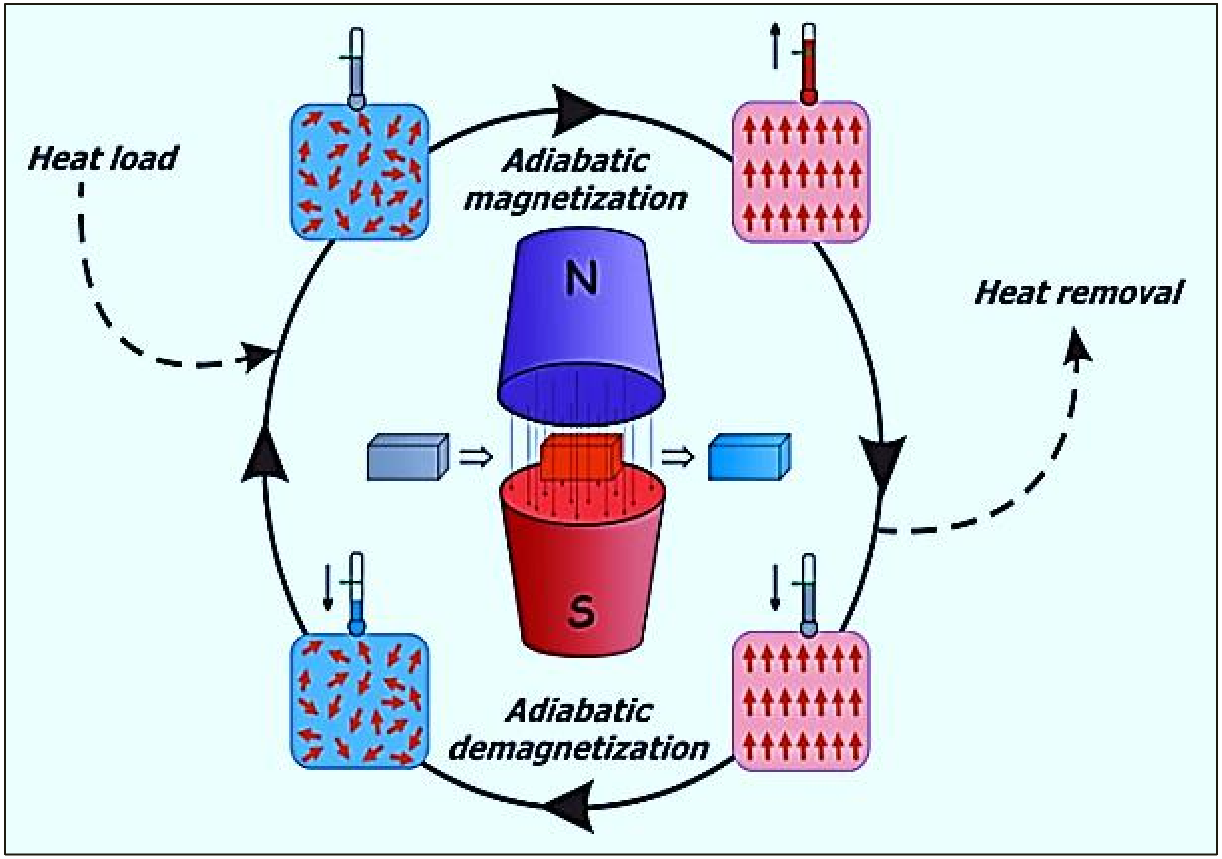
Magnetocaloric Refrigerator Freezer

2017 Building Technologies Office Peer Review



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Project Summary

Timeline:

Start date: August 1, 2013 (FY 2014)

Planned end date: January, 31, 2017

Key Milestones

1. Evaluation of MCM microchannels through collaboration with GEA (6/30/2016)
2. Improve the regenerator structure (9/30/2016)
3. Final optimization, testing and drafting final report (12/30/2016)

Budget:

Total Project $ to Date:
- DOE: $1588k
- Cost Share: $1689k

Total Project $:
- DOE: $2049k
- Cost Share: $2189

Key Partners:

General Electric Appliances

Project Outcome:

The main objectives of the magnetocaloric refrigerator project were to achieve:

☑ 100 watts of cooling

☑ 100°F temperature span

Purpose and Objectives

Problem Statement:

Decades of R&D efforts have gone into making a high performance, magnetocaloric refrigeration machine. Developing such a machine presents many challenges including material, flow hydrodynamics, rotating components, heat transfer limitation, and system cost. This project focuses on "developing the new manufacturing processes required to make microchannels from magnetocaloric material (MCMs)."

Target Market and Audience:

The principal target market is residential and commercial refrigerators (>200M units). In addition, the technology has the potential to be used in larger-scale HVAC, drying, and industrial heating/cooling applications.

Impact of Project:

Cooling/heating systems utilizing the magnetocaloric effect can be significantly more efficient than today's refrigeration systems.

