect
- Brief overview of magnetocaloric liquefaction
- Experimental Setup and Progress
- AC losses inherent to reciprocating designs
- Experimental results indicating other loss sources
- Geometric and temperature dependent magnetization effects
- Where to go with reciprocating designs



Five Layer Dual-Regenerator Air Liquefier Prototype (DOE Program)

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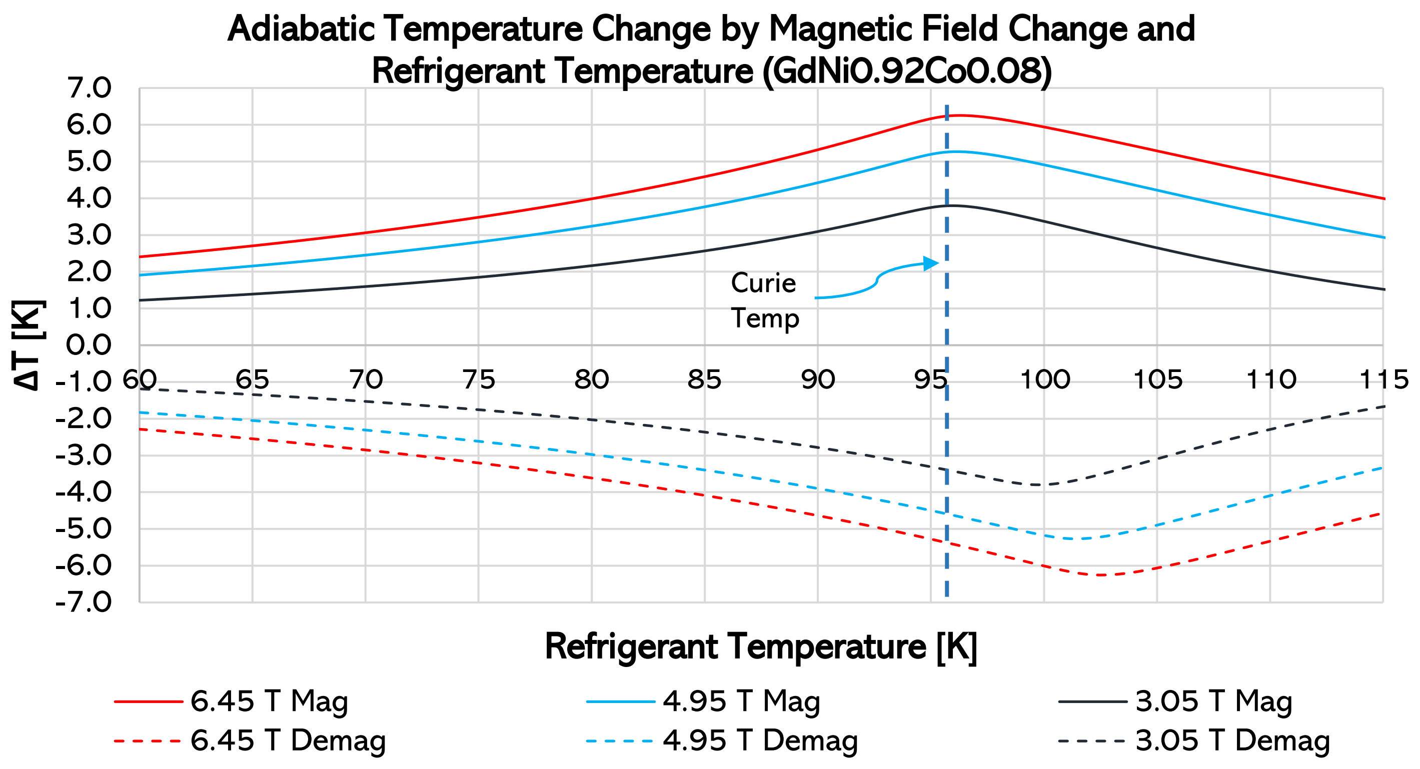
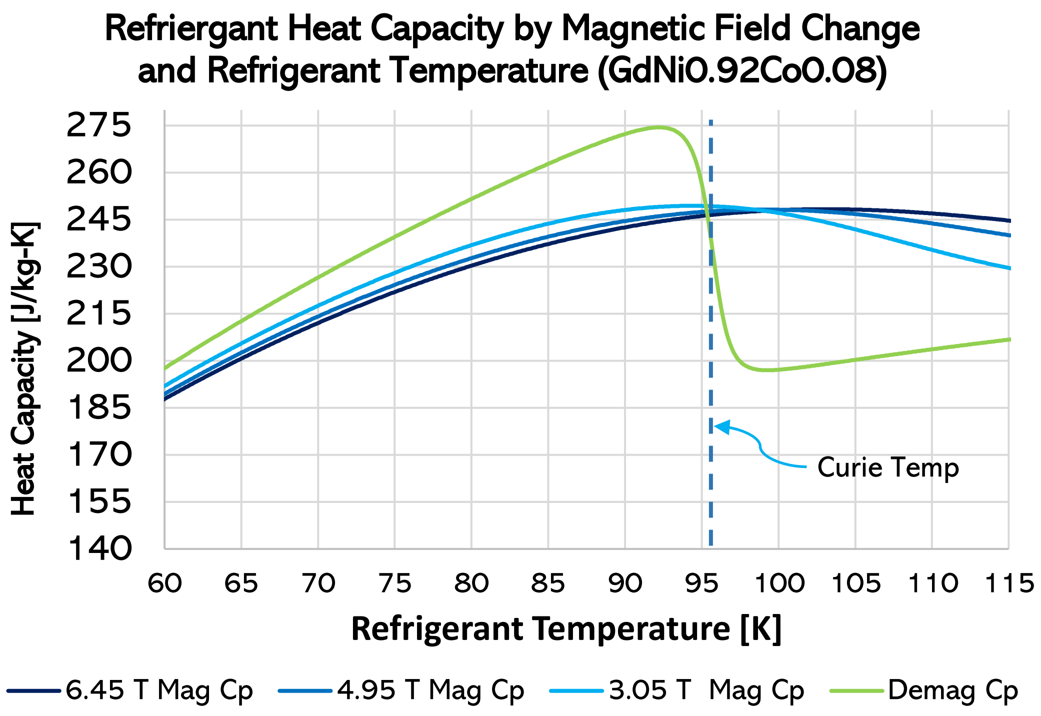
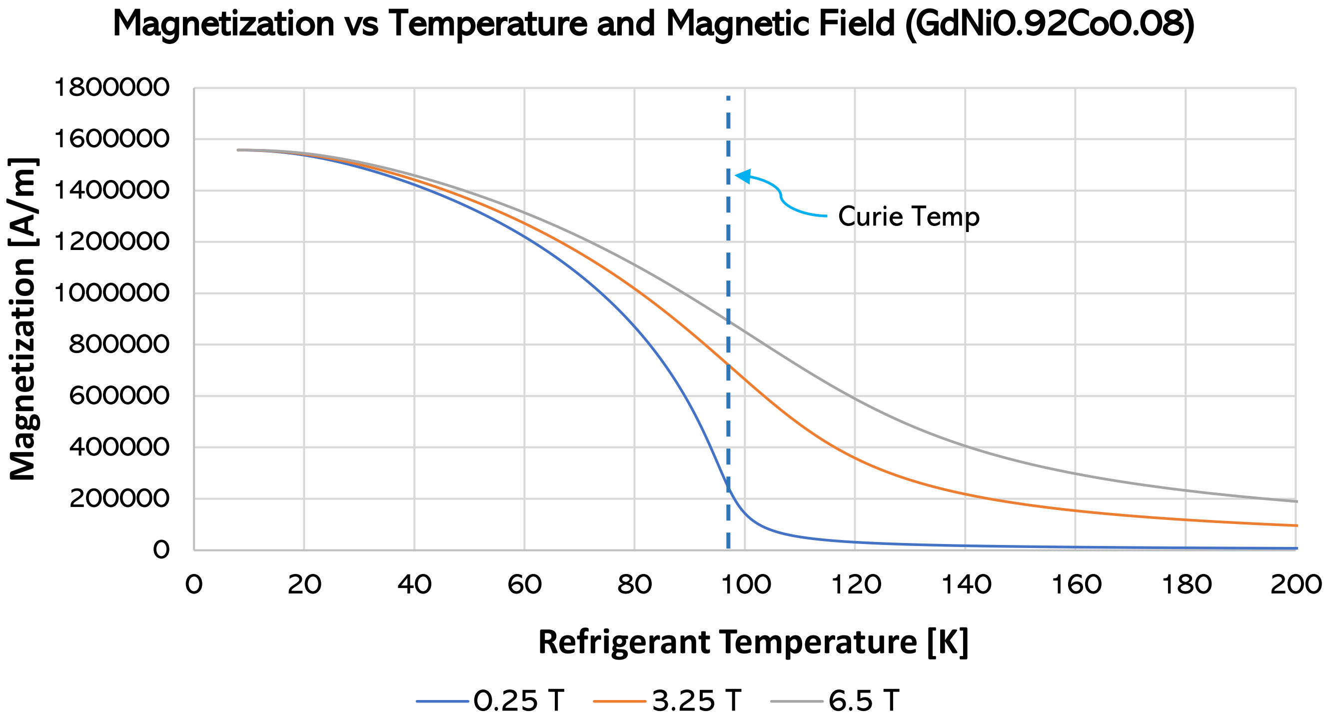
Basic Principles of the Magnetocaloric Effect

