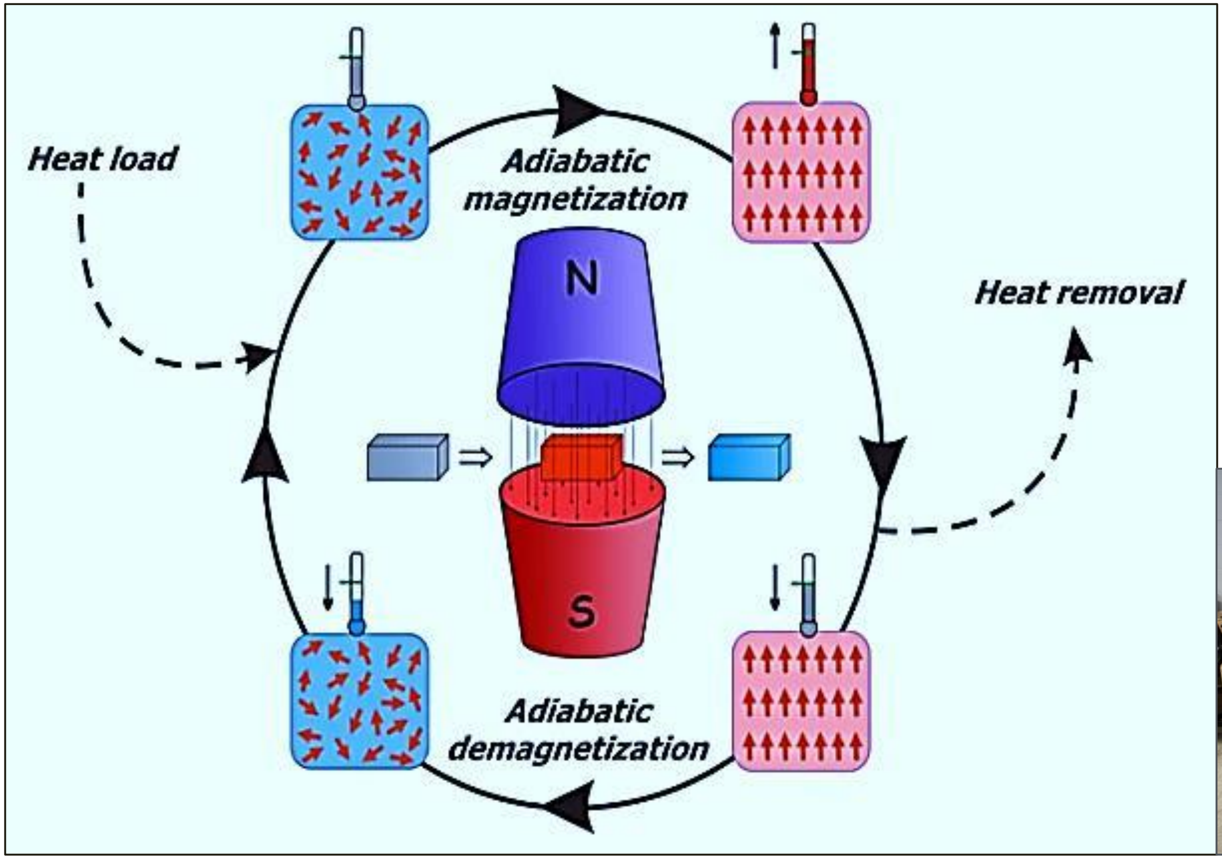
# Magnetocaloric Refrigerator Freezer

2016 Building Technologies Office

Peer Review




CRADA PARTNER

General Electric Appliances

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy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Oak Ridge National Laboratory

