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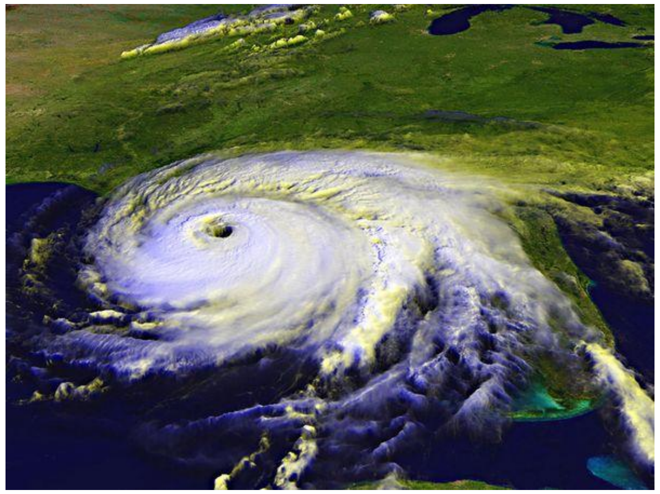

Magnetic Composites for Energy Storage Flywheels

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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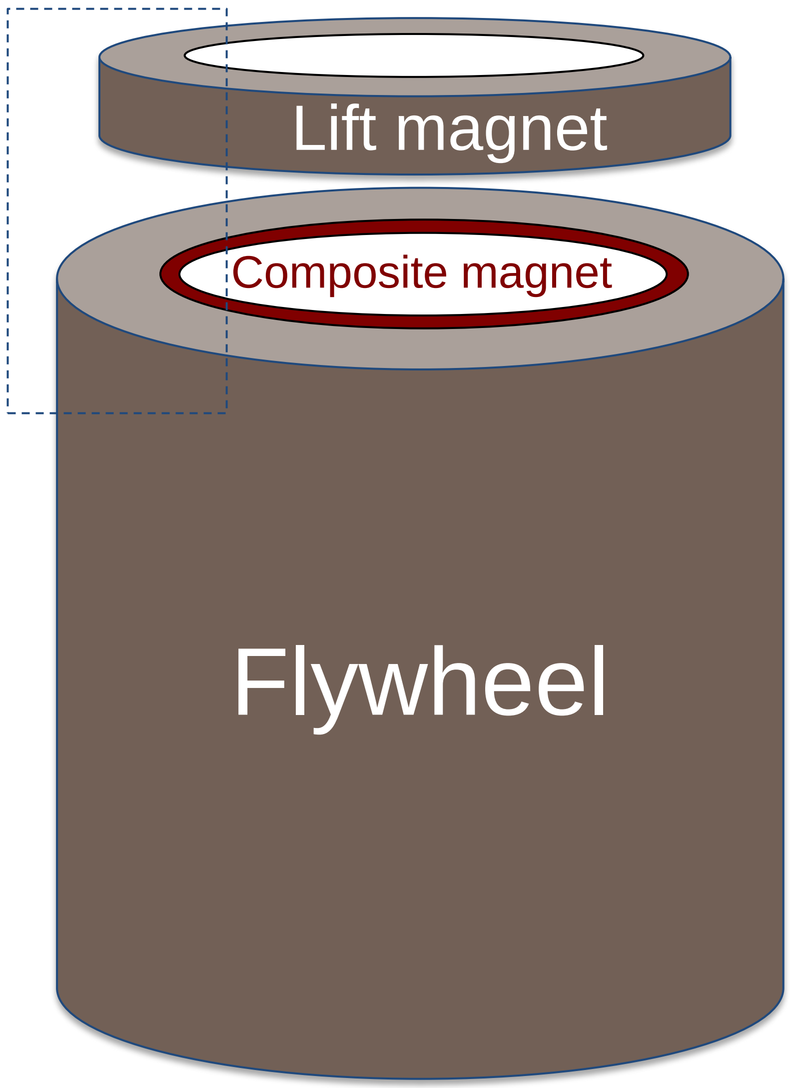
Project Overview

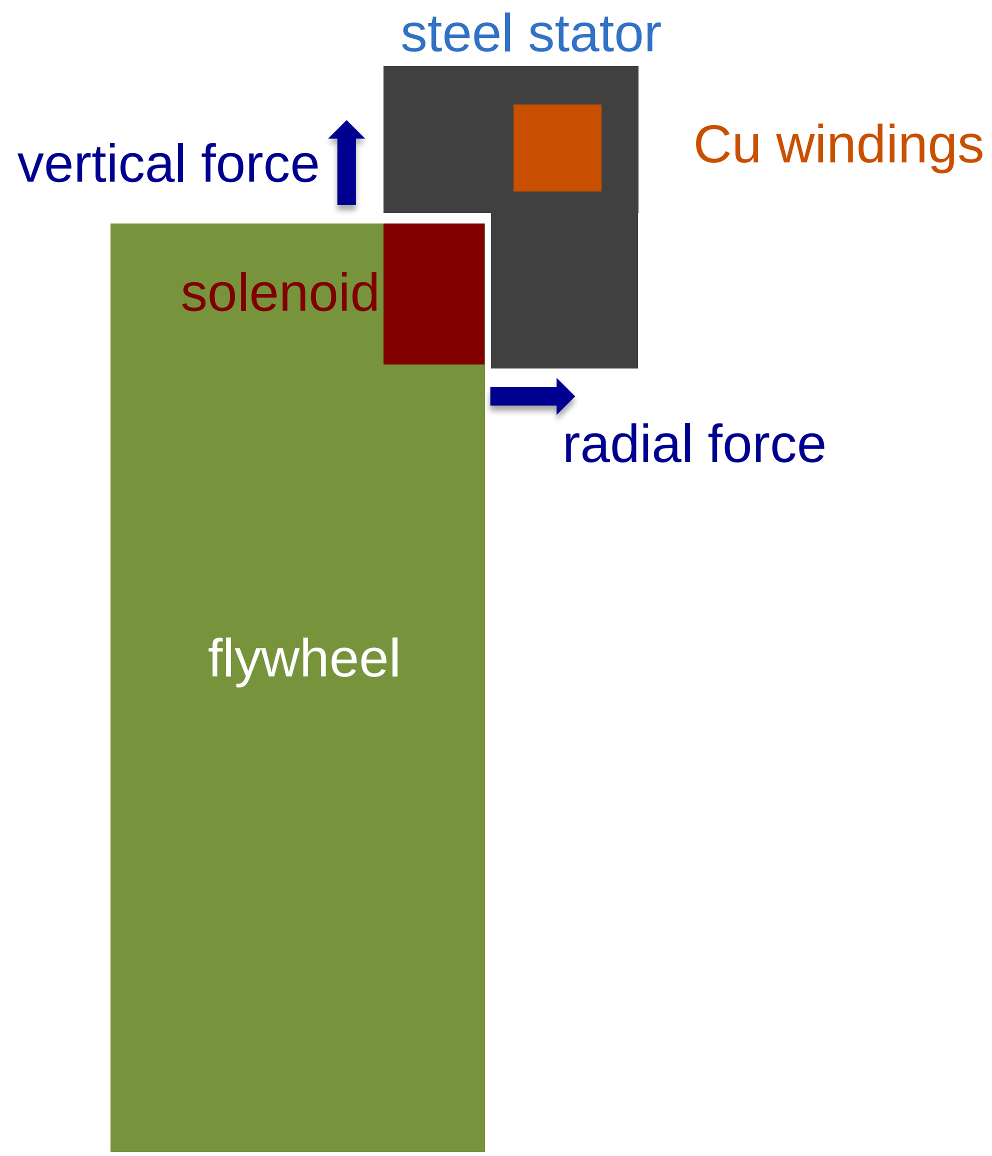
- The bearings used in energy storage flywheels dissipate a significant amount of energy. Magnetic bearings would reduce these losses appreciably.
- Magnetic bearings require a magnetically soft material on an inner annulus of the flywheel for magnetic levitation.
- This magnetic material must be able to withstand a 1-2% tensile strain and be mechanically compliant, yet stiff enough to maintain structural integrity.