$$\Delta T_{adiabatic} = -\int_{H_0}^{H} \left(\frac{T}{C(T,H)}\right)_H \left(\frac{\partial M(T,M)}{\partial T}\right)_H dH$$







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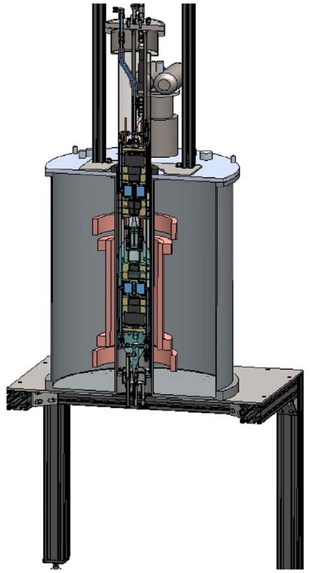
The Reciprocating AMR for Demagnetizing and Magnetizing Magnetocaloric Regenerators

There are several ways to apply and remove the magnetic field:

- Reciprocating: demagnetizing and magnetizing the magnetic regenerator by moving it out of or into a fixed high-field, superconducting, stationary solenoidal magnet, or move the magnet
- Rotating: Rotate the refrigerants through the field, or rotate the magnet
- Charge/discharge magnet

For experimental simplicity PNNL's team has been using a fixed solenoidal magnet and the refrigerants are moved through the field with a linear actuator.

- Cryomagnetics 6.5 T NbTi LTS, persistent mode, with trim and bucking coils to shape field for homogenous high and low field regions
- Cryomech PT-420 Pulse Tube Cryocooler with CPA1114 Compressor – 2 W of cooling at 4 K



Achievements and outcomes of reciprocating AMRR at PNNL:

- 2016 - Liquefied propane with a single Gd dual-regenerators
- 2019 - Liquefied methane with 4-layer dual-regenerators
    - 295 K to 135 K span – 9 W cooling power
- AC losses present but manageable in both systems
- **Scaling up systems to achieve larger temperature spans and cooling powers has led to unpredicted magnet heating**

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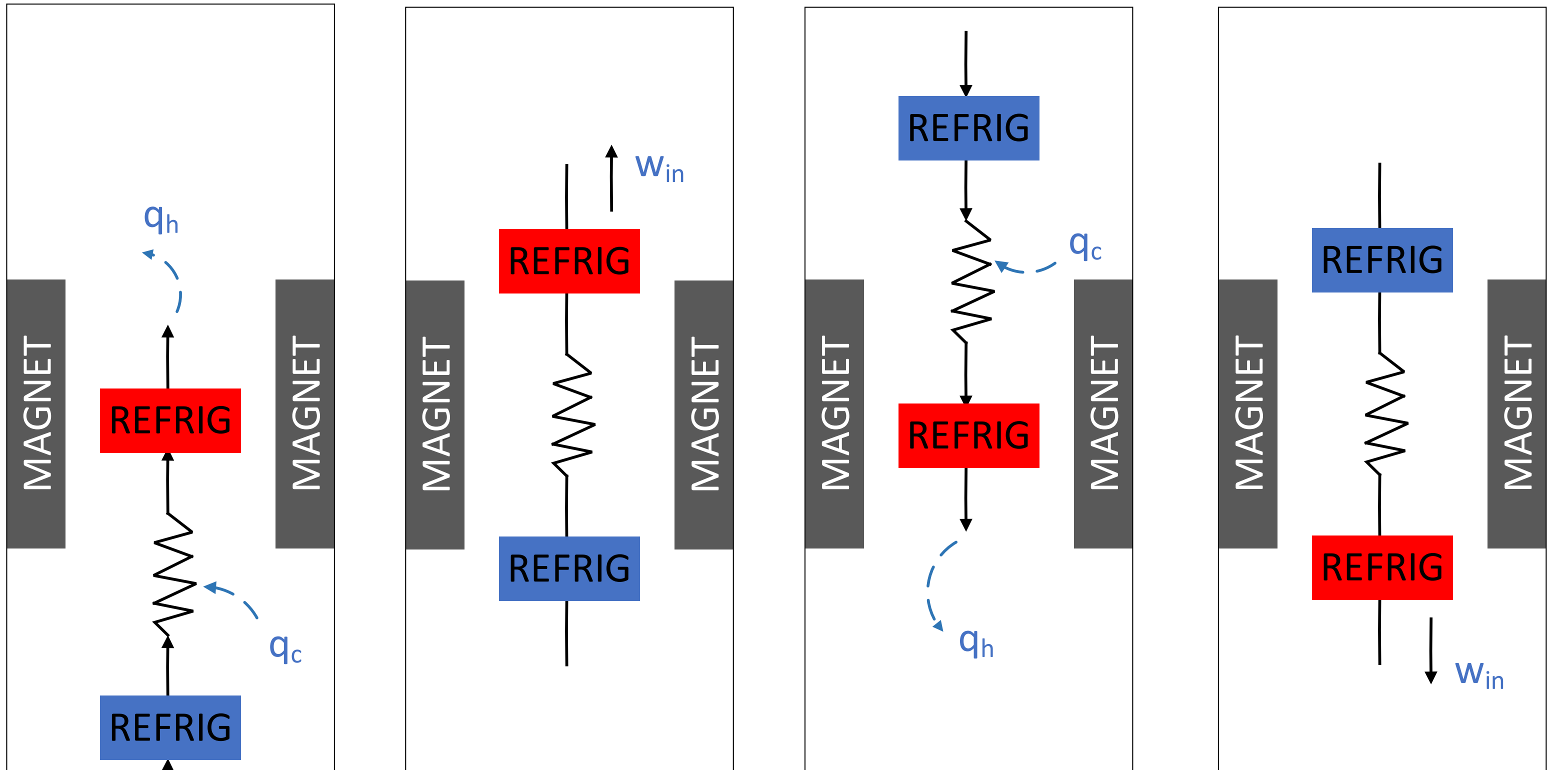
The Active Magnetic Regenerative Refrigeration (AMRR) Cycle Leverages the Magnetocaloric Effect for Efficient Liquefaction of Industrial Cryogens – LOX, LN2, LNG, LH2 (FOM = 0.6)



