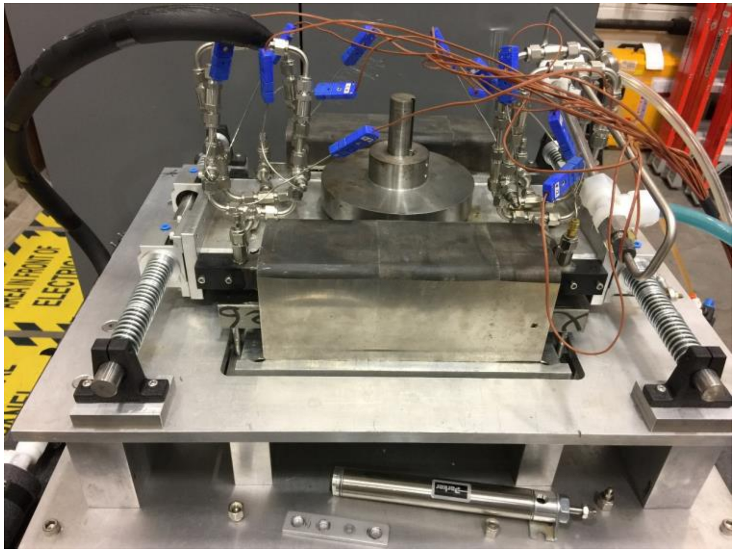
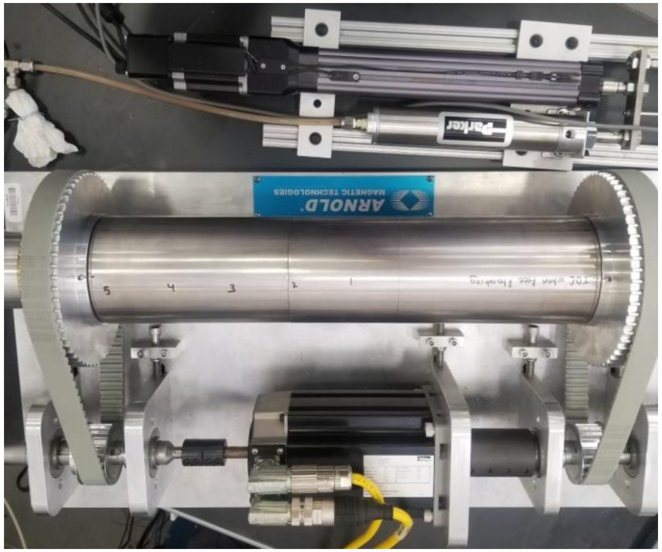
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Non-Vapor Compression - Solid-State Magnetic Cooling





Oak Ridge National Laboratory
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Project Summary

Timeline:

Start date: 10/1/2015

Planned end date: 9/31/2019

Key Milestones

1. Milestone 1; Complete baseline characterization
2. Milestone 2; Complete evaluation with Galinstan

Budget:

Total Project $ to Date:

- DOE: $1,183,523
- Cost Share: $340,000

Total Project $:

- DOE: $1,400,000
- Cost Share: $340,000

Key Partners:

VAC® VACUUMSCHMELZE

Project Outcome:

Prove performance advantage of using metal heat transfer medium over liquid and disseminate the results in publication.

This technology's primary energy savings technical potential is 1.27 quads/yr. in 2030, per DOE-BTO's P-Tool.

Team

Ahmad Abuheiba: PI and project manager. System level integration and operation
Ayyoub Momen: Subprogram manager, technical assistance and overall direction
Mingkan Zhang: modeling and experimental work
Alexander Barcza: MCM expertise
Hugo Vieyra: MCM forming expertise

Collectively, the team has expertise in MCM characterization, MCM forming, system-level integration and analytical and numerical modeling.