# 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 and testing and drafting the final report (12/30/2016)

**Budget**:

Total DOE $ to date: $1314K

Total future DOE $: $286K

**Key Partner**:

**CRADA project with General Electric Appliances**

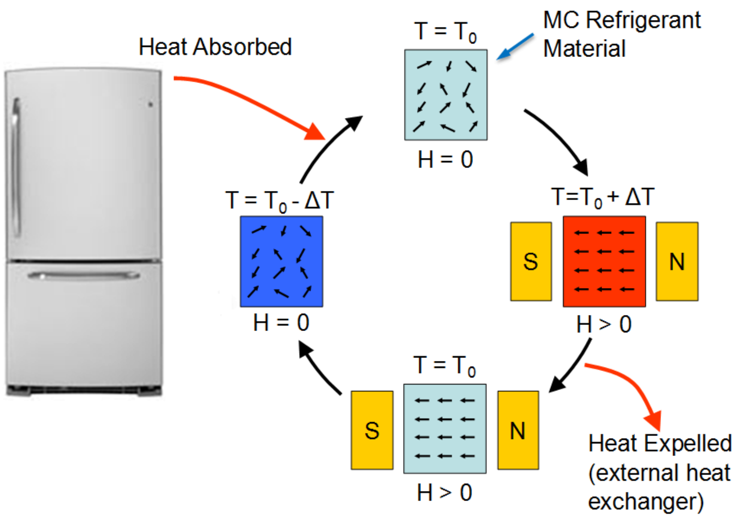
**Collaborators:**

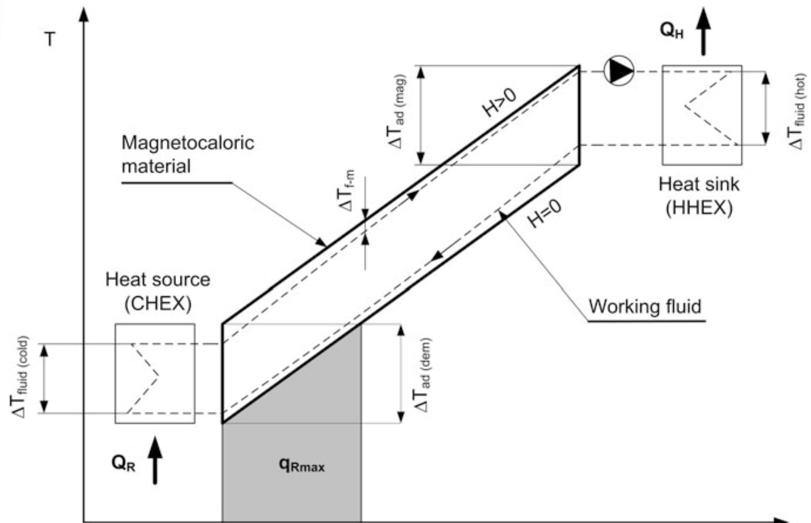
**Project Outcome**:

The objective of this project is to develop a residential refrigerator with 25% lower energy consumption and reduced emissions using magnetocaloric refrigeration technology.

# Brief Background: 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 refrigerated compartment; increasing its temperature to $T_0$ , and the cycle is repeated