Heat Transfer Fluid Blow Constant Pressure Heat Transfer

Refrigerant Regenerators Moved Isentropic Mag/ Demag

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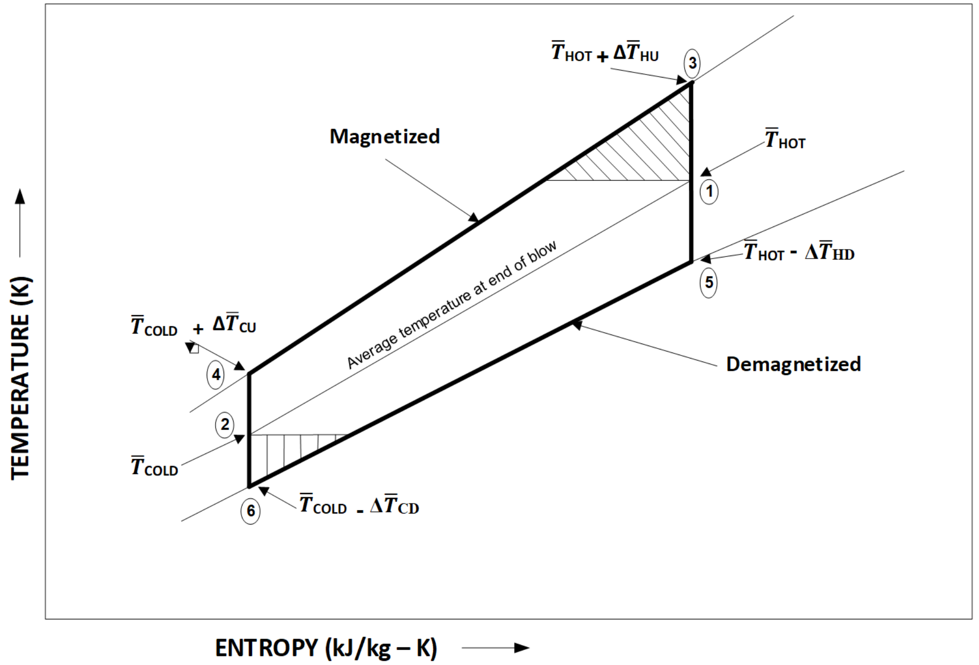
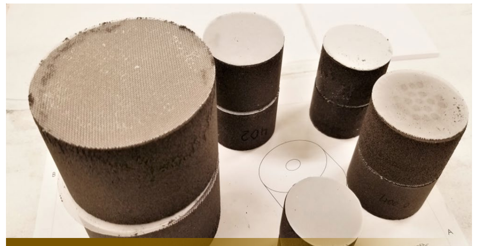




Five refrigerant regenerators for air liquefier

$$\dot{W}_{real_{Layer}} = \left(\dot{Q}_{CHEX} + \dot{Q}_{LC} + \dot{Q}_{Para}\right)\left(\frac{T_H}{T_C} - 1\right) + \frac{T_H \int_{T_C}^{T_H} \Delta\dot{S}_{IRR}\, dT}{\int_{T_C}^{T_H} dT}$$

$$FOM = \eta_{rel} = \frac{COP_{real}}{COP_{ideal}} = \frac{\dot{W}_{ideal}}{\dot{W}_{real}} = \frac{\frac{\dot{Q}_c (T_h - T_c)}{T_c}}{\dot{W}_{real}}$$

AC Losses are Inherent to Reciprocating AMR Designs – Scaling Becomes Challenging