- We will develop magnetic particle/polymer composites that meet this need.
- This composite must be capable of enabling large levitation forces.
- If successful, magnetically soft composites will enable more energy-efficient storage flywheels that do not require a hub or shaft and have increased reliability.

- Highly-filled polymer composites act like ceramic materials: strong under compression, weak under tension.
- Can we formulate a composite with the required tensile strain and the required lift?

Rotor lift magnet concept





- The solenoid is the composite magnet.
- The vertical forces add around the rotor but the radial forces cancel.
- There is, however, a radial instability.

FEA modeling of the actual lift magnet and solenoid

with Joe Stupak, Oersted Technologies, Tualatin, OR

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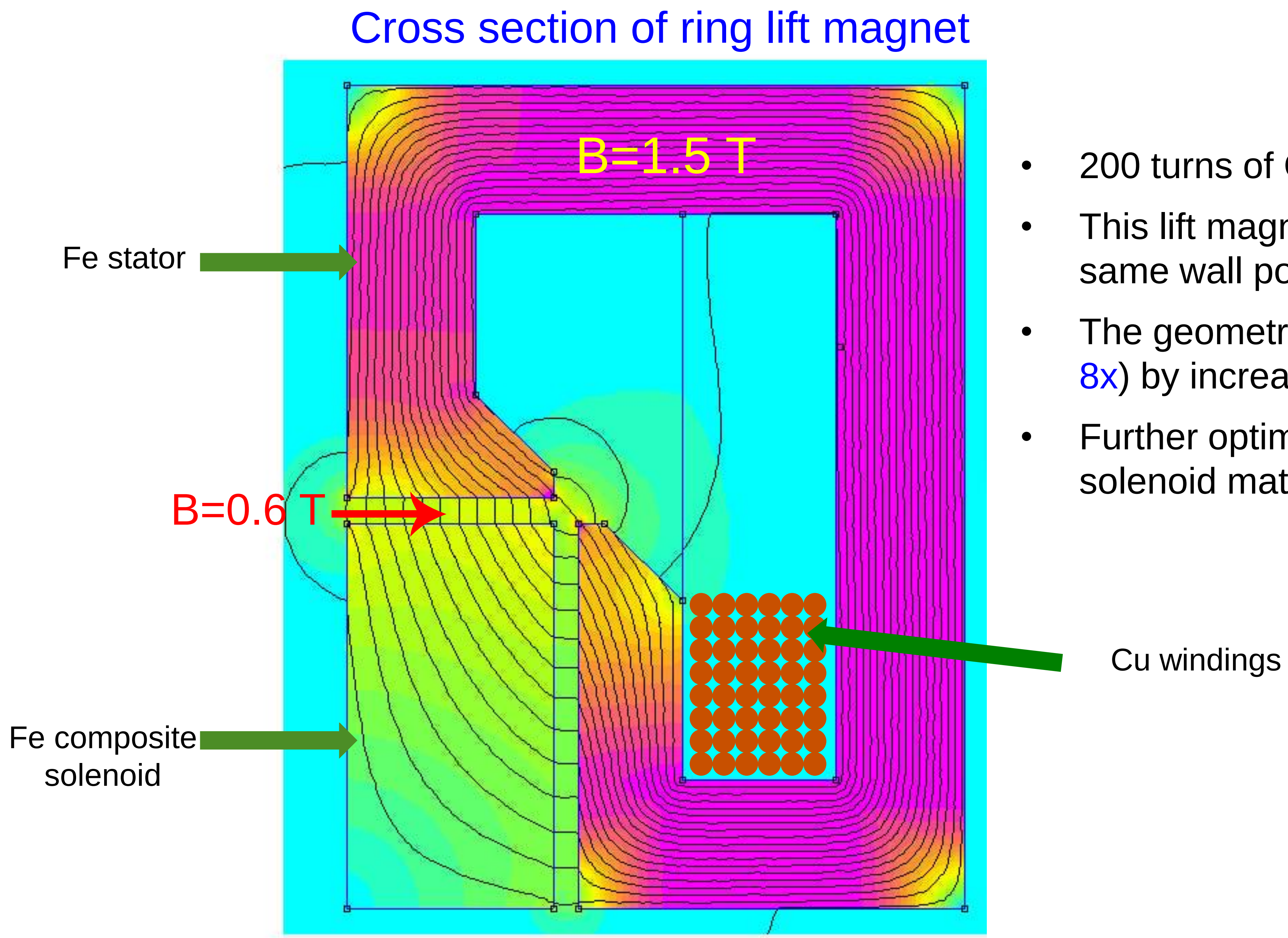
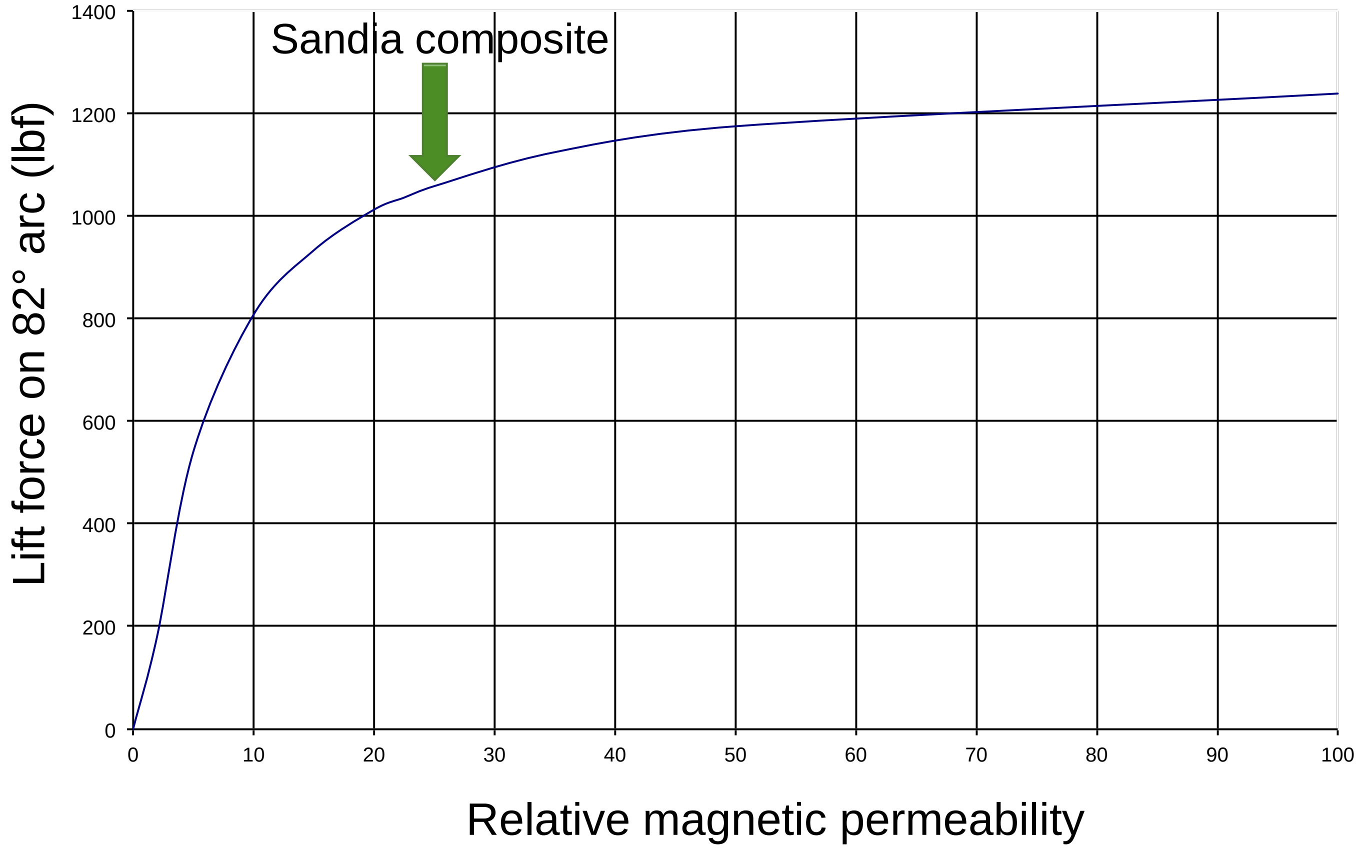