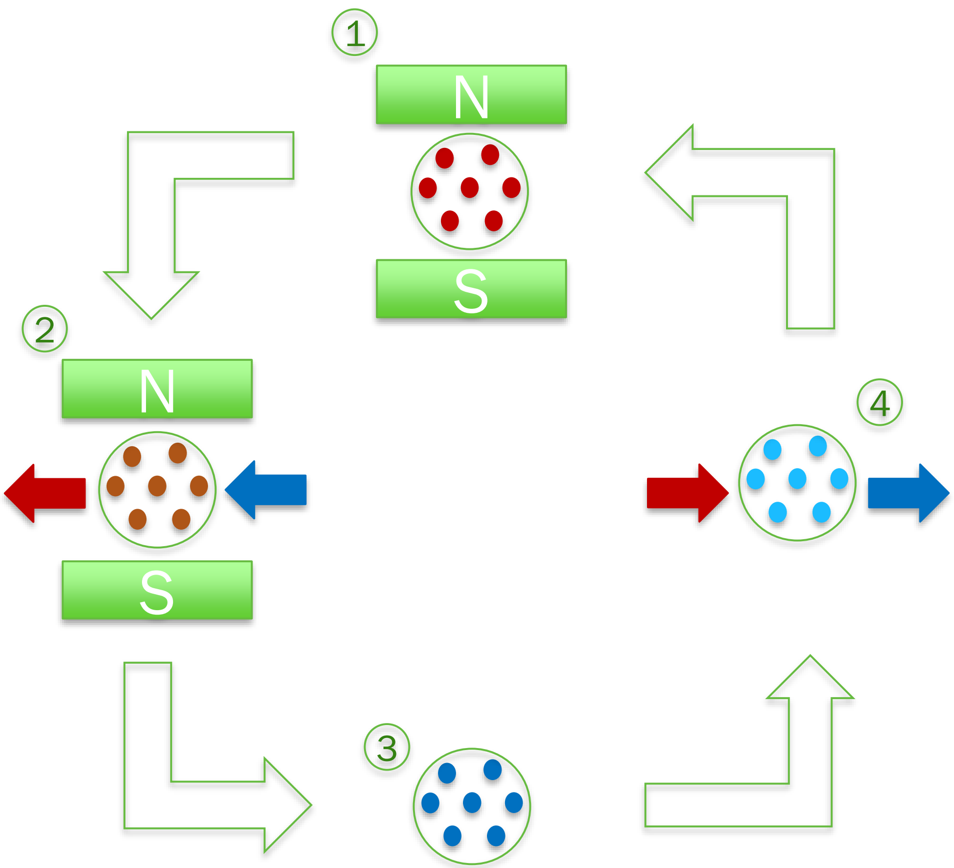
ORNL holds provisional patent of solid state magnetic cooling, provides access to HPC and modeling expertise.

Vacuumschmelze is one of the major MCM developers and suppliers worldwide.

Magnetic Cooling

- A magnetocaloric material (MCM) heats when exposed to magnetic field and goes back to initial temperature when magnetic field is removed.
- That property is exploited in a cyclic manner to produce cooling.
- The cyclic process is called Active Magnetic Regeneration (AMR).

Principle of operation



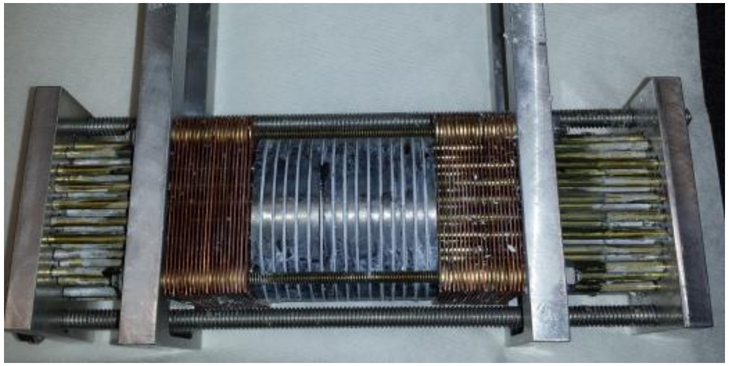
Challenge

Problem Definition:

Despite its energy reduction promise, the potential of magnetic cooling remains unrealized because of its low specific cooling power. The maximum cooling power of a magnetic cooling device is limited by the highest feasible operating frequency. This limitation is driven partly by mechanical design but mainly by the speed of heat transfer into and out of the system.

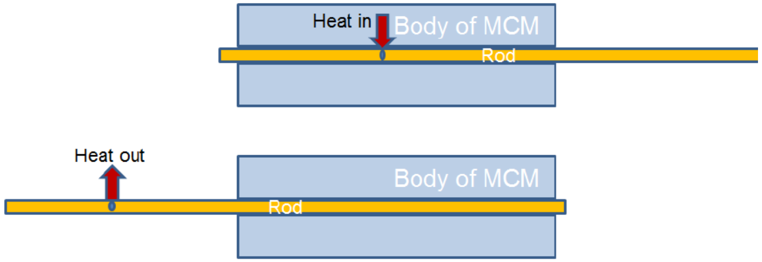
Approach

- To increase specific cooling power of an AMR device, higher operating frequency is needed.
- At higher frequency, shorter time is available for heat transfer.
- Metallic heat transfer medium (HTM) allows one order of magnitude higher frequency than fluidic HTM while, an order of magnitude higher operating frequency, yields an order of magnitude higher cooling power.