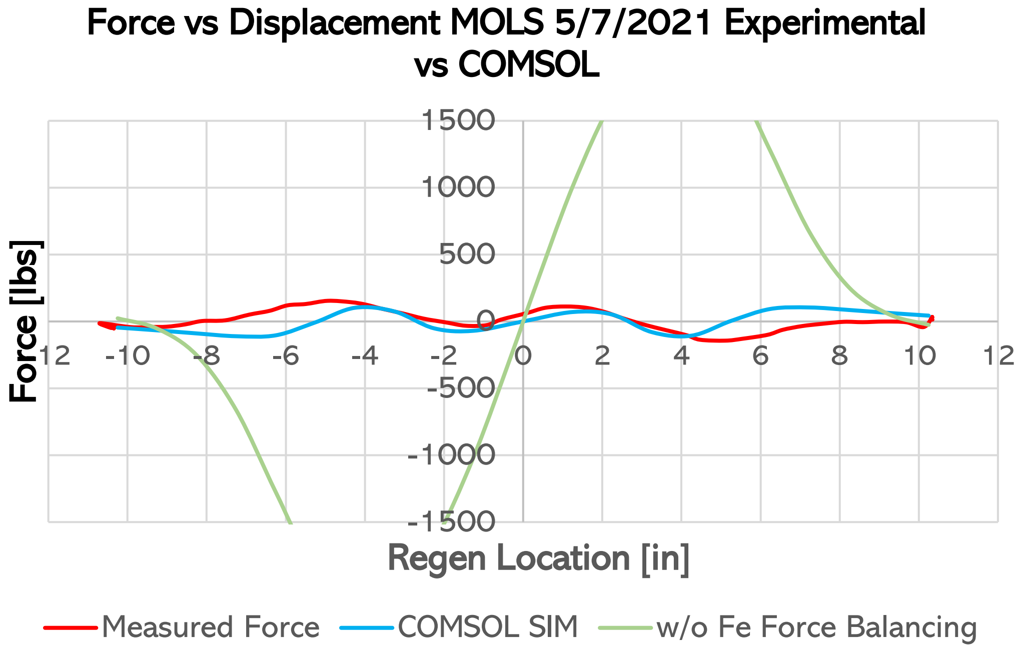
First Iteration w/ Force Balance Rods

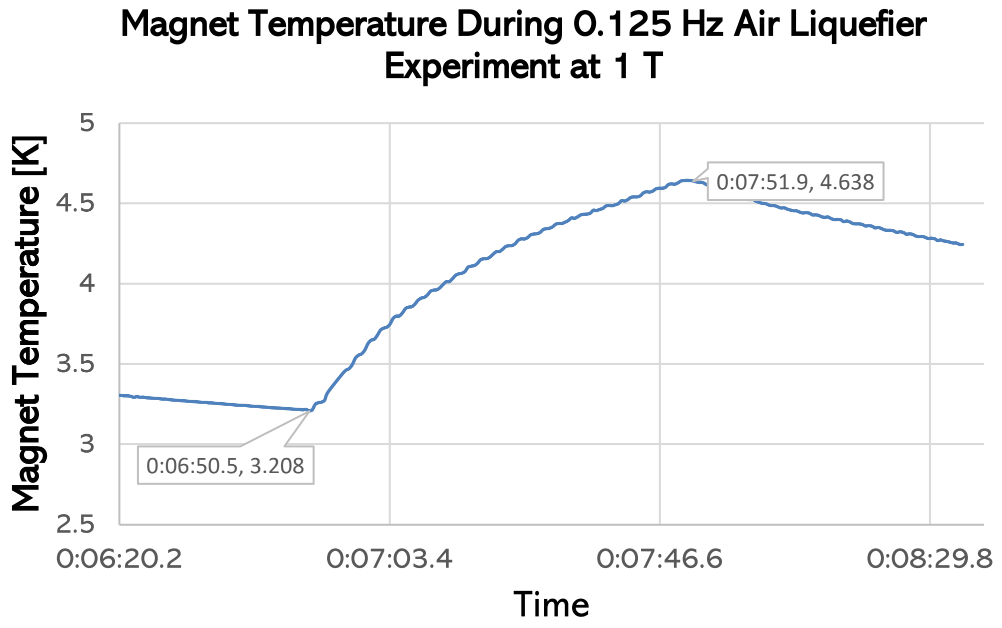
Soft Fe to balance forces and reduce AC losses

1st gen worked well in terms of force balance, but magnet heating prevented target cycle frequency of 0.25 Hz

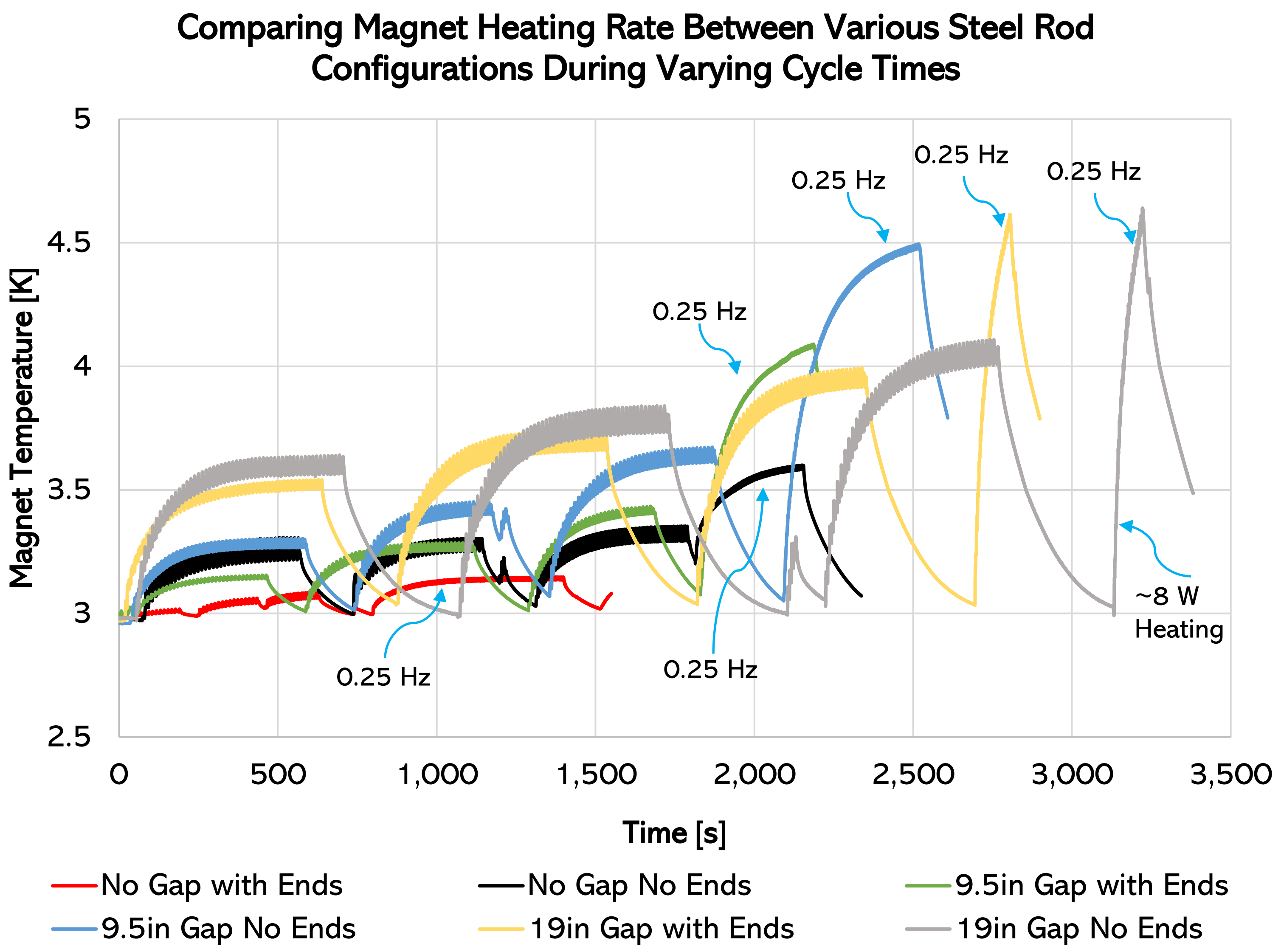
- AC losses are caused by changes in the current in the persistent mode magnet coil to keep the flux density B constant when the magnetization M of objects that move through the bore change where: $B = \mu_0(H + M) = Const.$
- COMSOL Multiphysics with AC/DC module used to simulate interaction between the refrigerants and magnets.
- Soft iron elements placed in or near gaps in the regenerator structures to reduce the geometry- and temperature- driven force imbalances.
- $Force = mass\frac{dB}{dz}\sigma$