- 200 turns of Cu wire at 20 amps per turn.
- This lift magnet gives 2.9x the lift force at the same wall power as the previous design.
- The geometry could be optimized further (to 8x) by increasing the number of wire turns.
- Further optimization is possible once the solenoid material permeability is decided.

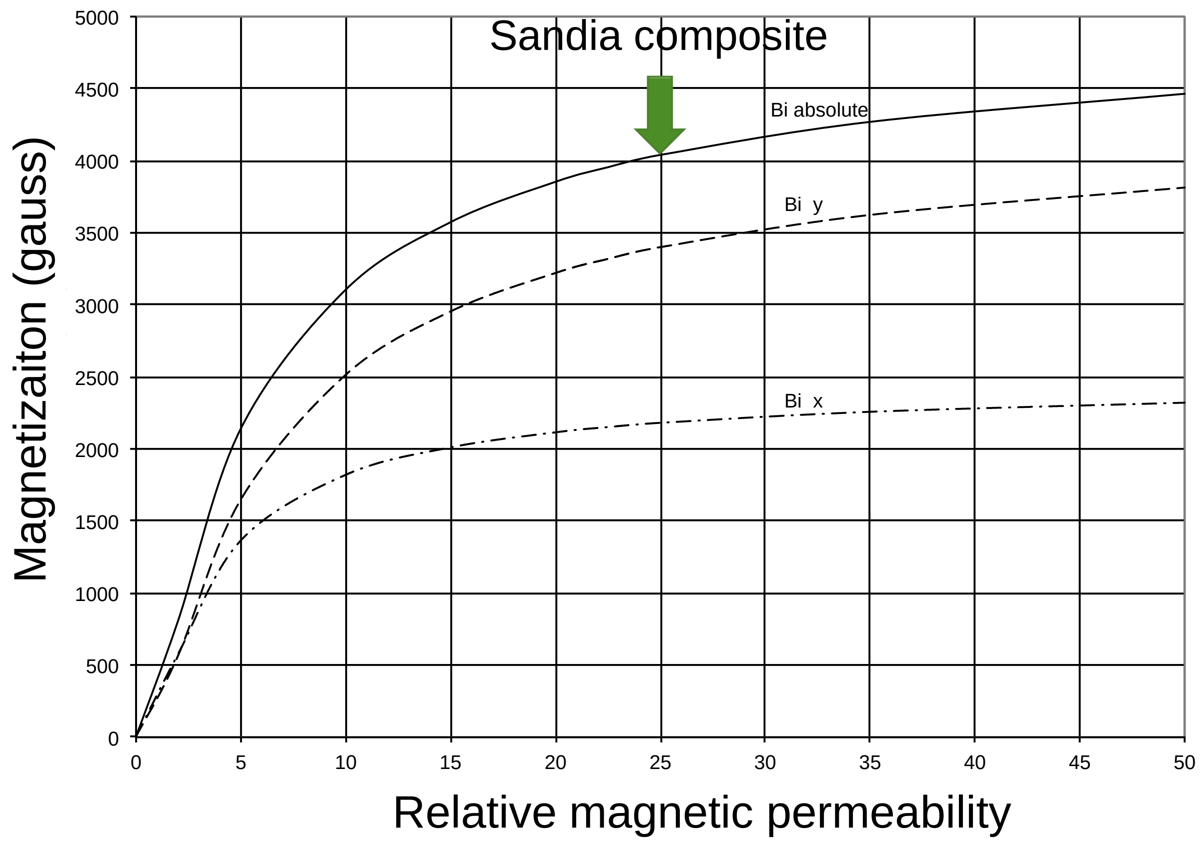
- Modeling is done both to improve the performance of the lift magnet and to quantify how the lift force depends on the permeability of our composite solenoid.
- The flux density within the iron stator is still lower than the saturation magnetism of transformer iron, which can reach 2.2 T. The composite is not even close to saturation (~0.4 vs ~1.2 T).