- Final product will be a full scale magnetocaloric refrigerator-freezer.
- The success criteria includes achieving a 100°F temperature span and approximately 100 watts of cooling capacity at 25% better efficiency.
  - Near-term: develop a feasible design with emerging MCM materials
  - Intermediate-term: design a magnetocaloric refrigerator-freezer
  - Long-term: introduce the technology to the market

Approach

Approach:

- Develop a manufacturing process for forming MCM microchannels
- Enhance the heat transfer rate, which translates into a higher system capacity
- Develop a high-efficiency magnetocaloric system design

Key Issues:

- Solid/liquid interstitial heat transfer limits the performance of the machine
- Manufacturability of MCM to make the shapes is a big challenge

Distinctive Characteristics:

- Develop unique additive manufacturing followed by a sintering process to fabricate MCM microchannels
- 3D MCM microchannels through non-traditional manufacturing
- Solid-state magnetocaloric machine

Progress and Accomplishments

Accomplishments:

- MCM successfully 3D printed in the form of microchannels
- Magnetocaloric microchannel successfully developed using a novel approach
- Patent 1: MCM microchannel has been patented
- Patent 2: Fully solid-state magnetocaloric machine has been patented
- Patent 3: Process of 3D printing of MCM microchannels
- Multiple publications/presentations
- GEA has developed several configurations of the prototype machines

Market Impact:

This project can potentially save 0.75 quads of energy

Awards/Recognition:

Recognized research by former EERE Assistant Secretary

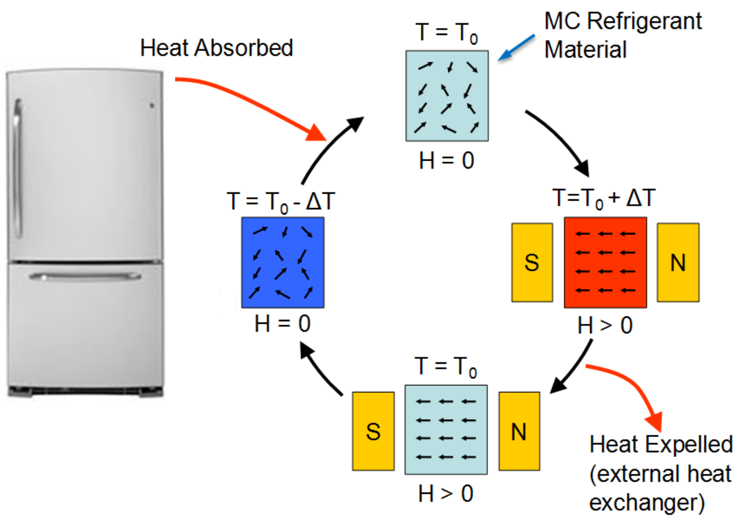
Lessons Learned:

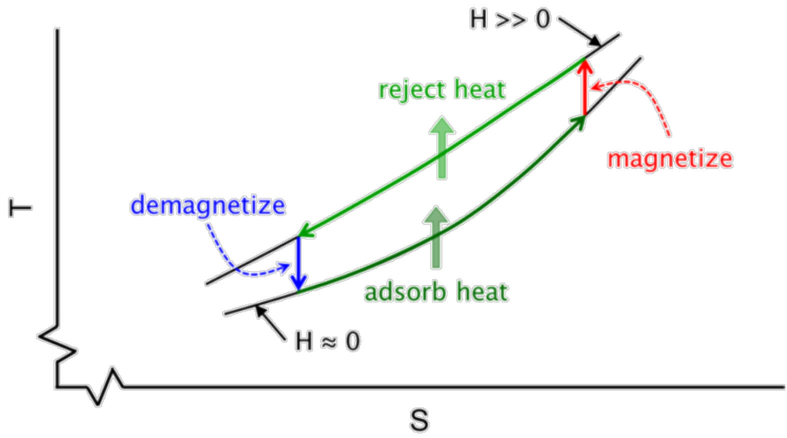
Pressure drop of MCM particulate regenerator is one of the primary loss sources of the MCM system. R&D needs to be devoted to this area.

How Magnetic Refrigeration Works

- Cycle starts with MC material (MCM) at T_0.
- MCM is placed inside a higher magnetic field resulting in MCM temperature increase to $T_0 + \Delta T$.
- Heat is rejected from the MCM to ambient while inside the higher magnetic field, reducing its temperature to T_0.
- MCM is removed from the higher magnetic field, resulting in reduced temperature to $T_0 - \Delta T$.
- Heat is absorbed by MCM from a refrigerated compartment; increasing its temperature to T_0 and the cycle is repeated.

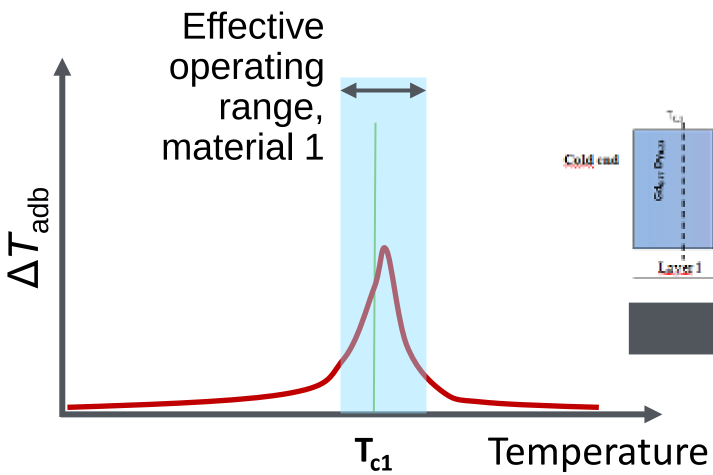
The magnetic refrigeration cycle is essentially a Brayton cycle with the potential for continuous regeneration that can approach Carnot efficiency.