Conventional

Innovation

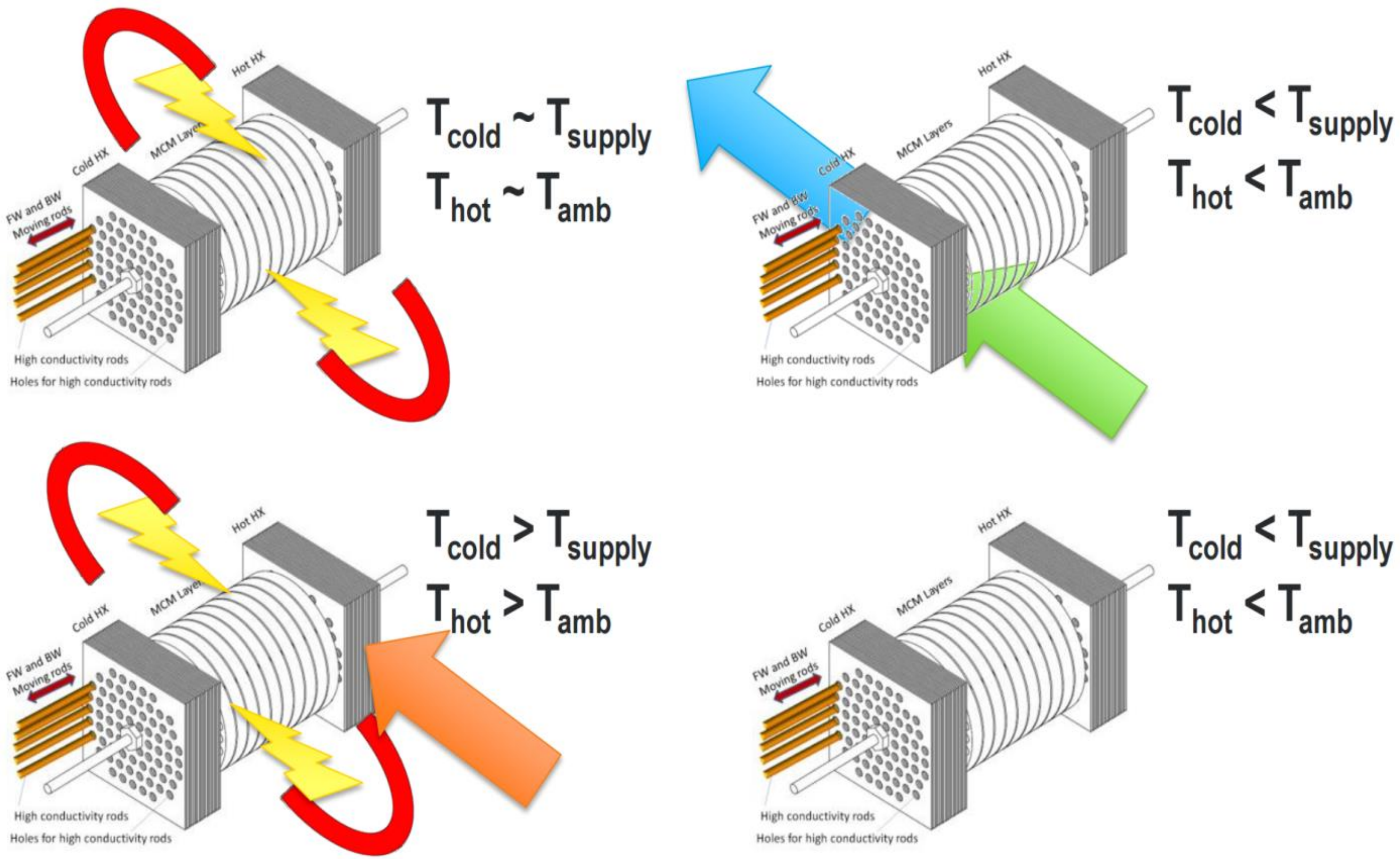


Metals transfer heat much faster than liquids.

Ideally $\alpha = \frac{k}{\rho\, C_p} \Rightarrow \frac{\alpha_{Metal}}{\alpha_{Liquid}} = O(100)$

Simulation showed 8 times more heat transfer when interface resistance included.

Approach


Hot HX
MCM Layers
Cold HX
FW and BW Moving rods
High conductivity rods
Holes for high conductivity rods
$T_{cold} \sim T_{supply}$
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Approach