Results of lift magnet modeling

Ring arc lift force vs. permeability at constant wall power

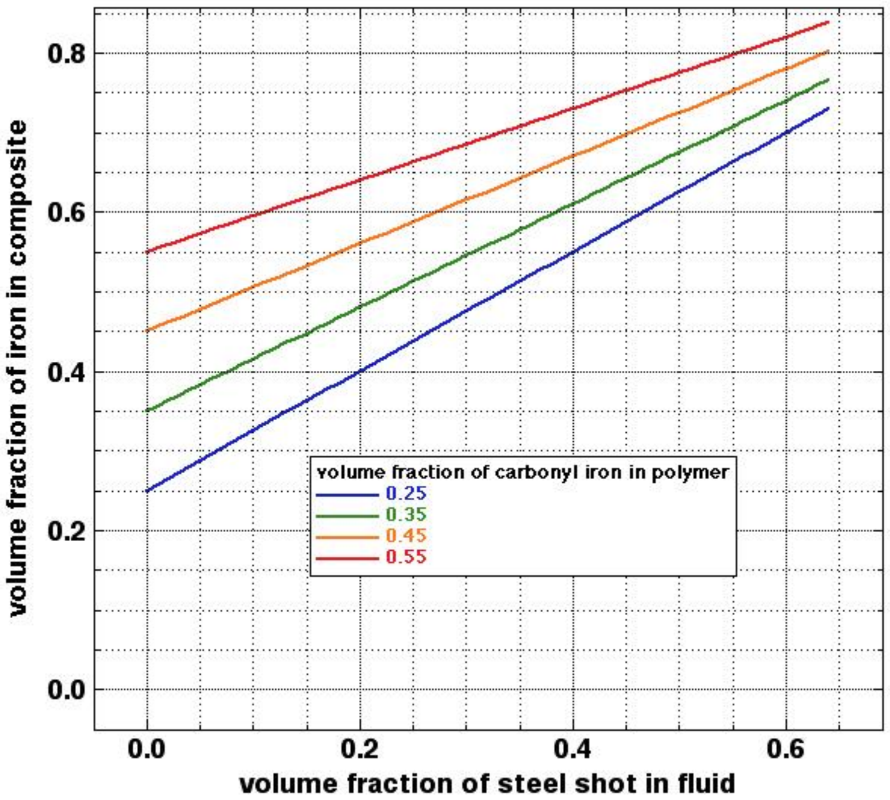


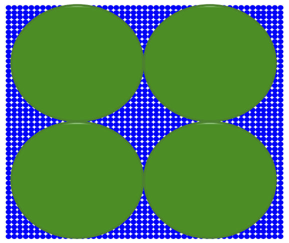
Magnetization vs permeability

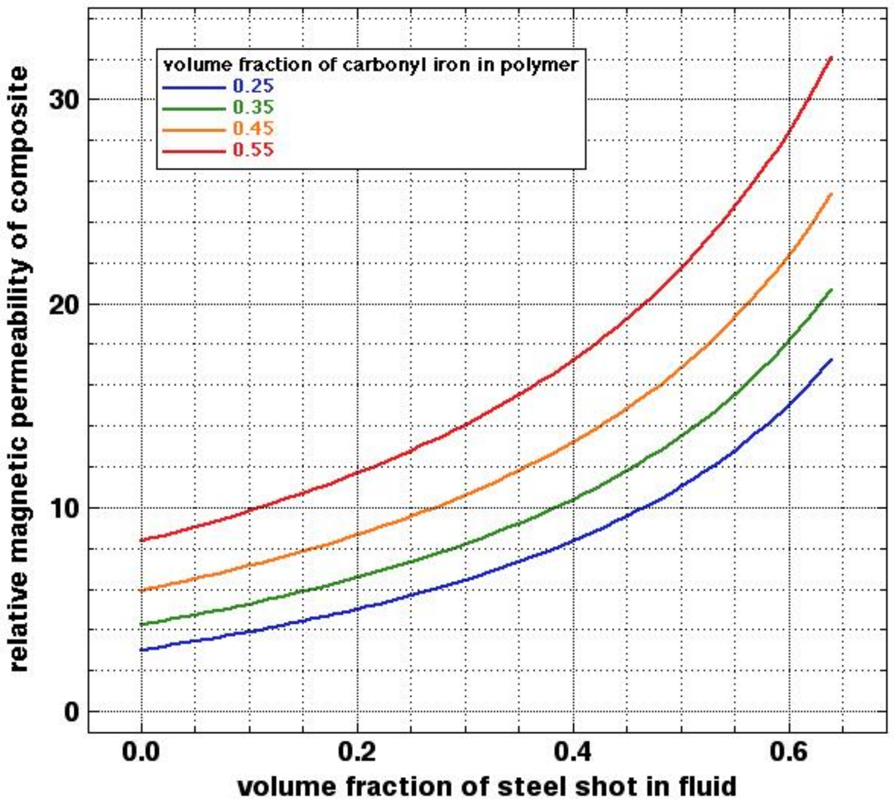


- A lift force of 1000 lbs is achieved with a relative magnetic permeability of only 19.
- Further increases in the permeability give diminishing returns.
- A composite with a permeability of 25 has a saturation magnetism of ~10,000 G.
- Saturation is not a problem at these lift forces.

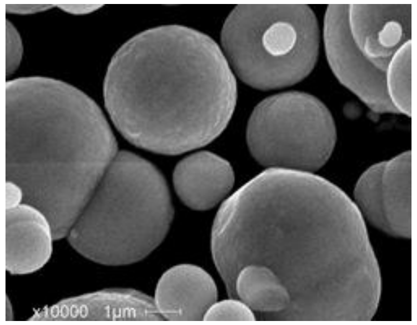
Bidisperse particle composites



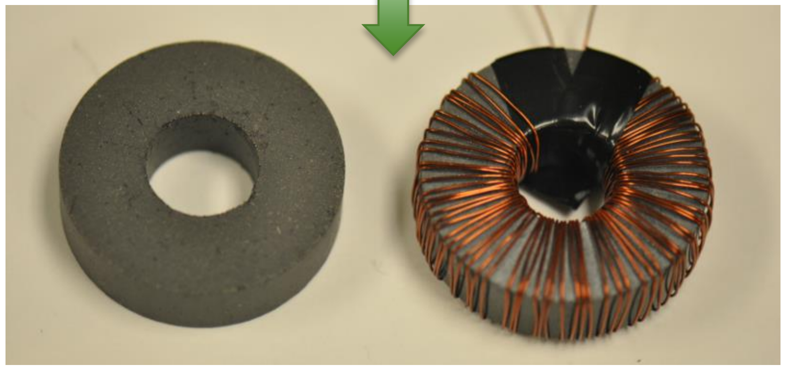




300 micron steel shot



4-7 micron carbonyl iron



Polymer-based co-composites

1. Blend 4-7 micron carbonyl iron particles into a polymer to create a dense colloidal suspension with a manageable rheology.

   1.0 g polymer + 7.7 g Fe particles = 8.7g Fe suspension

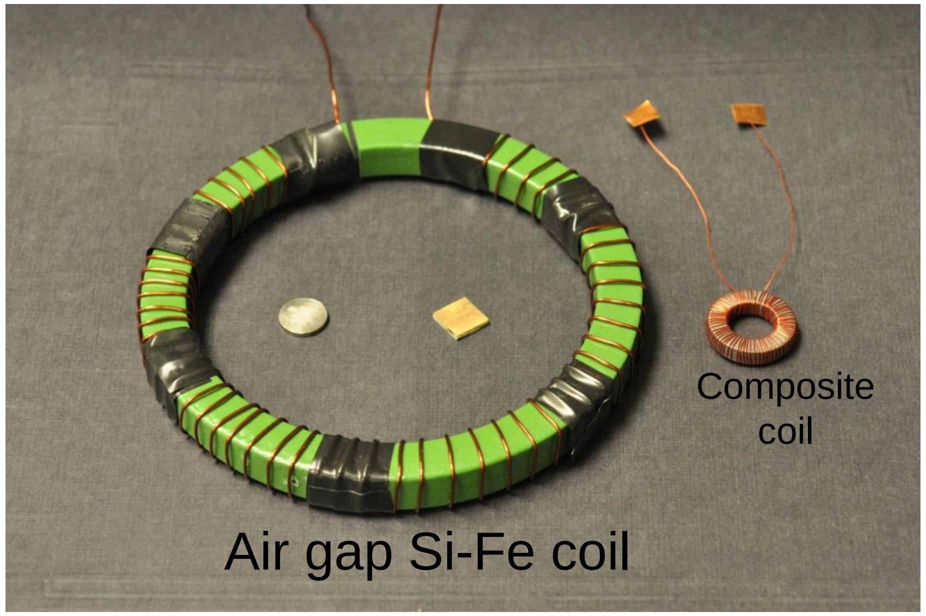
2. To this dense suspension add 300 micron steel particles to create a paste that has a Bingham plastic rheology

   8.7 g Fe suspension + 19.6 g steel shot = 1.0 g polymer +27.3 g Fe

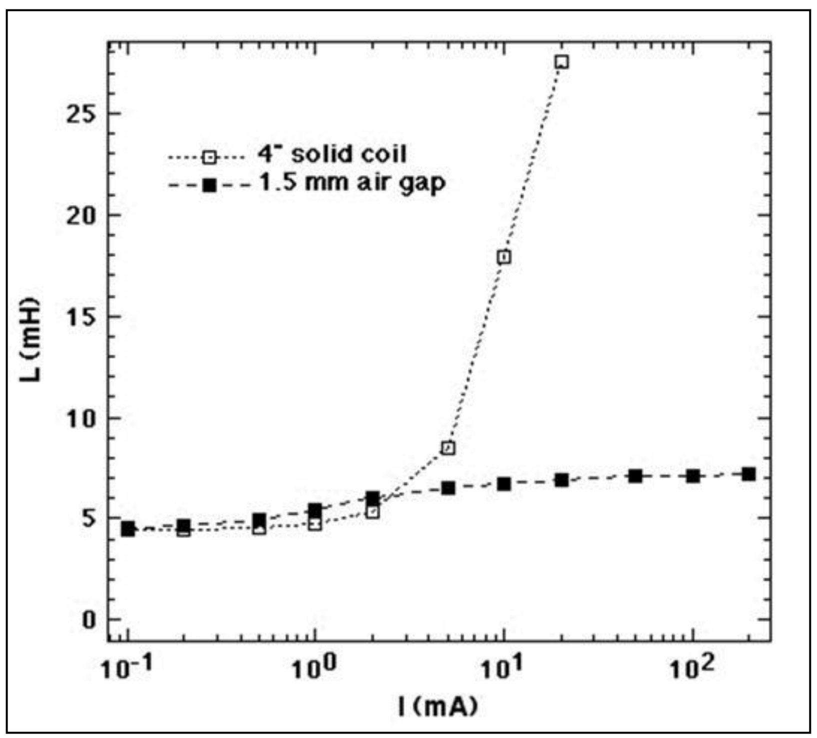
3. Press this paste into the desired shape in a hydraulic press at 5000 psi.