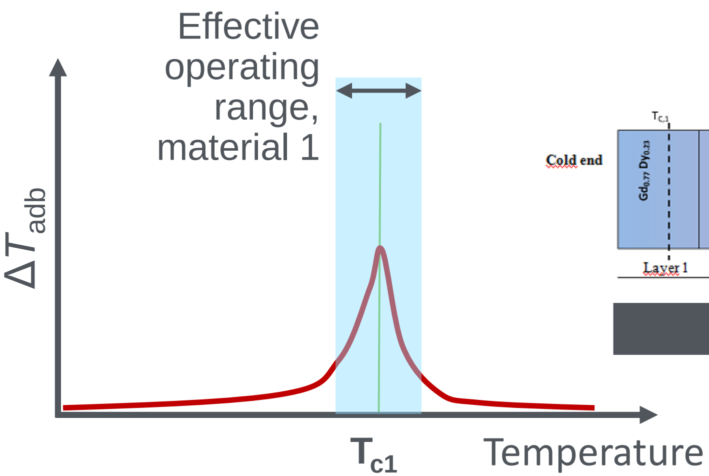


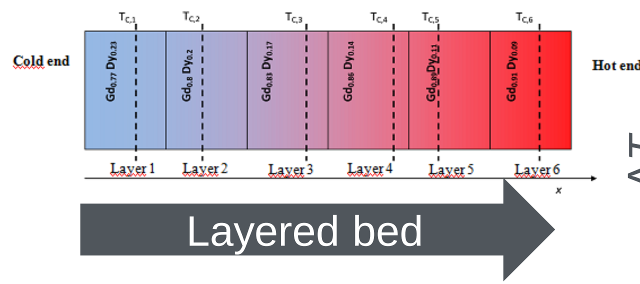



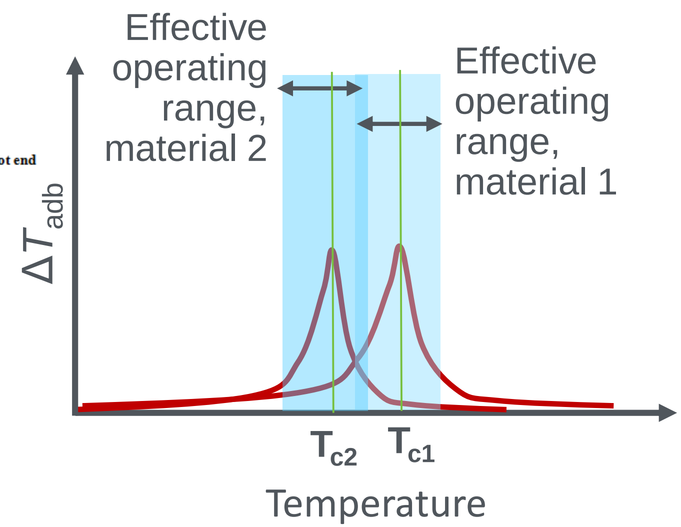

Schematic representation of the total AMR Brayton-like cycle in a T–s diagram [1]

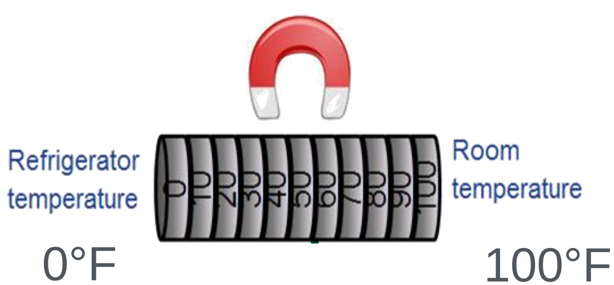
# Brief Background: Achieving large temperature span

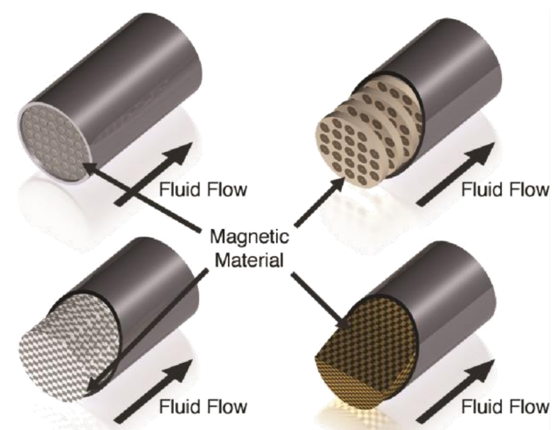
- Use different MCM alloys with different curie temperatures and layer atop one another.

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# Purpose and Objectives

**Problem Statement**: In 2015 we realized and resolved two main problems facing the development of a highly efficient system:

a) Developing the right manufacturing process for magnetocaloric material (MCMs)
b) Solid/liquid interstitial heat transfer limitation

**Target Market and Audience**: The principal target market is residential/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.

a) Final product will be a full scale magnetocaloric refrigerator-freezer
b) The success criteria are to achieve a 100°F temperature span and approximately 100 watts of cooling capacity.

- Near-term outcome: Develop a feasible design with emerging MCM materials
- Intermediate-term: Design a magnetocaloric refrigerator-freezer
- Long-term: Introduce a unit to the market

# Approach

**Approach**: Efforts are concentrated in three categories:

**a)** Develop manufacturing process for forming MCM

**b)** Enhance the heat transfer rate, which translates into a higher system capacity

**c)** Develop a high-efficiency magnetocaloric system design

**Critical Issues**:

**a)** Solid/liquid interstitial heat transfer limitation

**b)** Manufacturability of MCM

**MCM particles are difficult to be manufactured to shapes and parts. They are fragile, heat sensitive, and very reactive**

**Distinctive Characteristics**:

Research Efforts →

- **Develop unique additive manufacturing followed by a sintering process to fabricate MCM microchannels**
- **Magnetic stabilization to develop 3D MCM microchannels**
- **Solid state magnetocaloric machine**

→ Enhance heat transfer → **Better machine**

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# Progress and Accomplishments

**Accomplishments**:

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

**Market Impact**:

This project can potentially save 0.75 quad of energy.