The project has two parallel paths

Prove and Demonstrate Concept

Use liquid metal (Galinstan) as a substitute for metallic sheets/rods

Develop MCM Forming and treatment Processes

Manufacture MCM blocks to prescribed surface finish tolerance

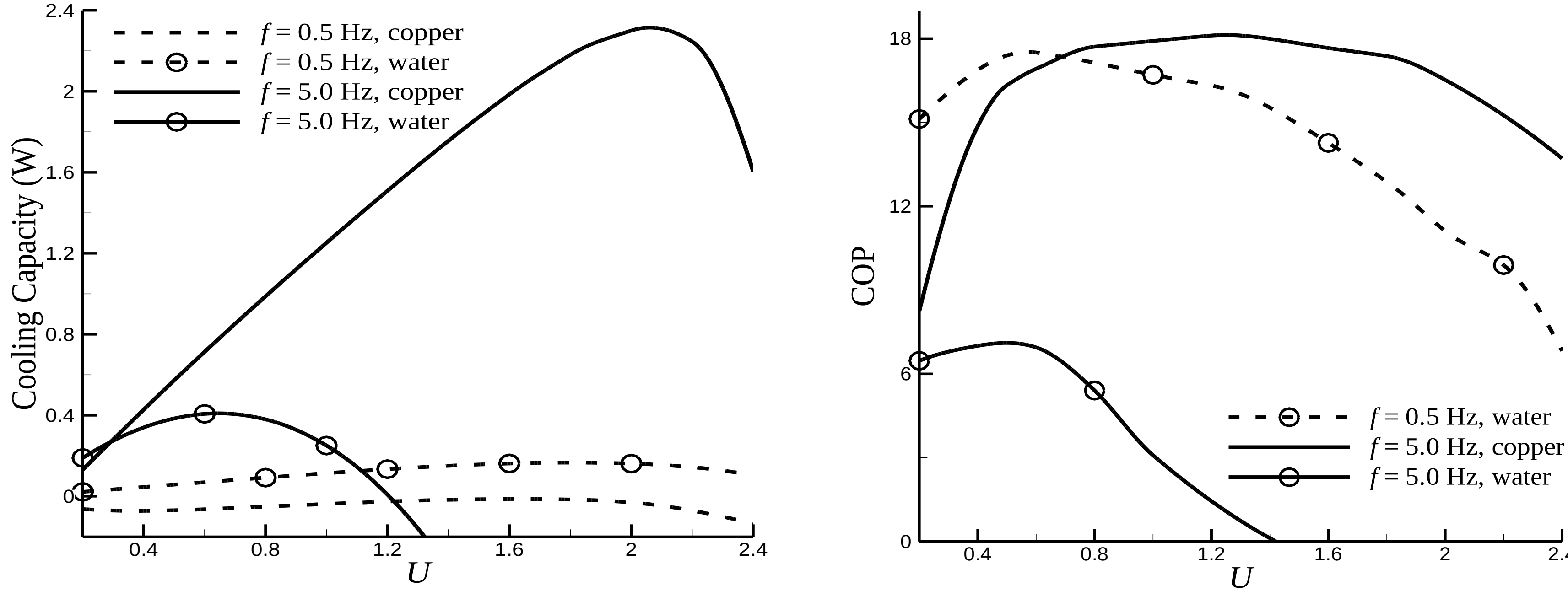
Impact

- Magnetic cooling could achieve 25% energy savings compared to state of the art vapor compression. Total technical potential is 1.27 Quad.
- Realization of its energy benefit is hindered by its low specific cooling power:
  - Requires large amount of MCM/Watt cooling.
  - Drives cost/refrigeration-ton up.
  - Increases weight significantly compared to baseline technology.
- Higher operating frequency mitigates all three barriers.
- Metallic heat transfer medium enables higher frequency operation well beyond the limit of any fluidic heat transfer medium.
- The current project demonstrate the feasibility of the concept.

Progress — Summary

- The project is at its late stages, with a planned end date of September, 2019.
- To date, the following has been accomplished:
  - Successfully developed process to tape cast MCM and post treat them while maintaining their magnetocaloric property. This process is scalable and has enough throughput for mass production.
  - Zhang, Mingkan; Mehdizadeh Momen, Ayyoub; and Abdelaziz, Omar, "Preliminary Analysis of a Fully Solid State Magnetocaloric Refrigeration" (2016). International Refrigeration and Air Conditioning Conference. Paper 1758.
  - Numerical model was developed and documented in a journal paper (*Mingkan Zhang, Ayyoub Mehdizadeh Momen, Ahmad Abu-heiba, Omar A Abdelaziz, A numerical analysis of a magnetocaloric refrigerator with a 16-layer regenerator, Scientific Reports, Volume 7, Issue 1, 2017*).
  - Commercialization report was published that identifies barriers of and market entry points (*Sikes, Karen, Blackburn, Julia, Abdelaziz, Omar, Mehdizadeh Momen, Ayyoub, and Abu-Heiba, Ahmad. Bringing Solid-State Magnetocaloric Cooling to the Market: A Commercialization Plan. United States: N. p., 2017. Web. doi:10.2172/1435268*).
  - Prototype was built and benchmarked using water as heat transfer medium.