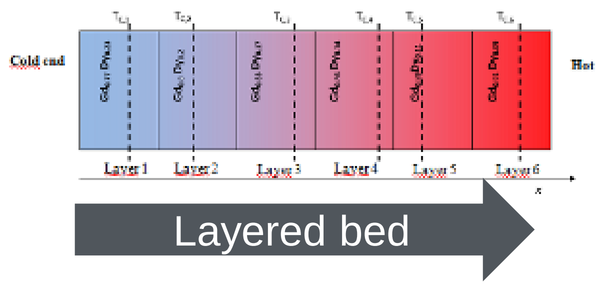


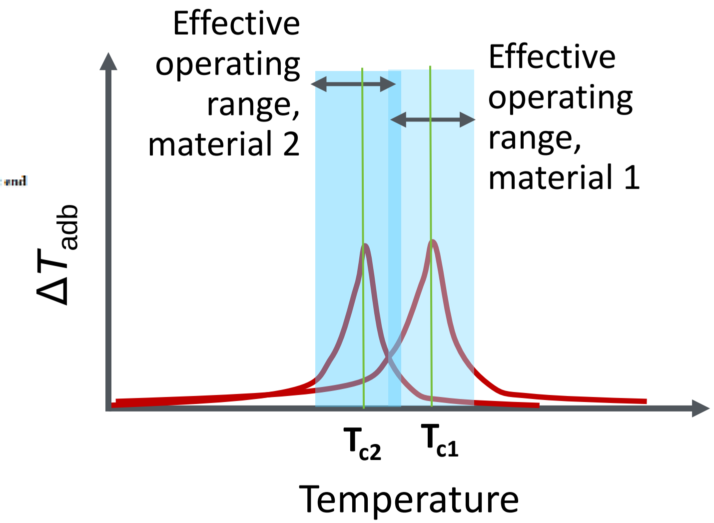


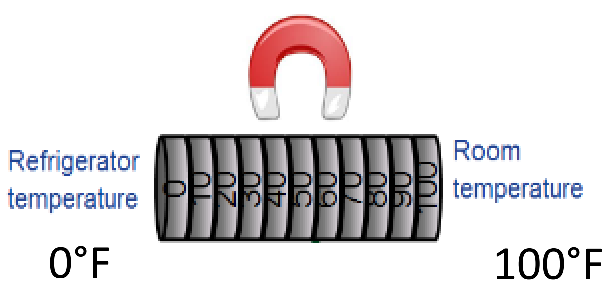
Achieving Large Temperature Span

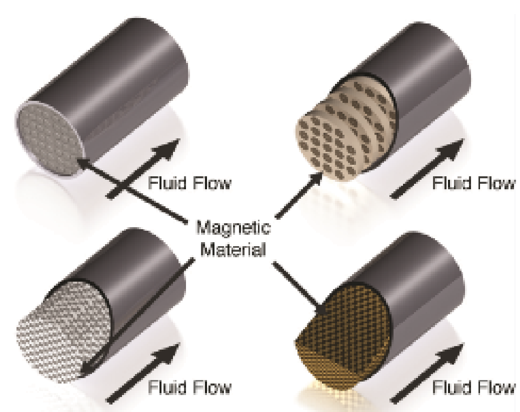
- Use different MCM alloys with different curie temperatures and layer atop one another.