**Awards/Recognition**:

- Recognized research by EERE assistant secretary Dr. David Danielson
- US Provisional Patent Application, Magnetically Stabilized Magnetocaloric Microchannel
- US Provisional Patent Application, The fully solid state magnetocaloric system

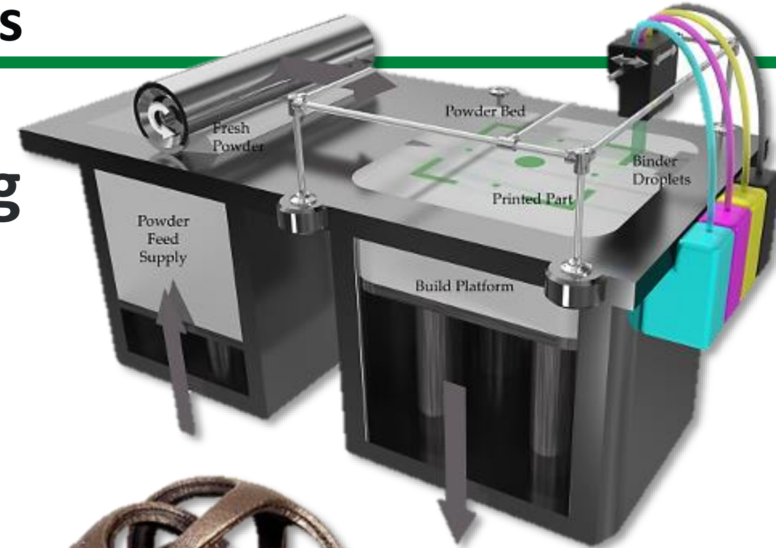
**Lessons Learned**:

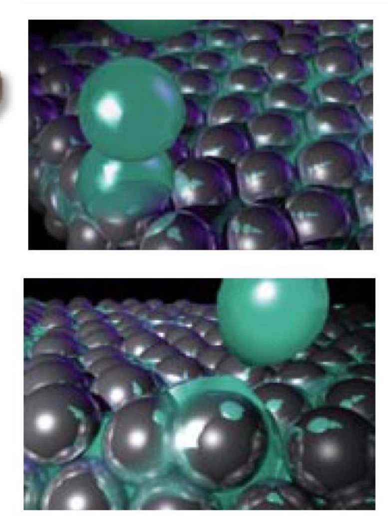
Pressure drop of MCM particulate regenerator is one of the primary loss sources of the MCM system.

# 1. Progress and Accomplishments: Developing manufacturing process to 3D print MCM microchannels

## Binder jet additive manufacturing

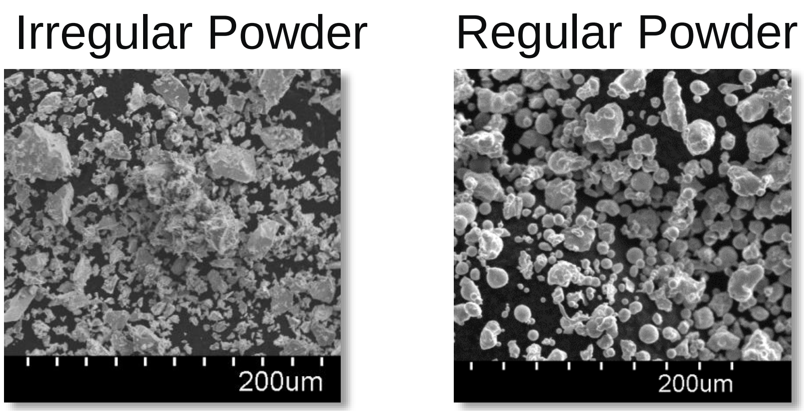
- Additive manufacturing (AM) eliminates waste by using material only where it is needed
- Binder jet AM is well-suited for MCMs due to its low-temperature processing. Low temperature help to preserve MCE properties.
- Because it is inkjet-based, binder jet AM can also create high-resolution features. This is an essential need to  fabricate small microchannels.