Progress — Modeling



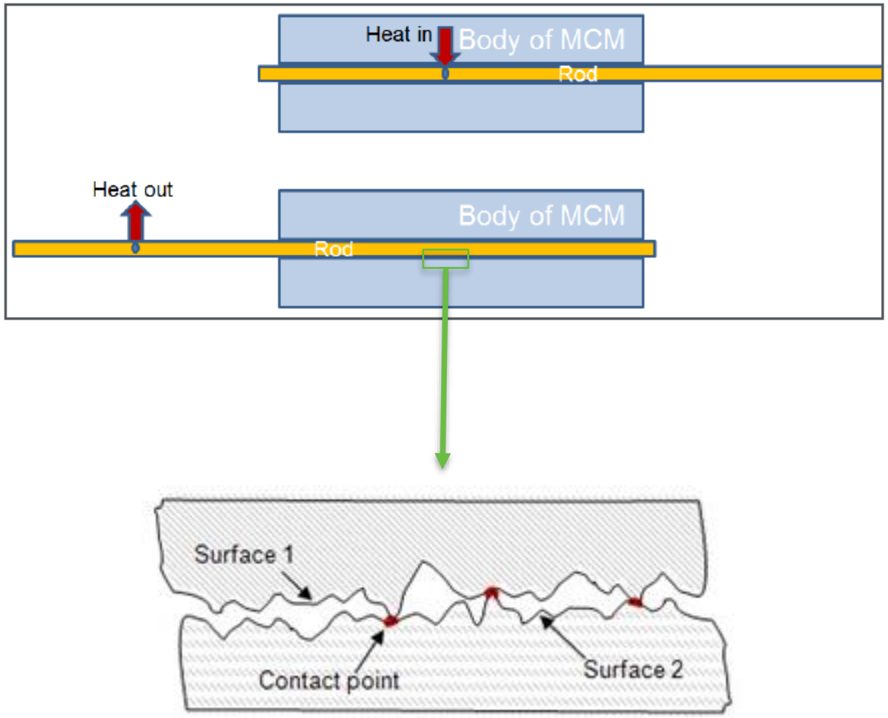
Cooling Capacity (left) and COP (right) as a function of utilization with *f* = 0.5 and 5.0 Hz

Take away:

- Metals can significantly enhance the heat transfer.
- Metals can significantly increase the operating frequency, hence cooling. capacity (up to 8X). Higher capacity = more compact = lower cost.
- Metals **cannot** significantly increase the system COP.