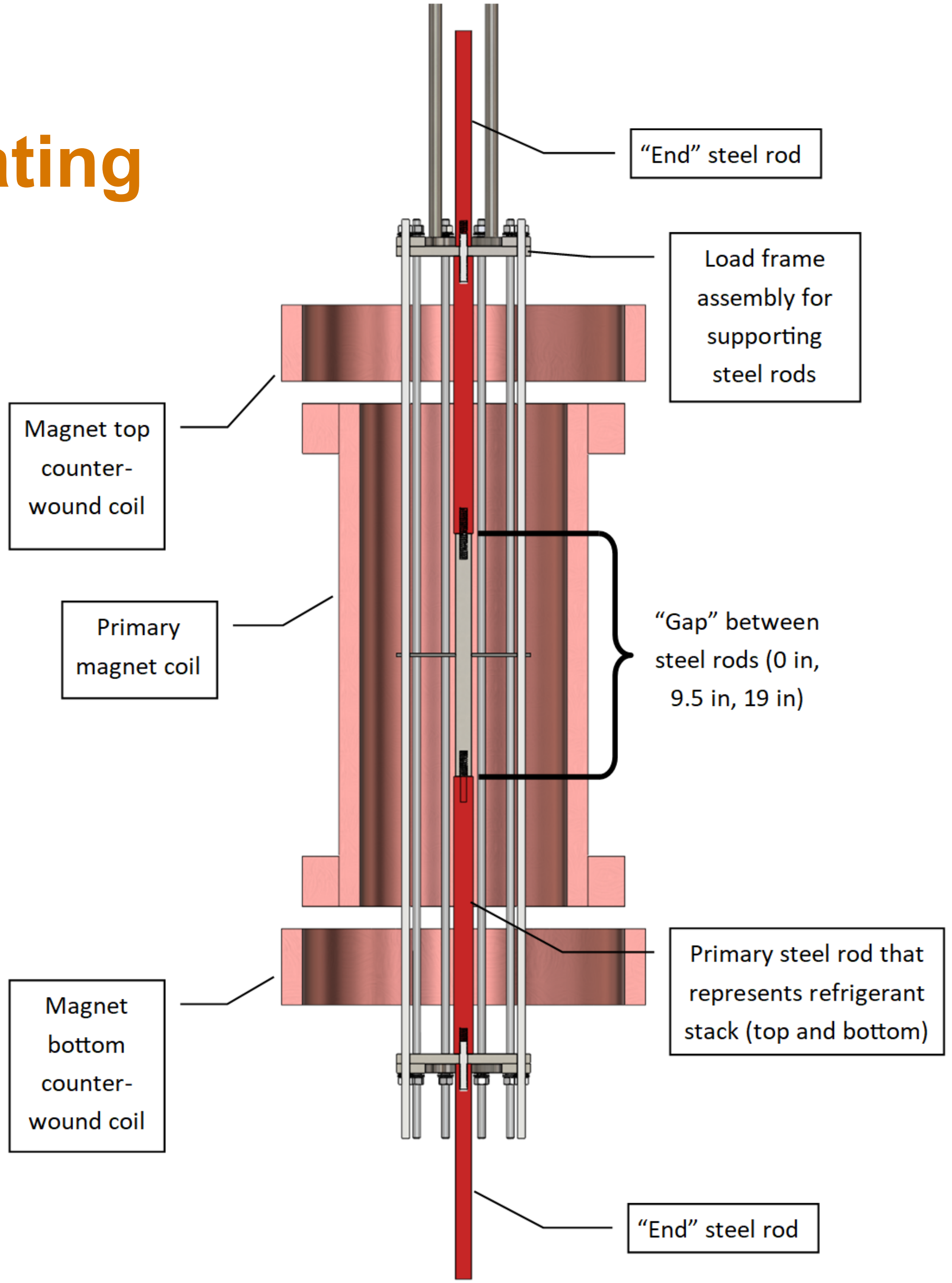
  σ: $(mass\ magnitization\ [^{Am^2}/_{kg}])$





Simple Steel Rod Experiment Identified Cause of Magnet Heating





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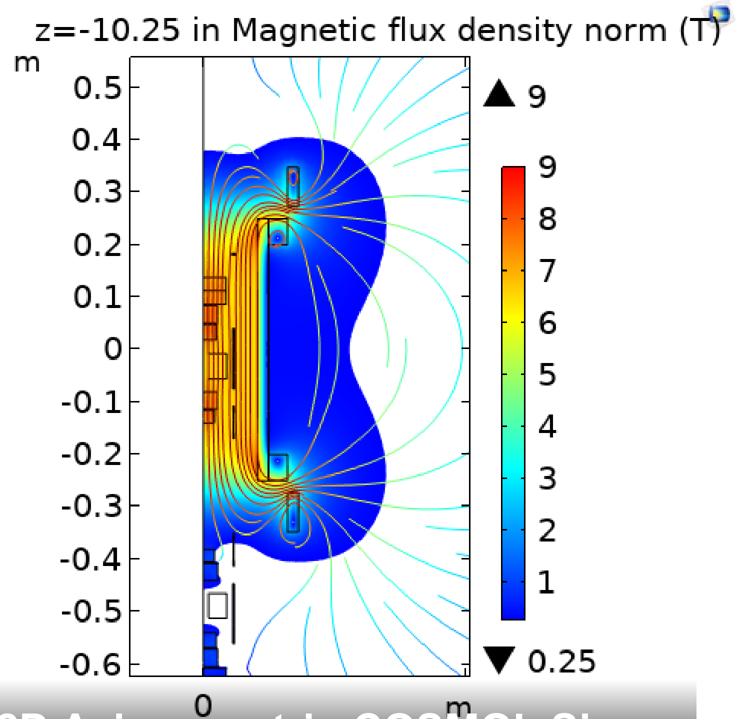
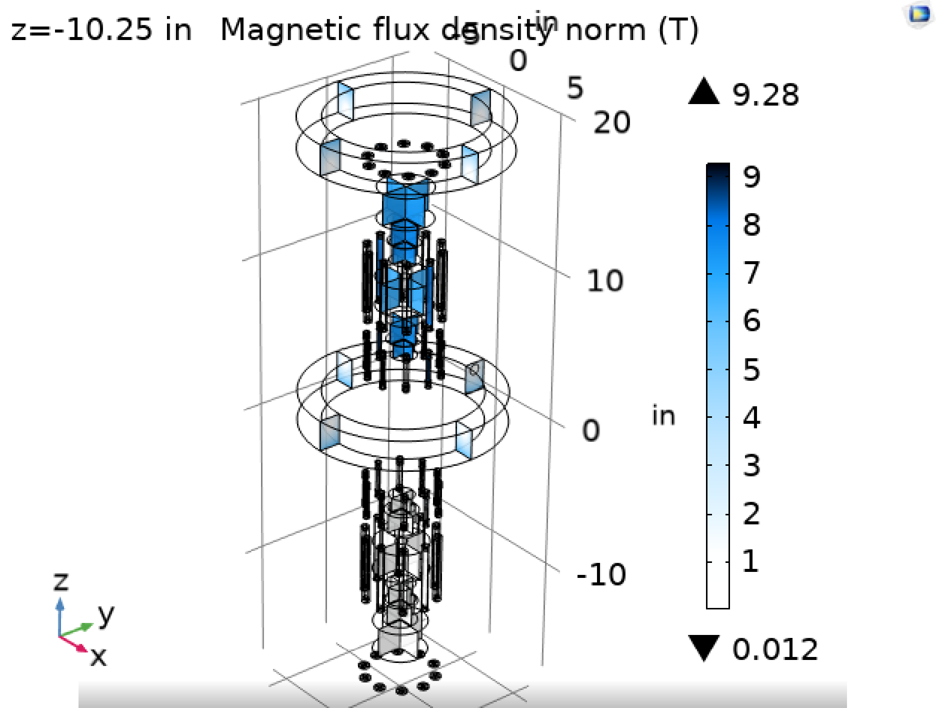
COMSOL and Experimental Results Used to Understand Secondary Heating Mechanism