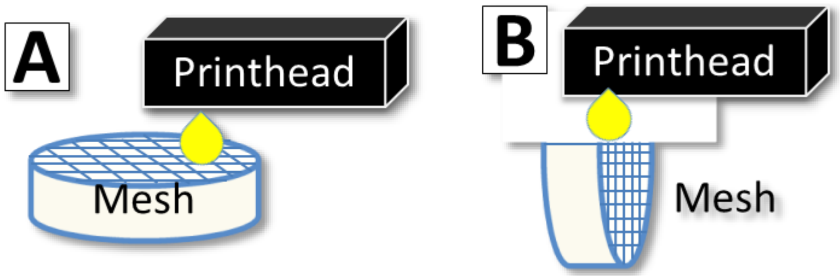


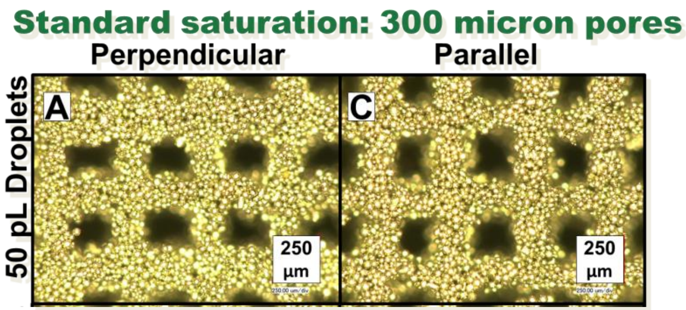



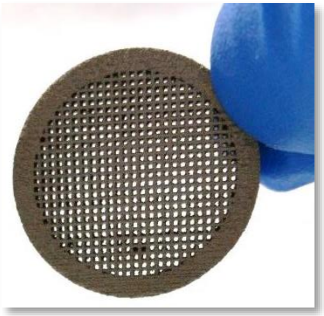
# Resolution in binder jet 3D printing

- Preliminary work revealed that powder shape, mesh orientation, and drop size affect resolution.
- Experiments were conducted to determine the most effective process settings for microchannel printing