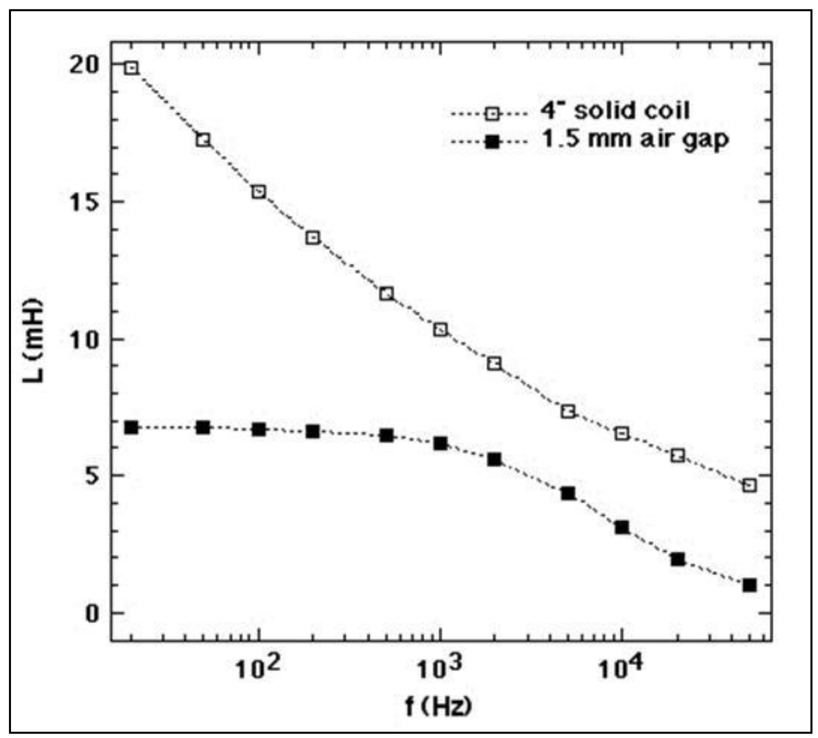
4. The result is a composite with an 80 vol.% loading.

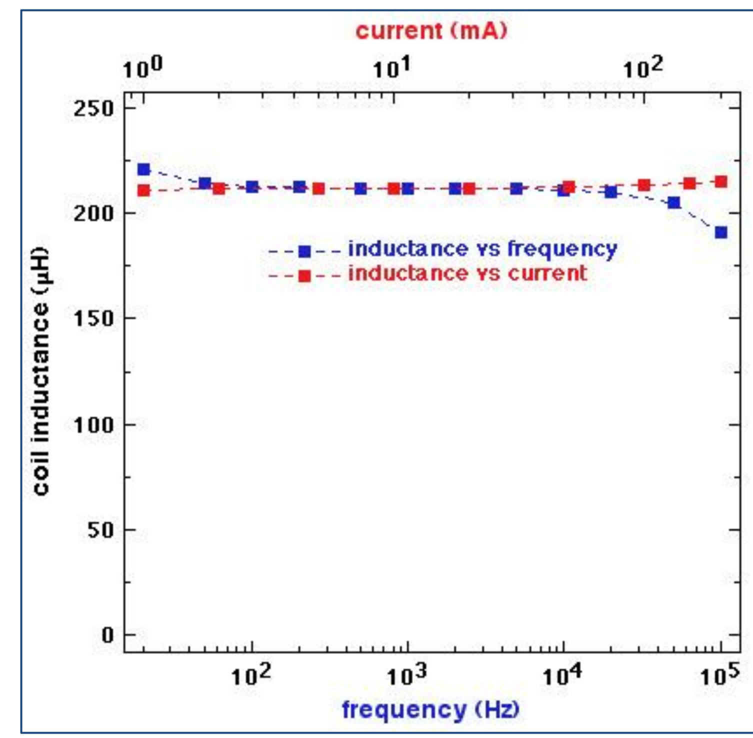
Sandia composites demonstrate ideal magnetism



$$\mu_r = L\,(\mu H)/[0.0117\,h(\text{in})\log(d_{out}/d_{in})]$$







- Conventional Si-Fe core shows a strong dependence of the permeability on the applied field and frequency.
- Cutting an air gap reduces these dependencies.

- Composite coil exhibits linear magnetism with a fast response.

Permeability and lift force for composites

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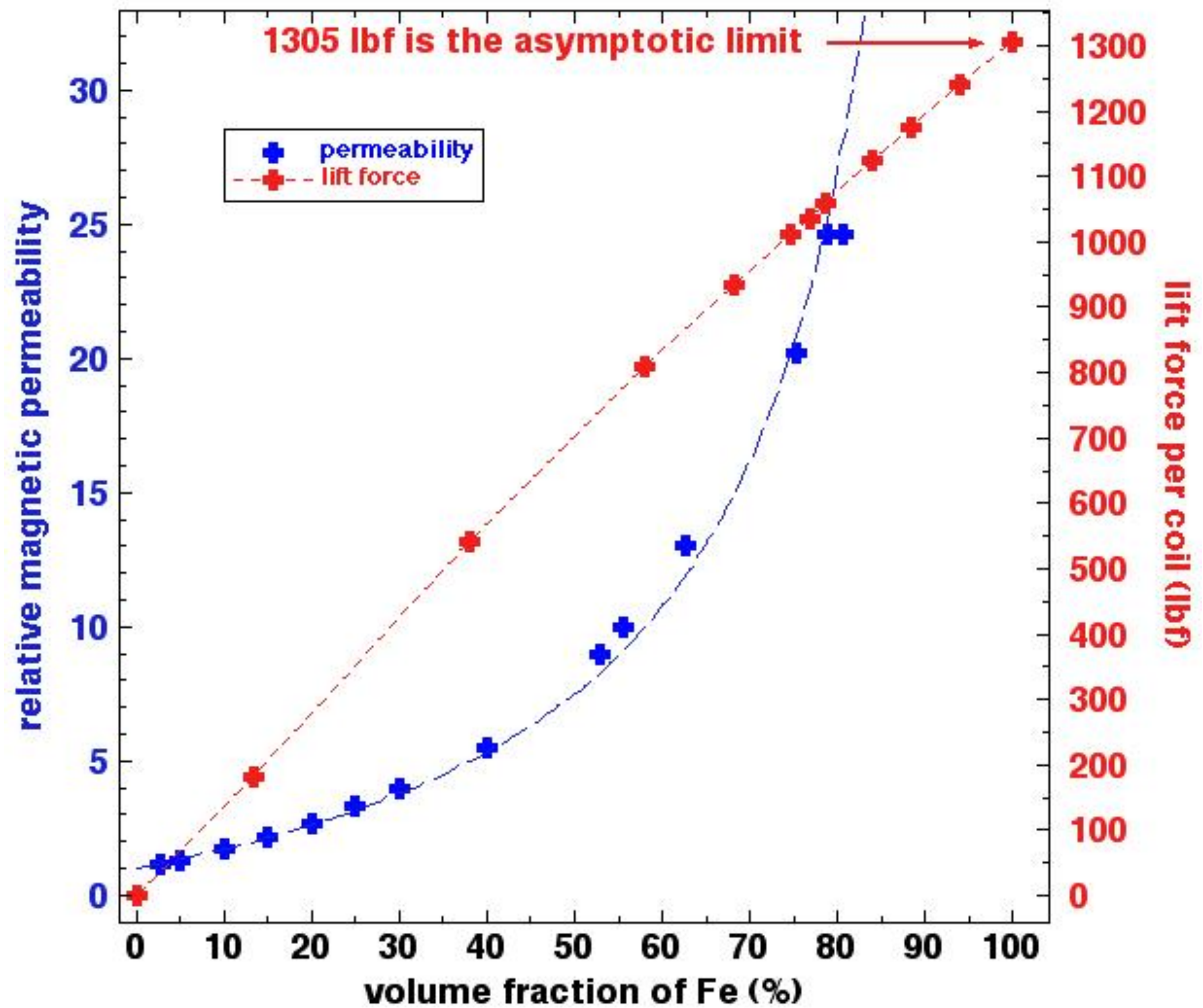