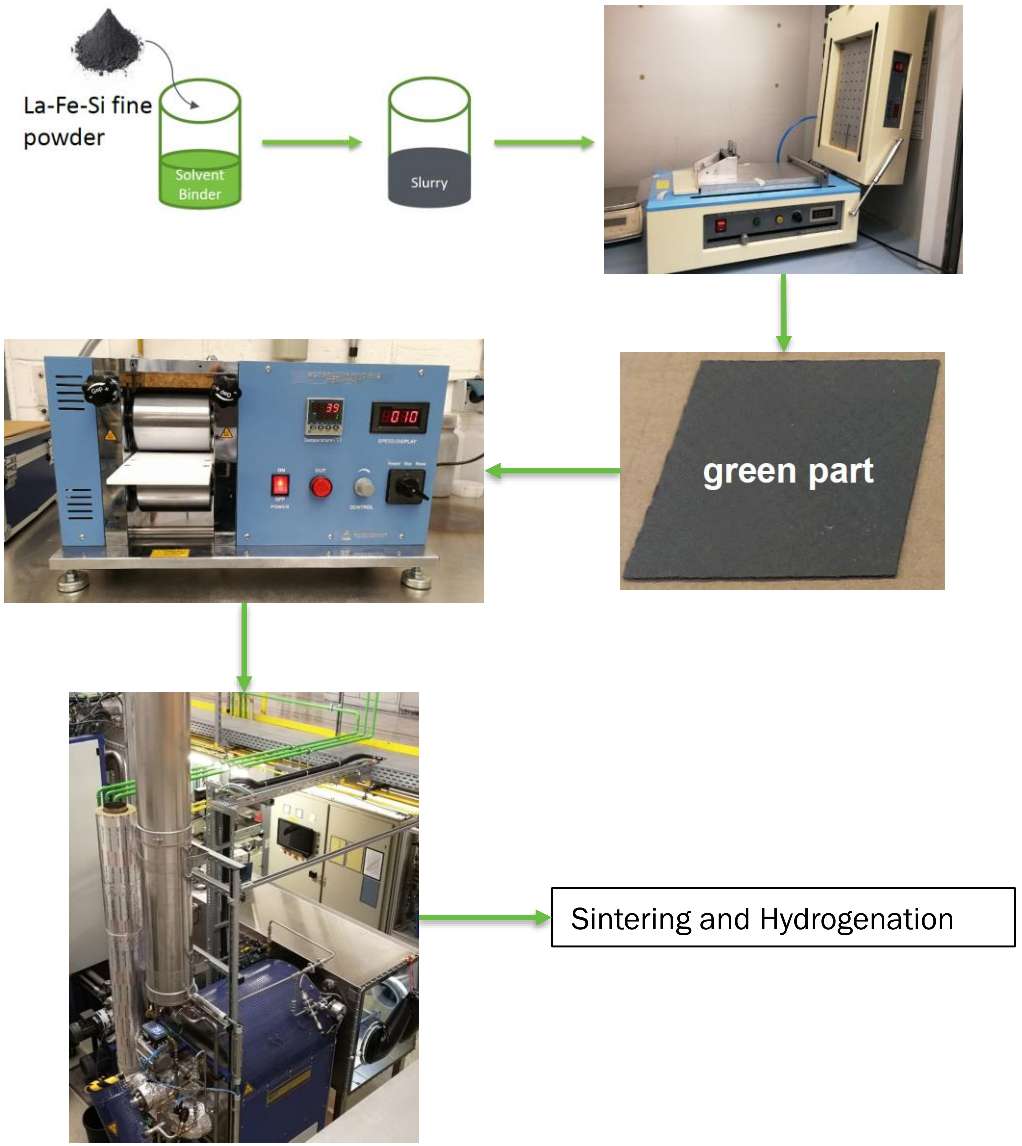
Progress — MCM forming

- Previously reported: Top down and bottom-up manufacturing (Refer to BTO Peer Review).
- Surface quality is important for good contact (lower heat transfer resistance) and structural integrity.
- Top down manufacturing was successful but has low utilization of MCM stock.
- Tape casting process has since been automated and proven.
- Post treatment process of tape-cast MCM was developed and preservation of MCE was proven.



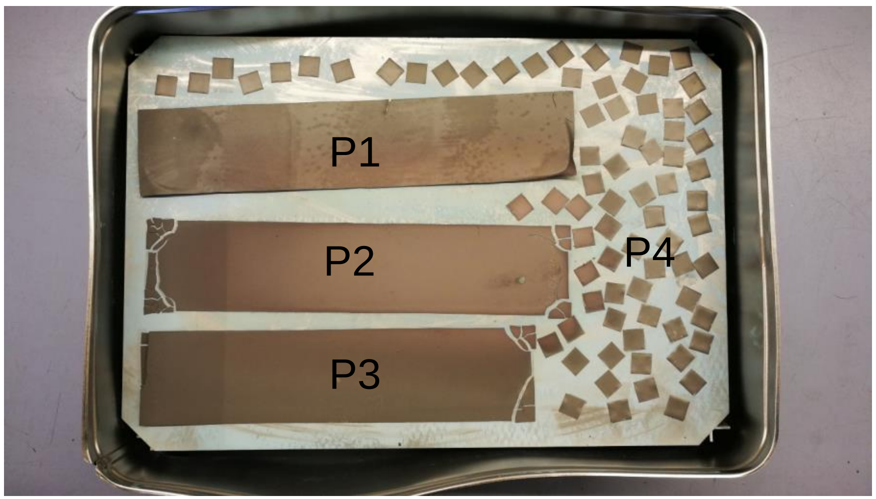
Progress — MCM Tape Casting Process

- Slurry is formed and tape cast.
  - Viscosity of slurry and casting speed were optimized for uniformity of thickness and drying.
- The tapes are hot rolled for thickness reduction, better surface quality and higher density.
- The tapes are then heat treated in a debinding furnace to get rid of binding material and oxygen.
- The tapes are then sintered and partially hydrogynated.

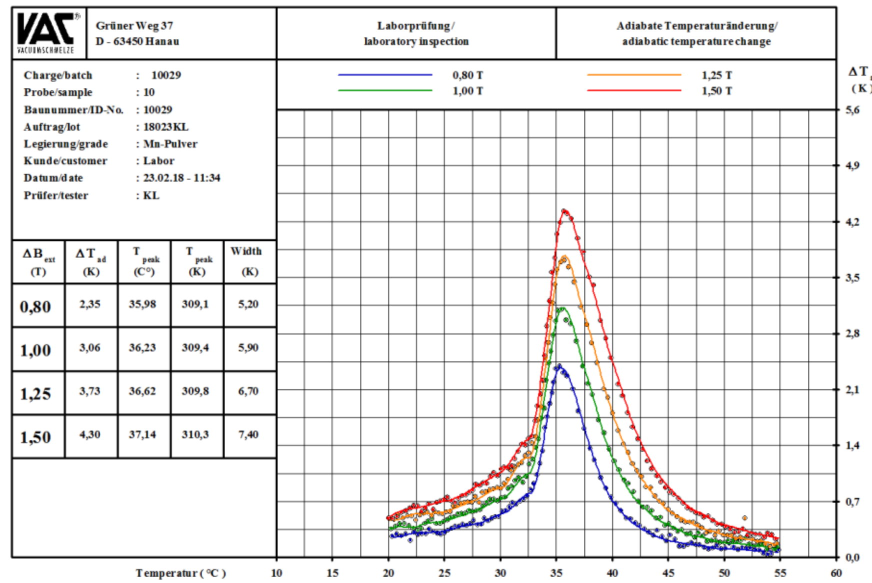


Progress — MCM Tape Casting Results

Tapes cast with different slurry compositions. All showed very good surface quality except P1. Density of the tapes is 7.1 kg/m^3. Thickness is < 500 µm.



MCM magnetic properties are affected by heat. It was important to ensure the tape cast parts retained their magnetic properties.