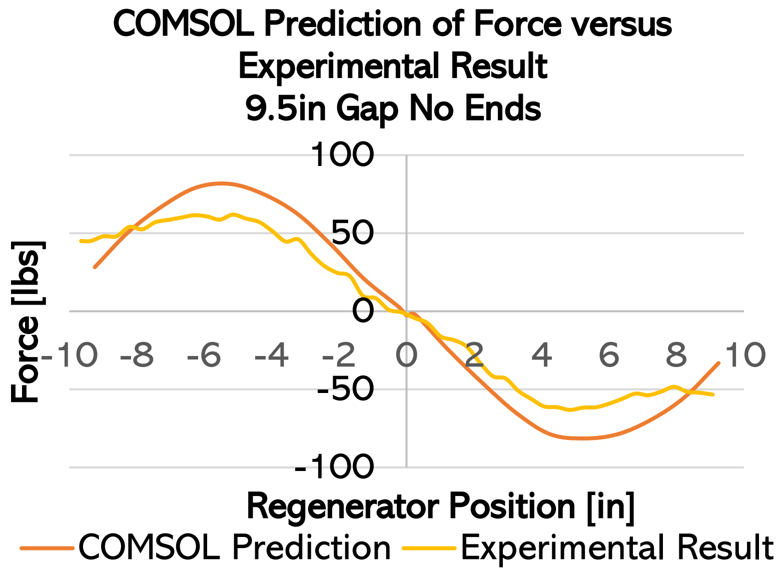
- 2D Axisymmetric and 3D simulations in good agreement
- Experimental and COMSOL force and flux density results agree
- Varying peak free-field flux density does not change heating rate