- The measured relative permeability increases steeply with loading, roughly as $\mu_r = 1 + 6.5 f / (1 - f)$.
- Remarkably, the computed lift force is nearly linear in the volume fraction of Fe!
- Our best composite has a computed lift force of 1058 lbf, which is 81% of the absolute limit (for $\mu_r = \infty$).
- A slight decrease in volume fraction immensely improves processing, but only marginally decreases the force.
- These composites demonstrate excellent magnetic properties but are weak under tension.

Compression tests of elastomeric composites

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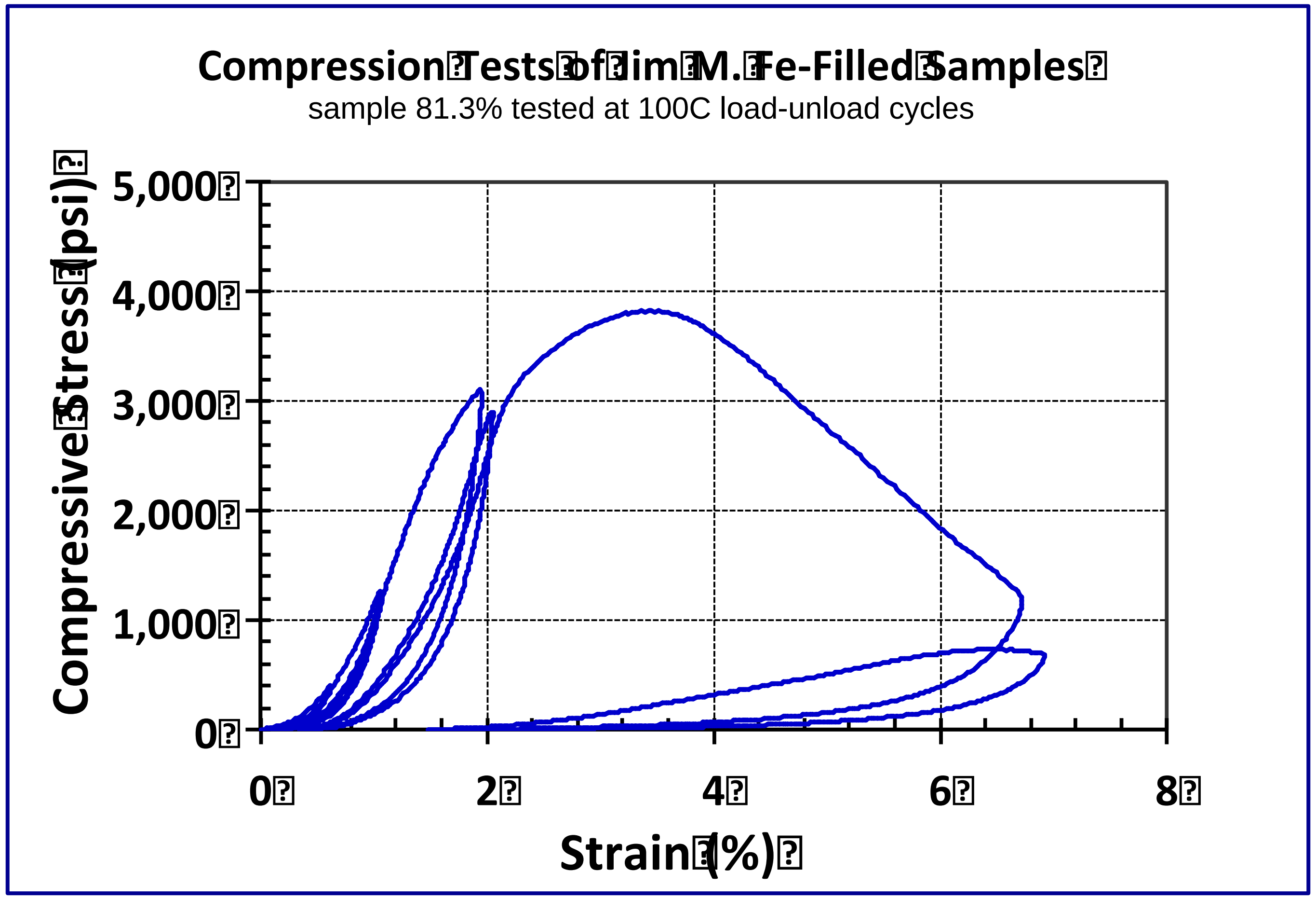
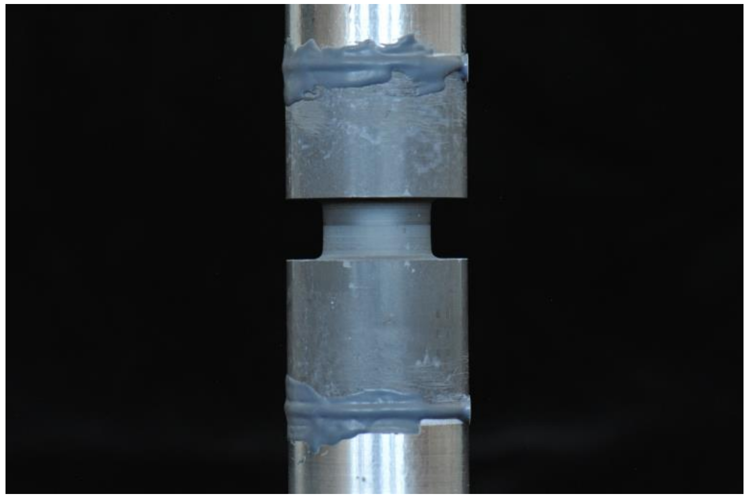


- The compressive modulus of an 80 vol.% composite made of a soft elastomer is ~125,000 psi, which is ~700X that of the silicone polymer.
- The compressive yield strain is 3.4%, but strains as high as 7% did not result in failure.
- We conclude that even soft elastomeric polymers give composites with excellent compressive strength.
- This same composite failed at a tensile strain of 0.1%.