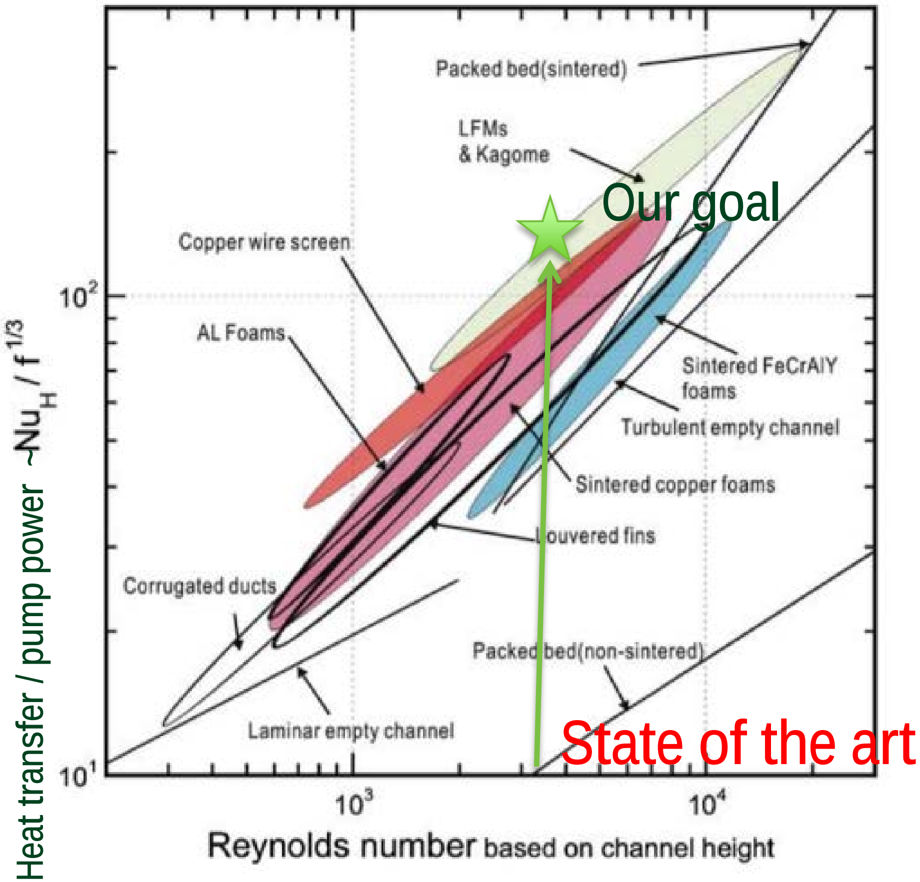




Impact of Finding a Way to Fabricate Microchannels from MCM

In competition between pressure drop and heat transfer, microchannels will win over a packed particle bed.

If we could develop a manufacturing process to make microchannels from MCM, then we could get a better heat transfer rate at the acceptable range of pressure drop and achieve a higher COP machine.



J. Tian, T. Kim, T.J. Lu, H.P. Hadson, D. T. Qucheillilt, D.J. Sypeck, H.N.H. Hadky. Int. J. Heat and Mass Transfer, 2004.

Message of the study:

- Heat transfer in porous media is mainly a function of ε, area.
- Pressure drop in porous media is mainly a function of ε, area, **orientation.**

Developing Manufacturing Process to 3D Print MCM Microchannels

Approach 1: Resolution in printing

Parameters studied:

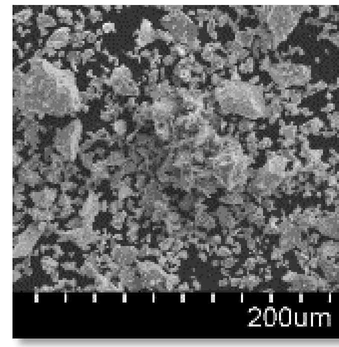
- Particle shape
- Particle size
- Orientation
- Process and more

✓ Two MCM powders were printed with two different particle shapes

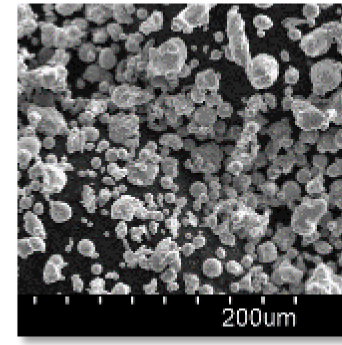
✓ 150-200 microns microchannels printed with one of these powders

✓ Enhanced structures printed

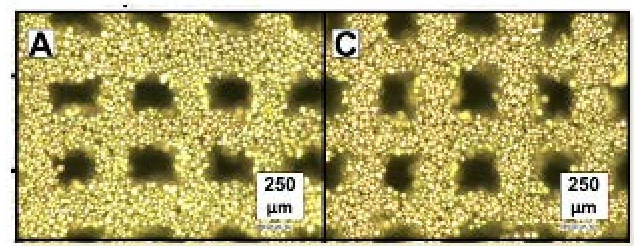
Irregular Powder

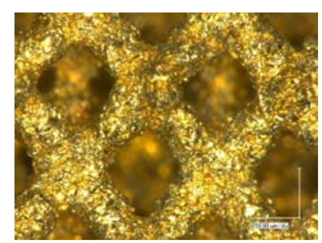


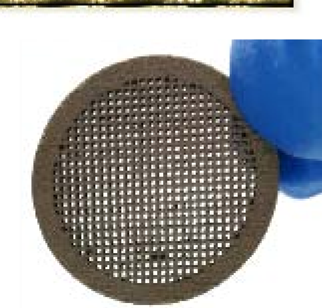
Regular Powder



Standard saturation: 300 micron pores







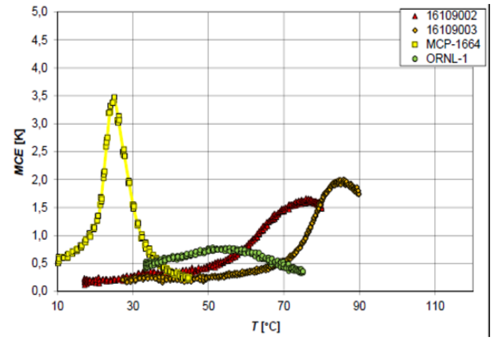
Developing Manufacturing Process for Sintering and Pressing MCM

Sintering and pressing MCM is very challenging and a necessary, intermediate manufacturing process in MCM microchannel development.
Note: Sintering is the process of compacting and forming a solid mass of material by heat and/or pressure without melting it to the point of liquefaction.

Very Challenging Process

After 8 months of R&D effort:
- MCM die was successfully pressed
- Mold-cast MCM parts were successfully sintered to high densities (up to 99% of material density)

Findings:
- Sintering conditions, including the right atmosphere, temperature, oxygen level, and type of furnace were realized.
- Final densities of 97–99% were achieved.