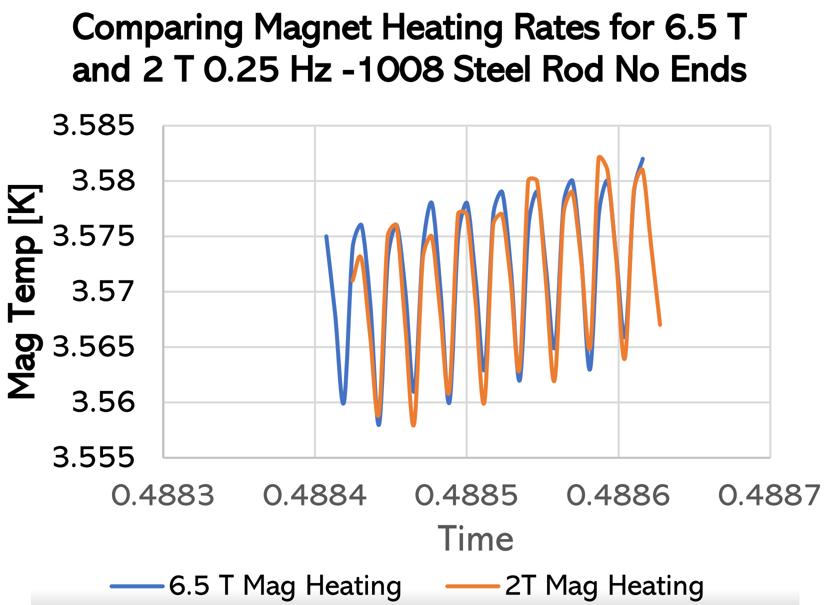
2D Axisymmetric COSMOL Sim



3D COSMOL Sim



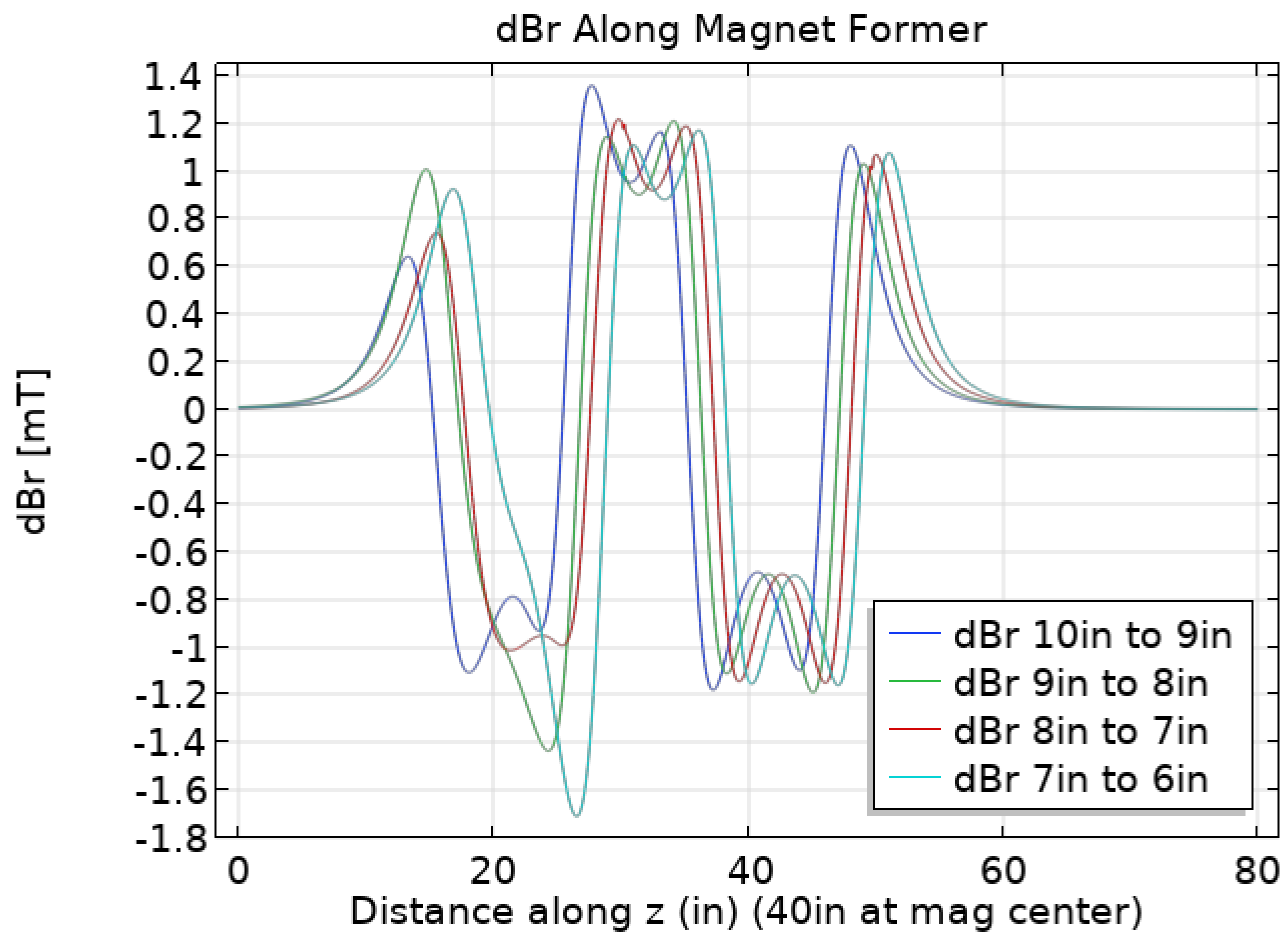
Measured and simulated forces agree

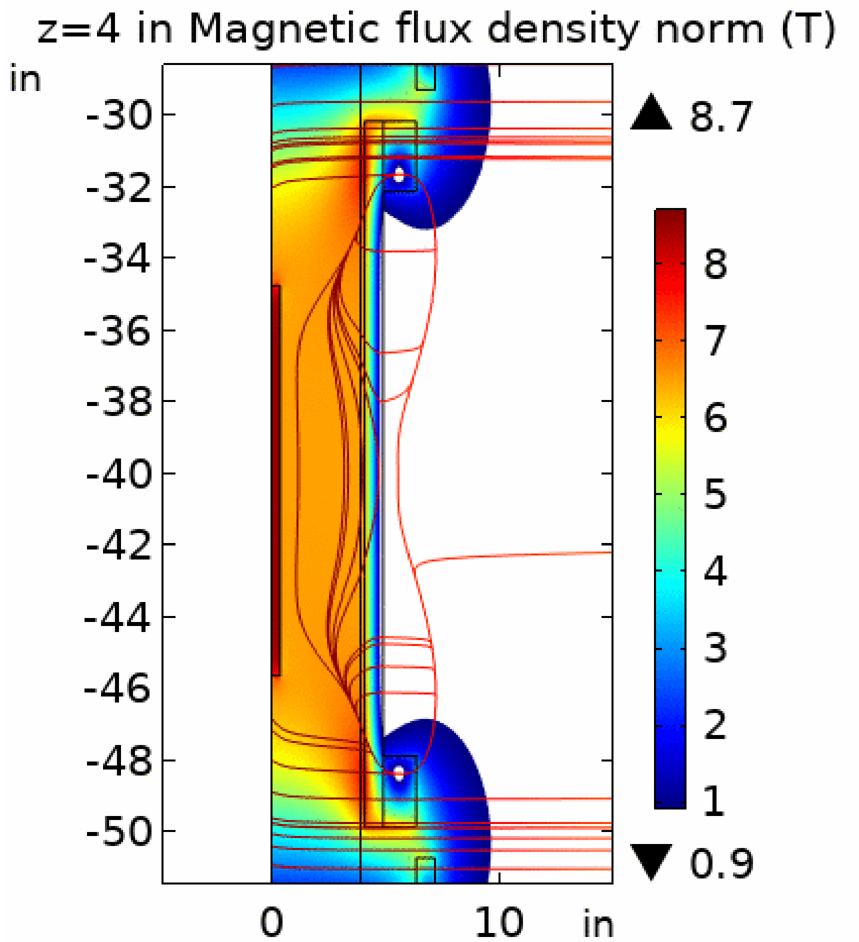


Varying free-field flux does not affect heating rate

Gaps and Discontinuities in the Dual-Regenerator Assembly Cause Flux to Move, Inducing Eddy Currents in Magnet Metallic Structures

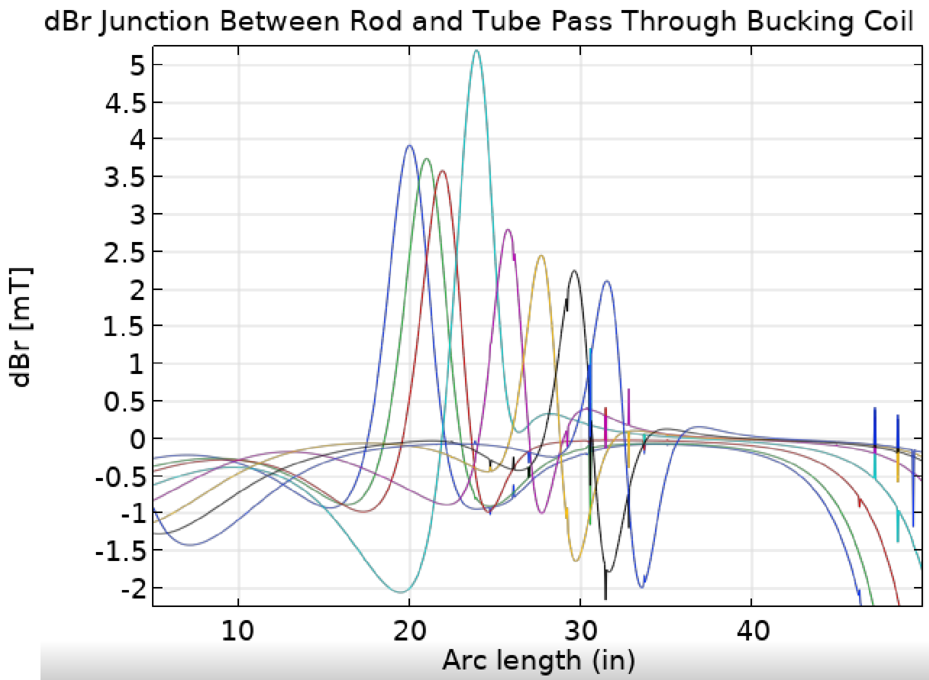
- Change in flux direction along magnet former results in electrical eddy currents in magnet structures and subsequent heating of the magnet.
- Assuming copper/aluminum magnet construction confirms mT magnitude flux changes result in 2-10 W of eddy current heating.