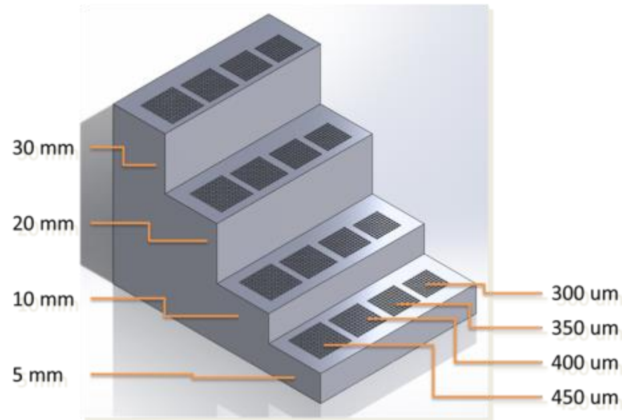



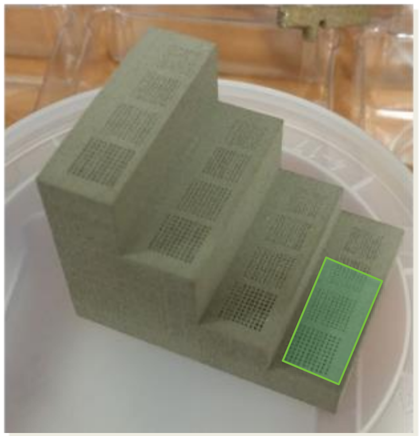



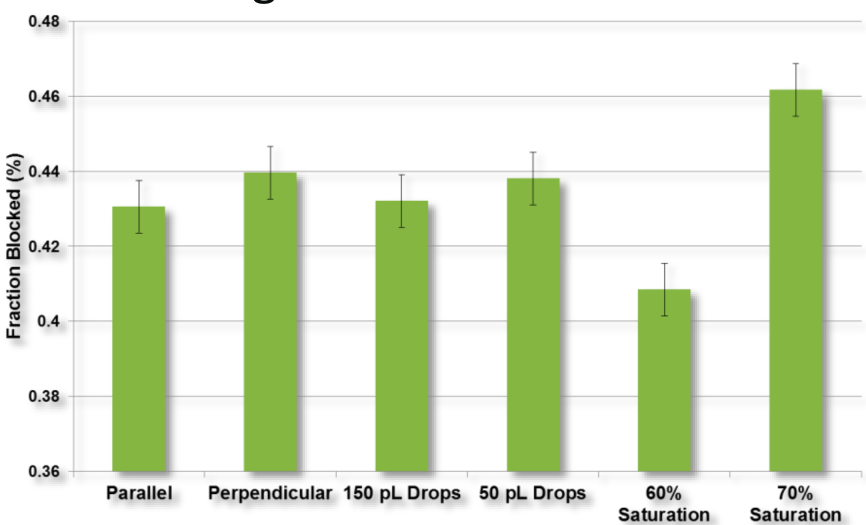



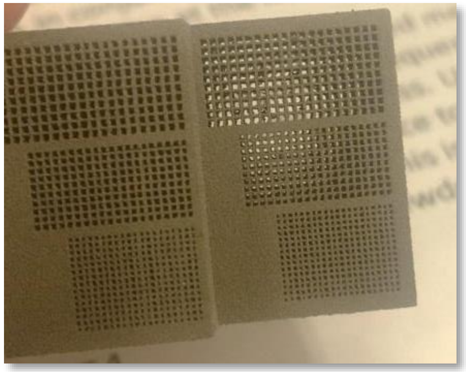
# Binder Jet 3D printing of Long Microchannels

- A study was conducted to determine how binder amount, drop size, and print orientation affected channel cleanability for various lengths of channels
- Cleaning was attempted with each channel, and the number of block channels per sample group was counted.
- It was found that binder amount was the most significant factor.

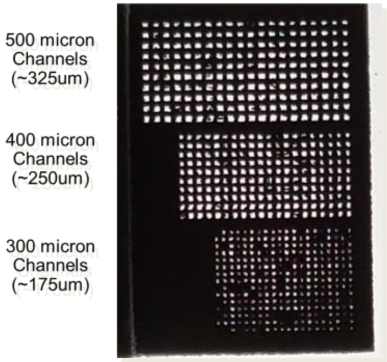




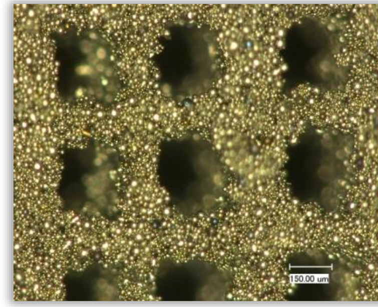



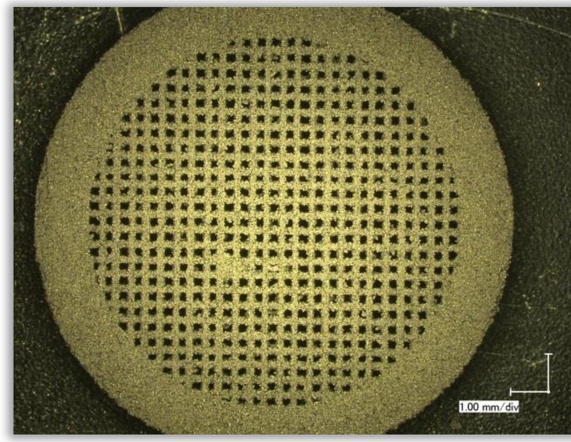
Top view

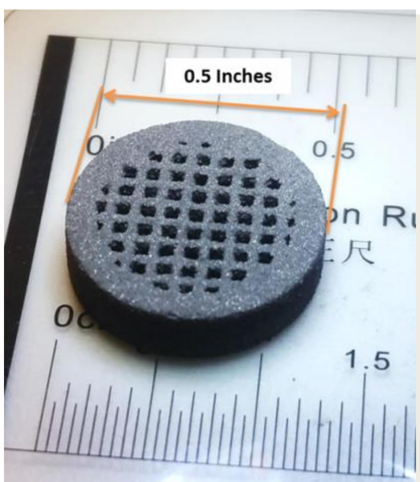


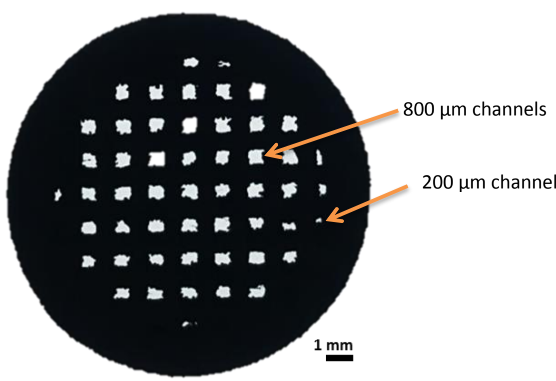
# Binder Jet 3d printing with MCM Powders

- Two MCM powders were printed: a jagged, hydrogenized powder and a spherical powder.
- Spherical MCM powder can reach very fine channel size (150-200 microns)
- The current focus is to improve high-resolution printing with the jagged powder.