Restoring MCE properties is still a challenge

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Developing a Novel Manufacturing Process for Making 3-Dimensional Microchannels

Approach 2: MCM microchannels

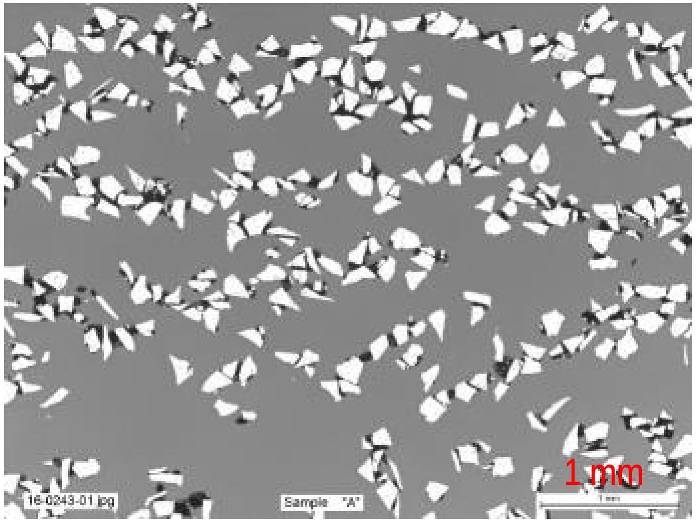
ORNL is working on an innovative way to produce random elongated microchannels.

This solution significantly reduces the pressure drop and provides very high interstitial heat transfer rates. It has the potential to produce random microchannels as small as 20–100 µm, which cannot be achieved by other manufacturing processes.

It is a propriety low-cost method which is different from the printing process.

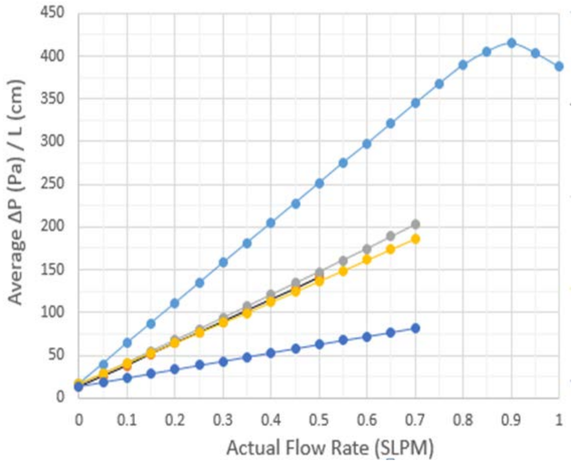
Developing a Novel Manufacturing Process for Making 3-Dimensional Microchannels

MCM microchannels

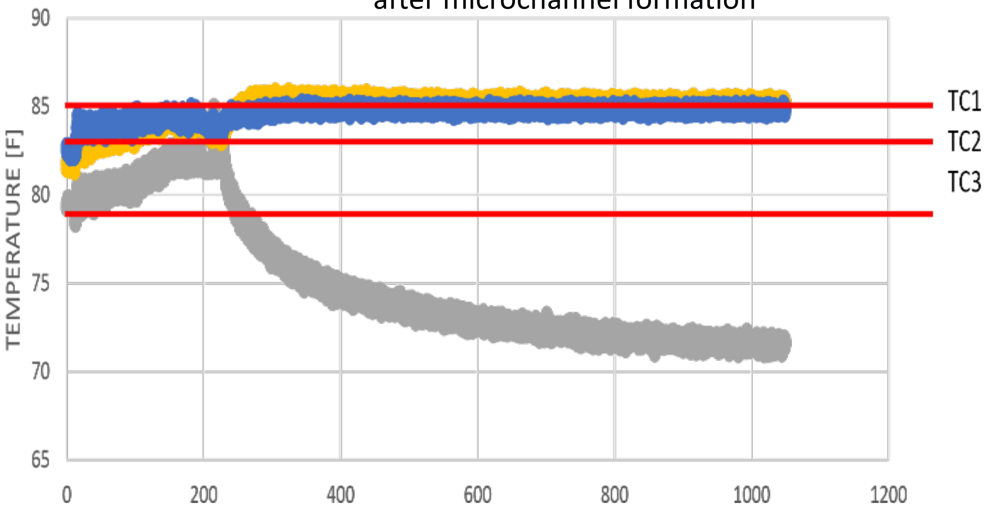


A slice of the fabricated structure

- Up to 10% enhancement of magnetization is achieved.
- Significant improvement in the hydrodynamic characteristics of MCM microchannel is reached.