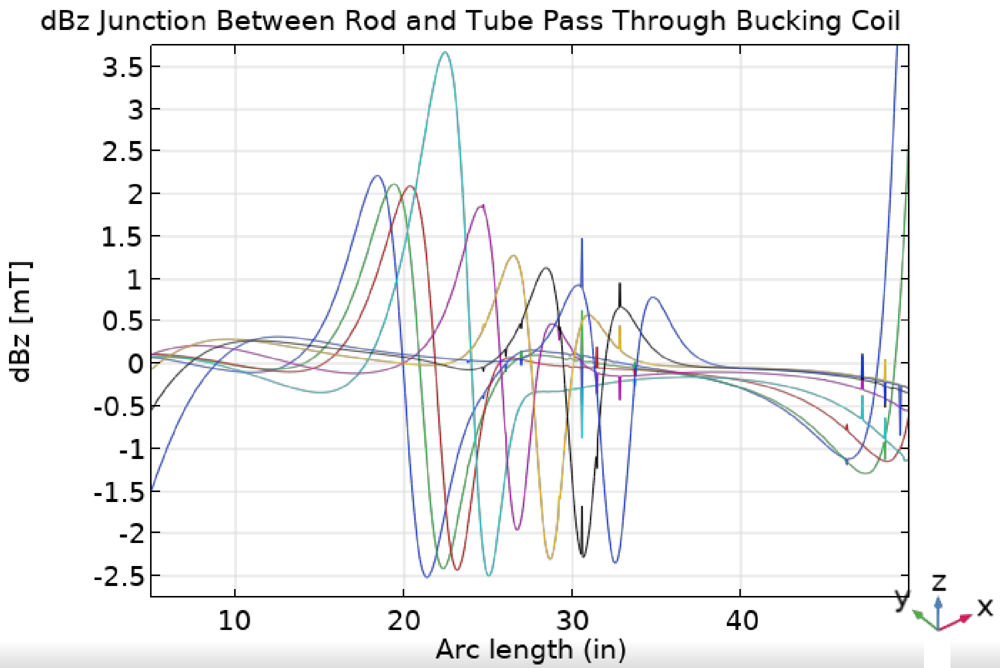




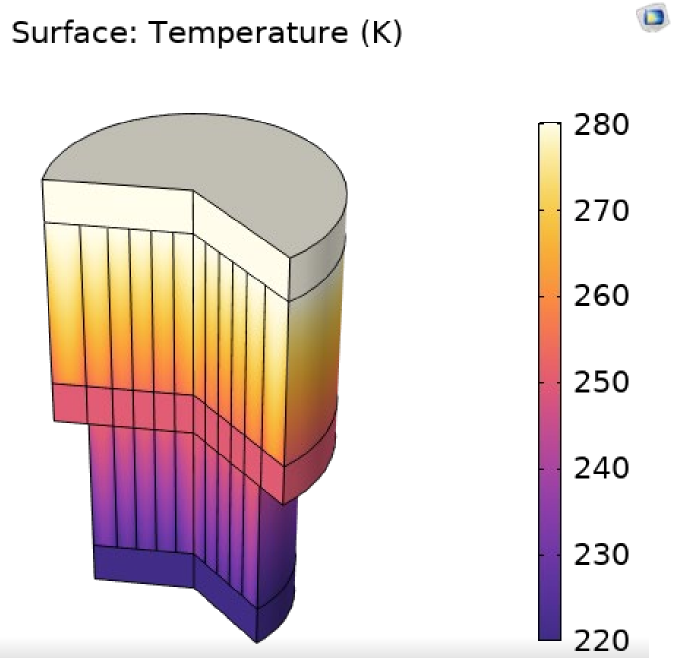
Temperature Dependent Magnetization of the Refrigerants and Geometric Discontinuities Make Scaling and Increasing Frequency of Reciprocating Designs Challenging

- Flux uniformity designs are possible for *single layer* reciprocating systems – though some flux movement will be generated by varying temperature dependent magnetization along regenerator thermal gradient
- Flux uniformity for *multi-layered* reciprocating designs is much more complicated given inherent geometric discontinuities and temperature/magnetization gradients



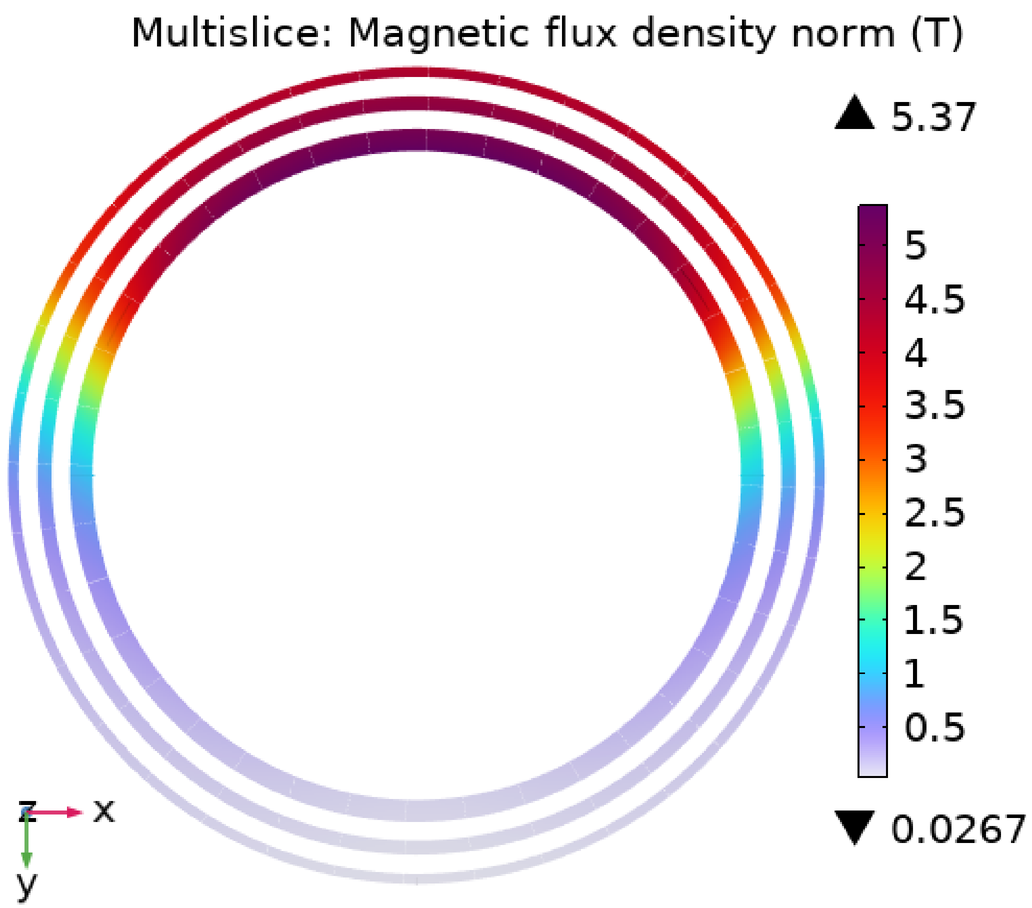


Flux discontinuity where tube meets rod with same x-section area passing through bucking coil region and main coil



Temperature gradients along regenerators result in magnetization gradients and uneven flux distribution

Scale Up of AMRR Systems Require Constant Uniform Magnetic Flux & Effective Magnet Design



Rotary designs result in constant flux, built in work recovery, and possibility for high frequency operation

Flux movement in reciprocating designs is virtually unavoidable:

- Magnet design must focus on reduction of AC and eddy current losses
- Flux uniformity techniques that magnetically “fill” geometric gaps and discontinuities in all directions required (z, r, Φ)

- Fixed magnet, rotary designs are an example of a steady-state magnetic flux system
  - Slow and minor flux movement during cooldown

Thank you