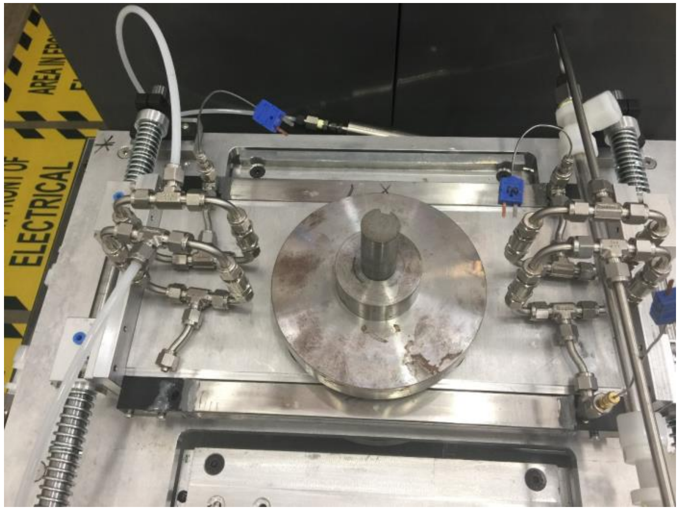


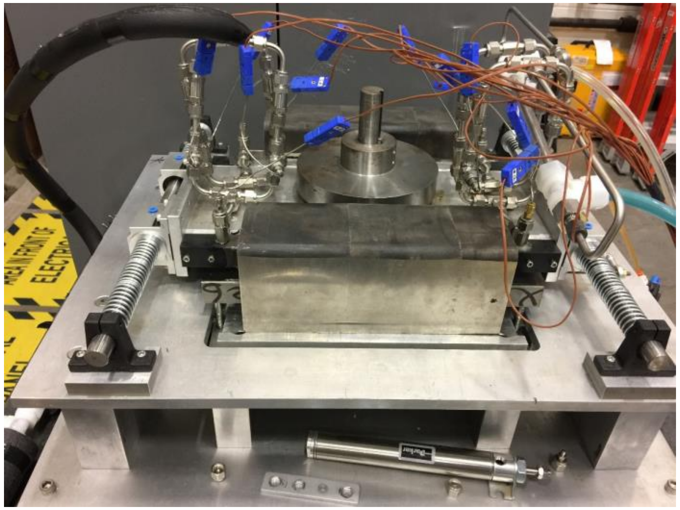
ΔB_{ext} (T)	ΔT_{ad} (K)	T_{peak} (C°)	T_{peak} (K)	Width (K)
0,80	2,35	35,98	309,1	5,20
1,00	3,06	36,23	309,4	5,90
1,25	3,73	36,62	309,8	6,70
1,50	4,30	37,14	310,3	7,40

Manufactured plate was tested in calorimeter to characterize its magnetocaloric effect. The graph shows that it retained its magnetic properties.

Progress — Prototype 1

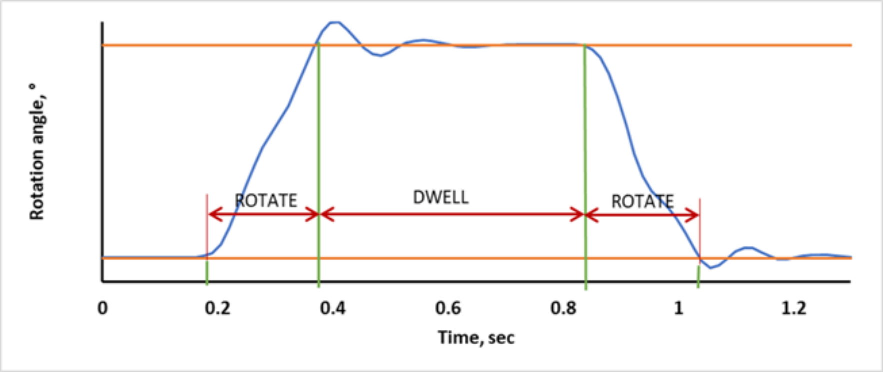
- Magnets are stationary.
- A cam drives the regenerators in and out of the magnetic field and drive syringe pumps.
- No temperature span!
- After exhausting possible adjustable parameters, it was found out the magnetic field was only 0.3 Tesla (Too low!) due to the manufacturing defect or handling errors.