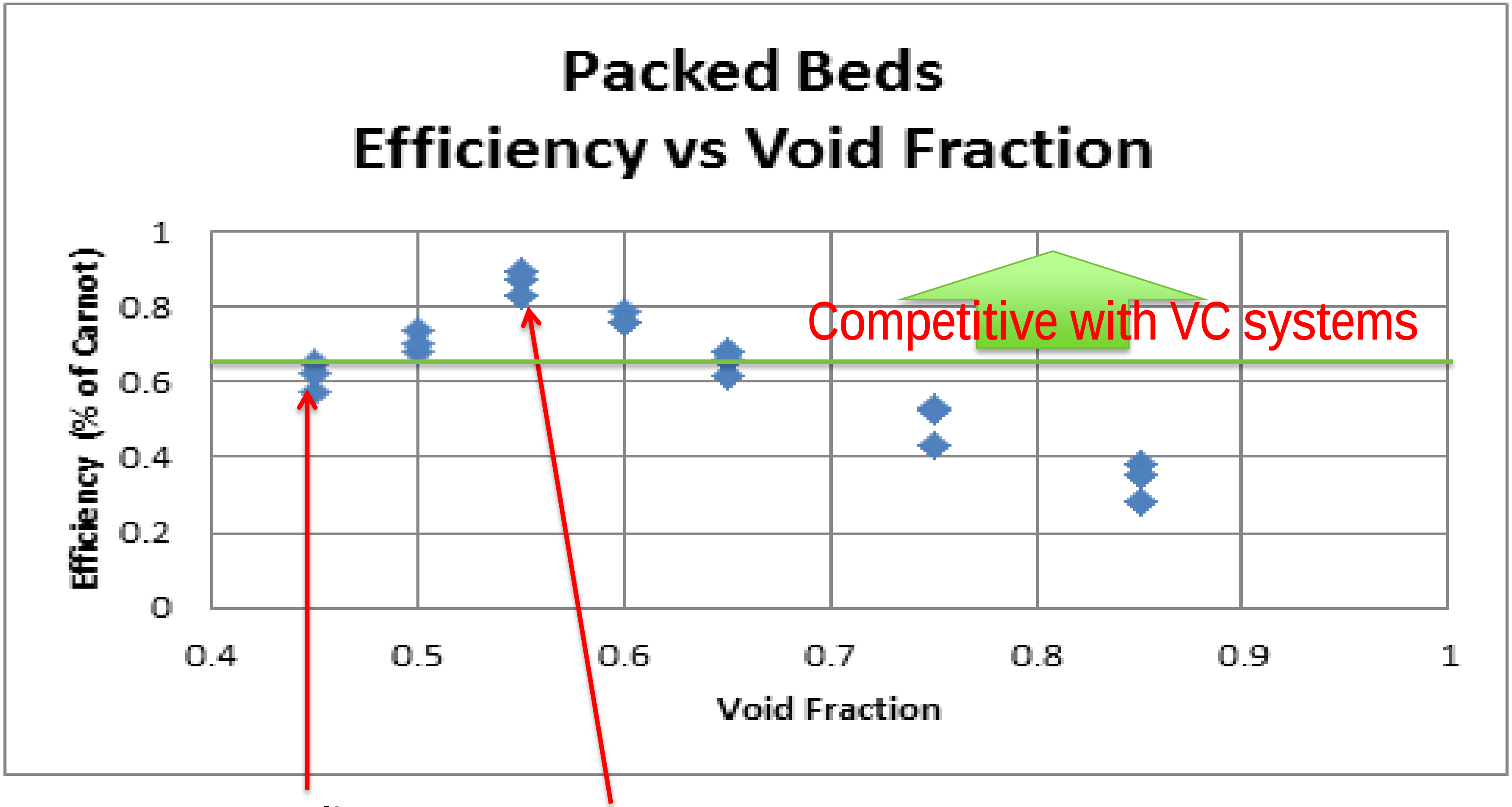
Pressure drop across the MCM before and after microchannel formation



The graph shows the temperature span across the three-stage, 3-dimensional microchannel AMR.

GEA performed 1000 cycles in its prototype magnetocaloric refrigeration unit to achieve this temperature span.

GEA's Recent Simulation will be the Guideline for Future Multi-stage Regenerator Development



Baseline as received powder

New process can do this

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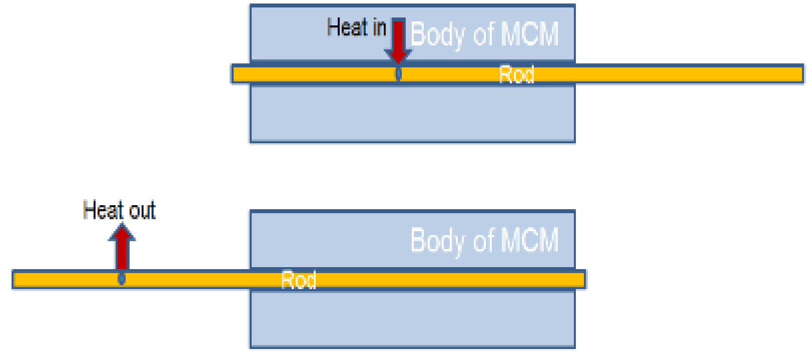
Solid-State Magnetocaloric Refrigerator

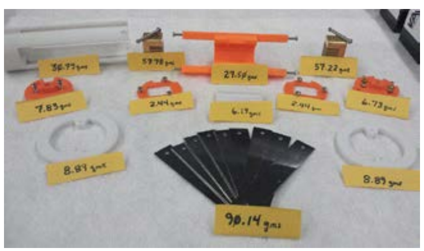
Approach 3: ORNL/GE estimate

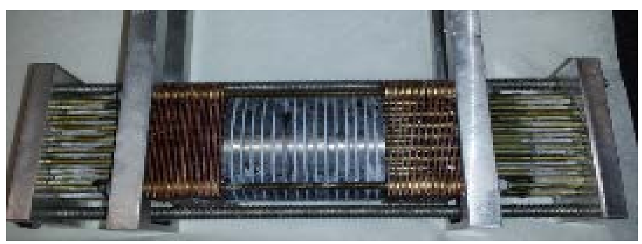
8x improvement on heat transfer could be achievable after including the air gap thermal resistance.