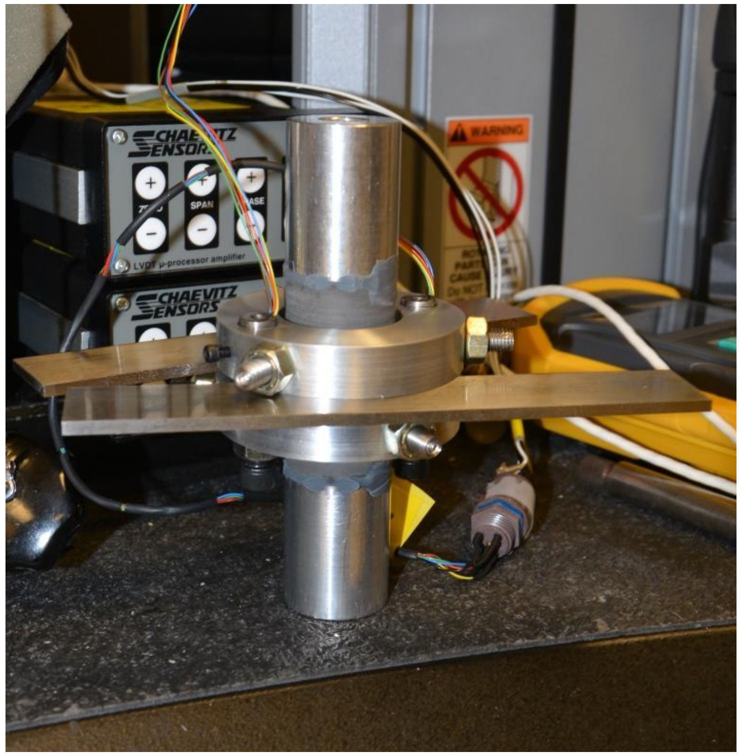
Composites of "glassy elastomers"

- We have identified two thermosetting resins that produce glassy polymer networks that have remarkable failure strains.
- One of these polymers was formulated at by Matt Celina, Sandia, the other by industry.
- Both polymers have a tensile modulus in excess of 100,000 psi.
- Tensile strains in excess of 30% are possible for these polymers.
- These resins provide the best route to obtaining the desired tensile strains for highly-loaded magnetic composites.