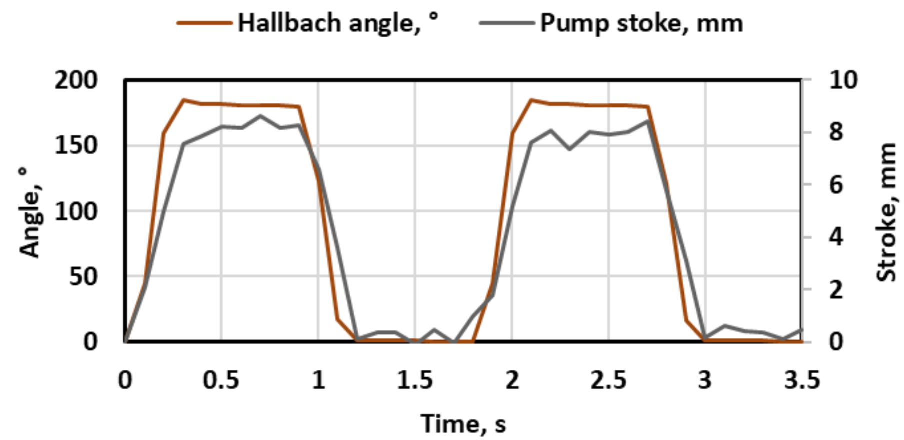
Progress — Prototype 2

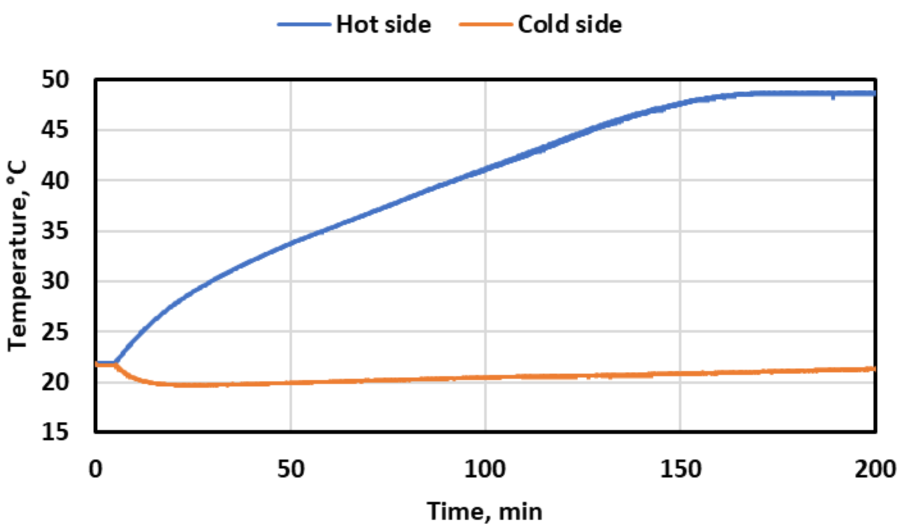
- Hallbach array magnet driven by a servo motor.
- Separate pumping system (linear actuator + hydraulic cylinders).
- Magnetic field goes from 1.35T to 0.45T with 180° rotation.
- Timing can be precisely controlled through LabVIEW.



Progress — Prototype 2

- Upper graph shows timing of rotation and pumping for 0.8Hz, 8mm pumping stroke and 30ms delay between magnet rotation and initiation of pumping.
- Lower graph shows adiabatic temperature span for 0.5Hz, 15mm pumping stroke and 150ms delay.





Stakeholder Engagement

- Vacuumschmelze is one of the major MCM developers and suppliers worldwide.
- ORNL holds patent US20160146515A1, Magnetocaloric refrigeration using fully solid state working medium.
- Commercialization study conducted.

Experimental results

Outreach to OEM

Remaining Project Work

1. Validate and calibrate the numerical model.
2. Prepare the prototype for Galinstan operation:
   a. Higher thrust pumping system.
   b. Higher pressure tubing.
3. Characterize performance with Galinstan:
   a. Operate at highest possible frequency.
   b. If needed, use the model to extrapolate performance at higher frequencies.
4. Document performance enhancement in journal paper.
5. Outreach to potential OEMs.

Galinstan is a metal that is in liquid phase at room temperature.

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $1.74M ($1.4M DOE, $340K Cost Share)
Variances: None
Cost to Date: $1.15M DOE, $340K Cost Share
Additional Funding: None

Budget History					
10/1/2015 – FY 2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1.15M	$340K	$250K	0	0	0

Project Plan and Schedule

Delays in schedule and missed milestones were caused by:

- Delays in approval of subcontract with Vacuumschmelze
- Supplied permanent magnets did not meet requirements (expected 1.5T, delivered 0.3T)

Project Schedule									
Project Start: 10/1/2015		Completed Work							
Projected End: 9/30/2019		Active Task (in progress work)							
		Milestone/Deliverable (Originally Planned) use for							
		Milestone/Deliverable (Actual) use when met on time							
	FY2016				FY2017				
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	
Past Work									
Q1 Milestone: Review state-of-art									
Q2 Milestone: Develop AMR 1st order model									
Q3 Milestone: Proof of concept AMR unit									
Q4 Milestone: Demonstrate proof of concept									
Q4 Milestone: Post treatment process of MCM									
Q5 Milestone: Optimize hydrogenation of MCM									
Q6 Milestone: Build 2nd generation unit									
Q7 Milestone: Evaluate 2nd generation unit									
Q8 Milestone: Complete cost analysis									