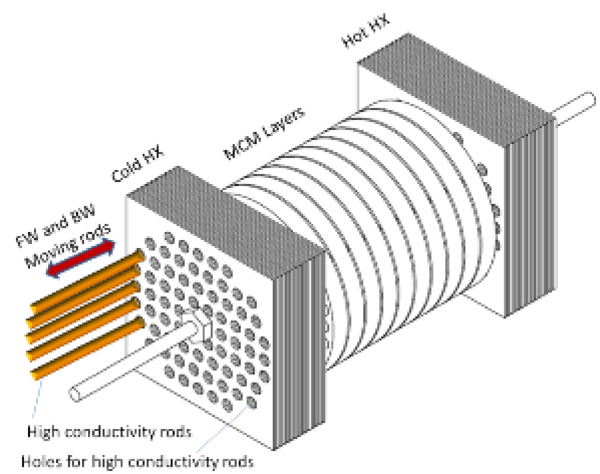
This is equivalent to 8x faster machine or 8x larger capacity or 8x reduction in size.



$$\frac{\mathrm{Nu}_{\text{Novel approach}}}{\mathrm{Nu}_{\text{Conventional}}} \approx \frac{k_{Brass}}{4k_{water}} \approx O(100)$$







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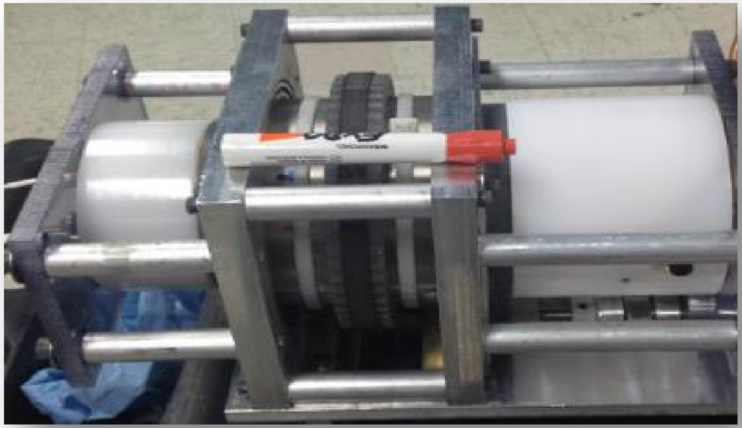
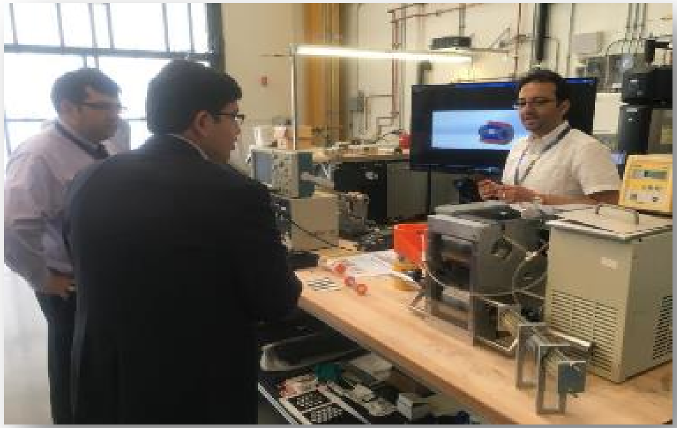
Prototyping: GEA's Prototype Development Progress