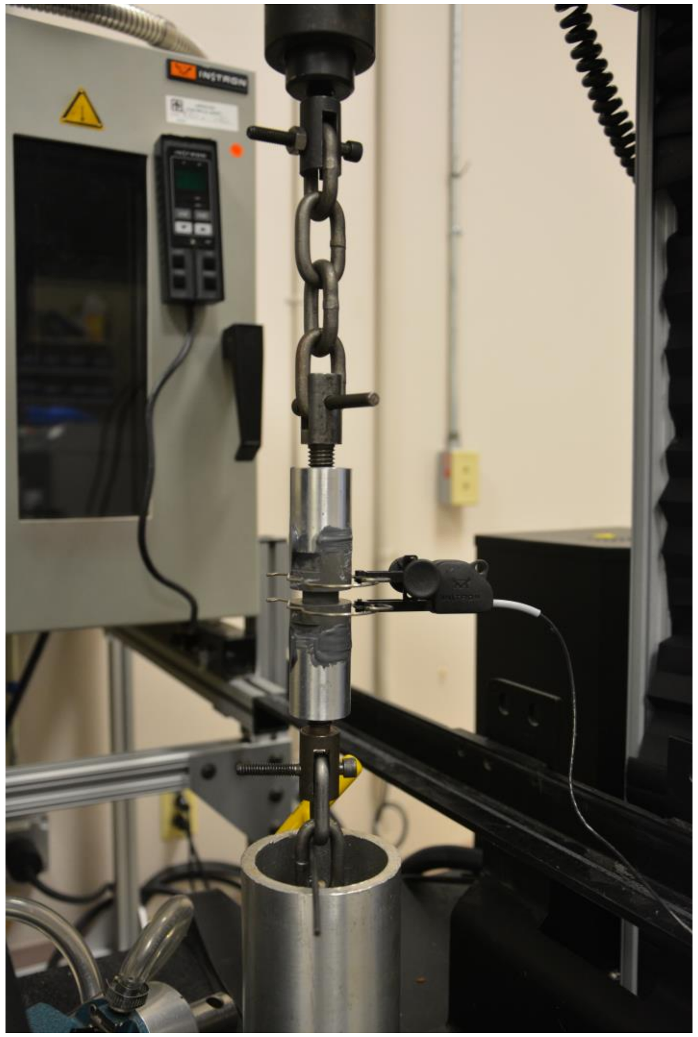
Tensile measurements



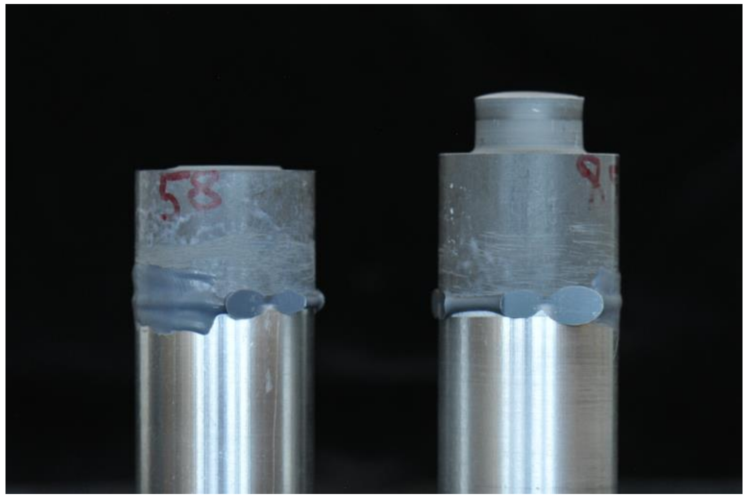
Fixtured Fe composite



Strain gauge jig



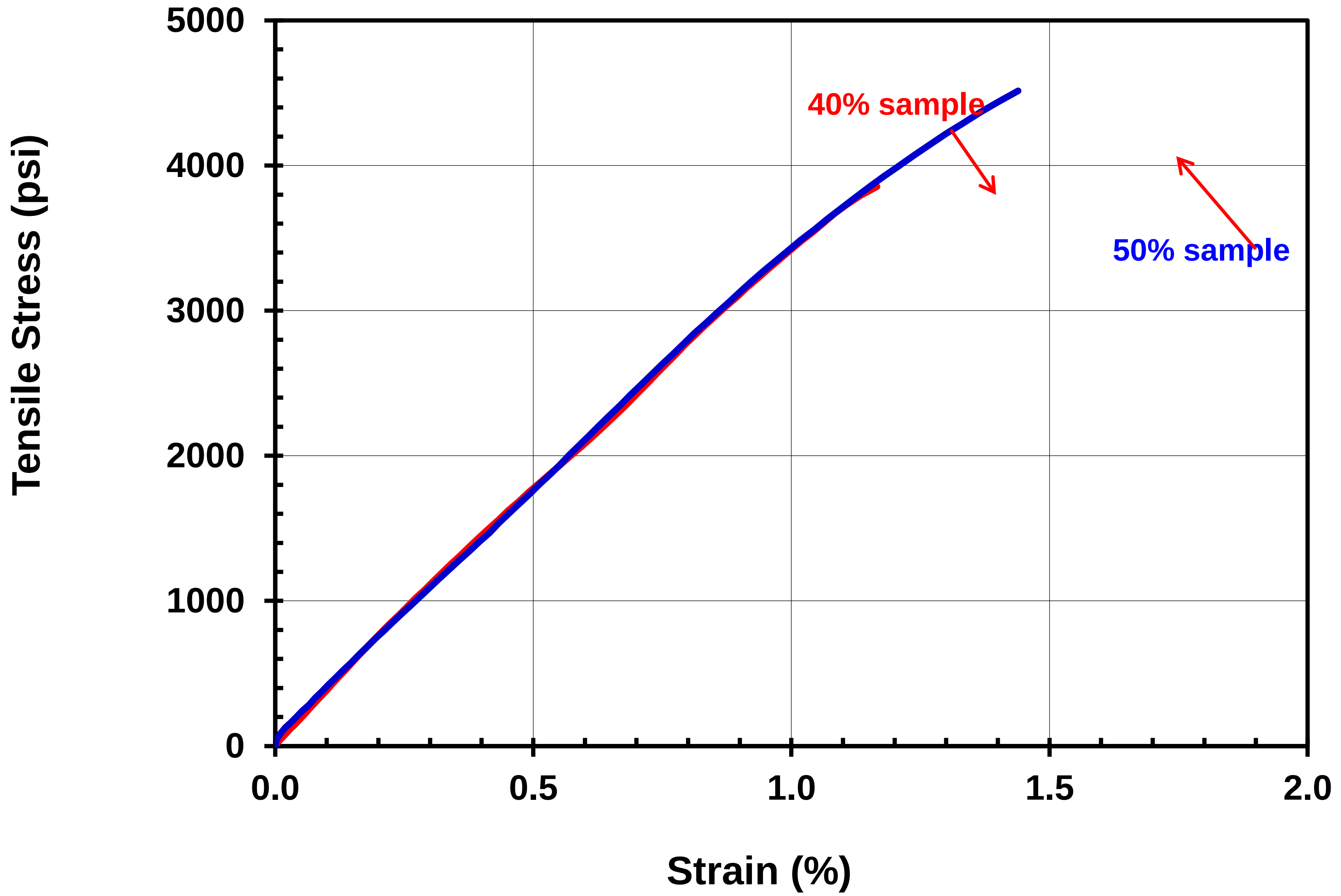
Chains insure a pure tensile load



Fractured sample does not show necking

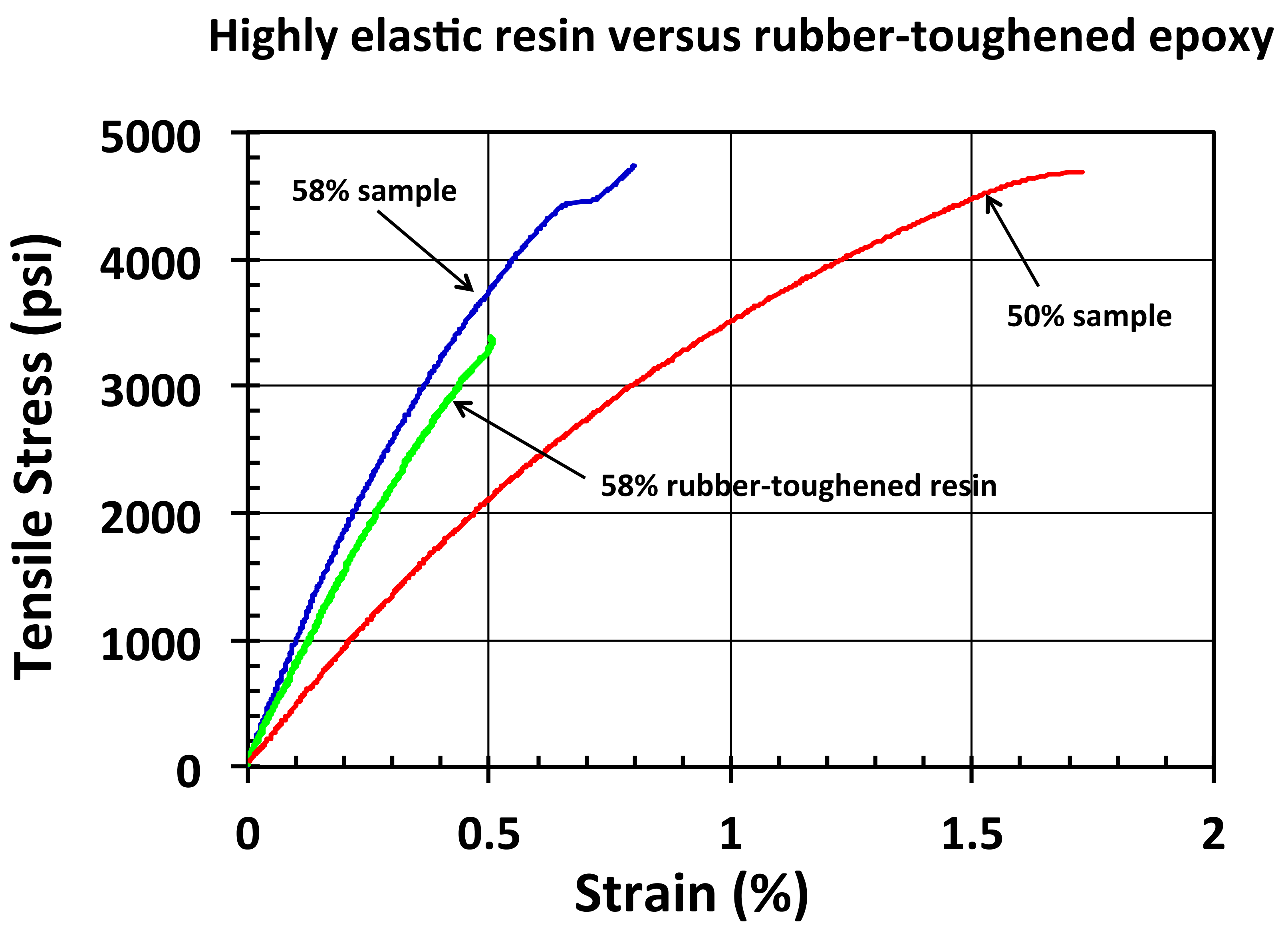
Sandia formulated rubber-modified epoxy

HyPox™ RF1341 (epoxy/carboxyl-terminated polybutadiene-acetonitrile)
+
Jeffamine™ D230 (polyetheramine)



- The tensile moduli of both the 40 and 50 vol.% samples is ~340,000 psi, more than 3X the requirement.
- Strains at failure as high as 1.45 % were obtained without observable yield.

Commercial thermosetting resin



- The 58 vol.% sample has a tensile modulus of 740,000 psi, yet has a 0.8% strain to failure, 60% greater than the rubber-modified epoxy.
- The 50 vol.% sample has a modulus of 420,000 psi and a strain to failure of 1.75%. This material would give 650 lbs of lift with the current magnet specs. Further changes to the magnet could increase this value substantially.

Summary/Conclusions

- We have developed strongly magnetic, mechanically stiff composites that have the tensile elasticity attractive for lift magnet applications for energy storage flywheels.
- These composite magnets exhibit ideal magnetism and ultrafast response.
- Composite magnets made of “glassy elastomers” exhibit tensile moduli in the range of 420,000-740,000 psi, yet can support maximum tensile strains ranging from 0.8-1.75%.
- Optimizing the lift magnet has tripled the lift force at fixed wall power and a further 2.7x increase is readily possible.
- We have two series of samples awaiting tensile testing and one sample undergoing fatigue testing cycles from 0.25-1.0%.

Future Tasks

- Conduct fatigue testing under tensile strain. The composite must survive 100,000 cycles of 0.25-1% tensile strain.
  - This may require improvements in the mechanical properties of the composites.
  - We will surface functionalize the Fe particles to improve adhesion of the cured resin.
- Once the final composite material is specified, and the final permeability known, we will fully optimize the lift magnet geometry to give the required lift at the lowest possible power.
- We will team with industry to develop a practical method of lift ring fabrication.

Thanks to the DOE Office of Electricity and especially to Dr. Gyuk for his dedication and support to the ES industry and Sandia's Energy Storage Program.

Questions?

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