Prototype 1 - early 2014

Prototype 2 - 2014



Prototype 3 - 2015



Prototype 4 - 2016

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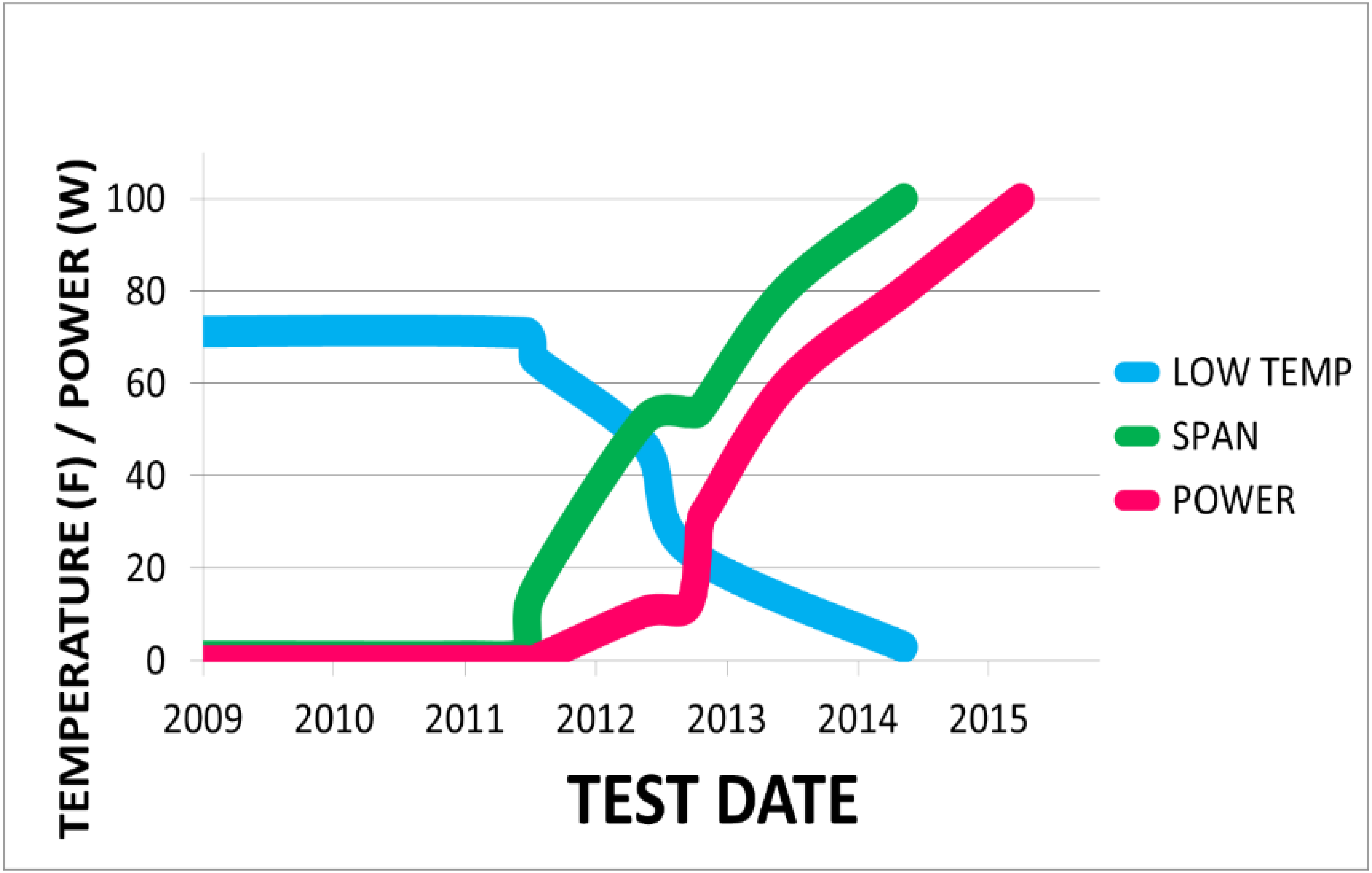
Prototype Development Progress



Project Integration and Collaboration

Project Integration:

Three collaborating patents, with GEA weekly meetings between ORNL team members:

- Bi-weekly meeting between ORNL and GEA
- ORNL and GE have quarterly site visits

Past successes in similar CRADAs show that such close collaboration with manufacturers is the best path to success.

Partners, Subcontractors, and Collaborators:

GE Appliances for machine design

ORNL for component improvement

Communications:

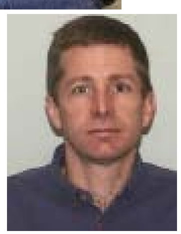
- Two conference papers
- ASHRAE presentation in 2016
- Google Hangout http://www.youtube.com/watch?v=uDF_COU1OJI
- Several visitors from public, private, media, industry, DOE

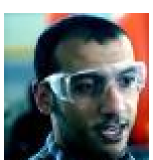
REFERENCE SLIDES

Acknowledgments

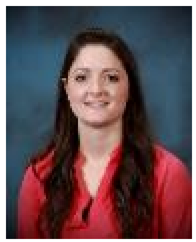
ORNL Team

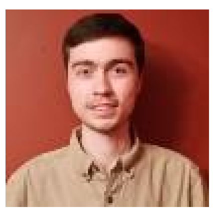
Building Eqpt. Res. Center



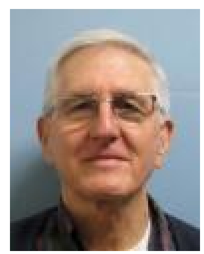


Additive Manufacturing





Material Sciences



GE Appliances Team

Project Budget

Project Budget: DOE total $1588k
Variances: None
Cost to Date: $1689k
Additional Funding: $286k

Budget History					
FY 2016 (past)		FY 2017 (current)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$539k	1-1	$360k	1-1	$286k	1-1

Project Budget

Project Schedule		
Project Start: 01-Aug-2013 (FY13)		Completed Work
Projected End: 30-Sept-2016		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missec
		Milestone/Deliverable (Actual) use when met on time

Task	FY2015				FY2016				FY2017		
	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)
Past Work											
Descrip.hypothetical manuf. to shape regenerators											
Development of at least 3-stage regenerator using at least one of the selected manufacturing processes.											
Developing complete regenerator via the selected manufacturing process.											
Indentify testing procedures for comparable bed testing											
Testing, fabrication MCM microchannels by collaborating with GEA											
Improve preformance of regenerator strructure											
Final optimization, testing and drafting the final report											
Current/Future Work											

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