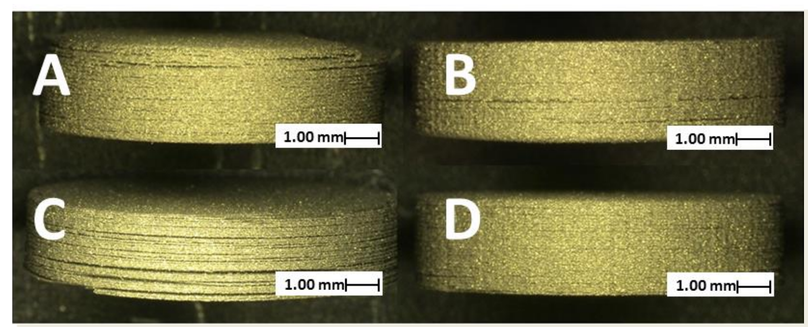




Figure 2: Isometric view of printed MCM material

# Developing manufacturing process for sintering and pressing MCM

Why?

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.

After 8 months of R&D effort (In FY15):

- MCM die was successfully pressed
- Mold-cast MCM parts were successfully sintered to high densitie (up to 99% of material density)

MCM Powder

**Very Challenging Process**

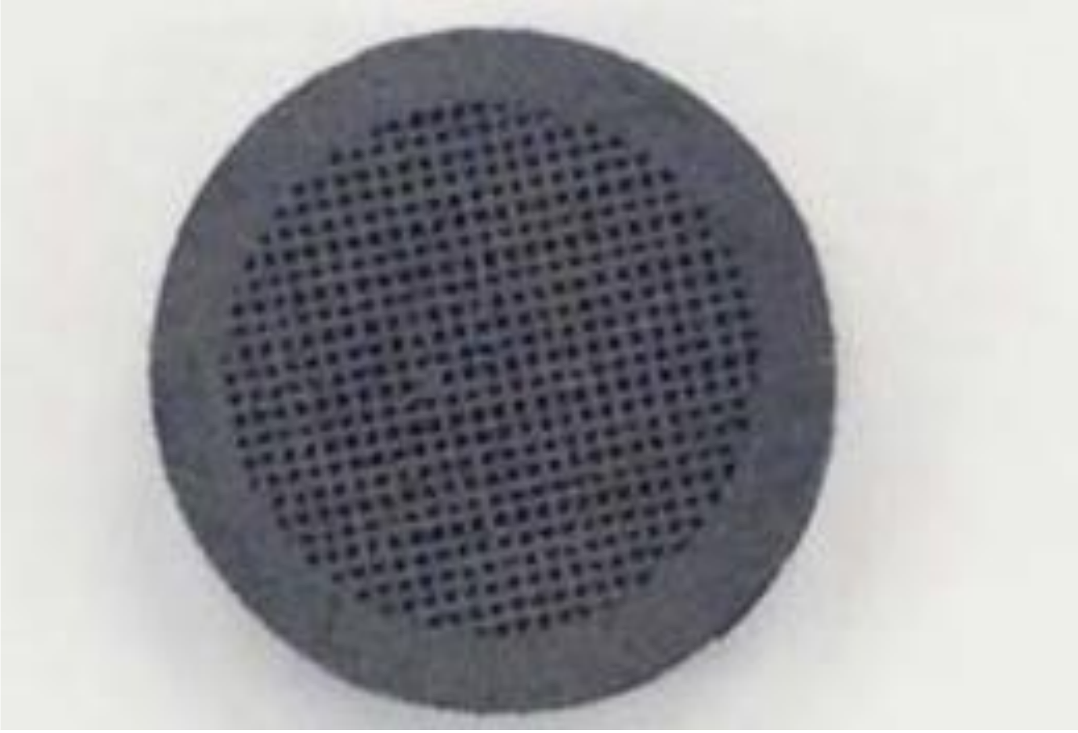
MCM sintered MCM press die

**Findings:**

-Sintering conditions including the right atmosphere, temperature, oxygen level, type of furnace were realized.

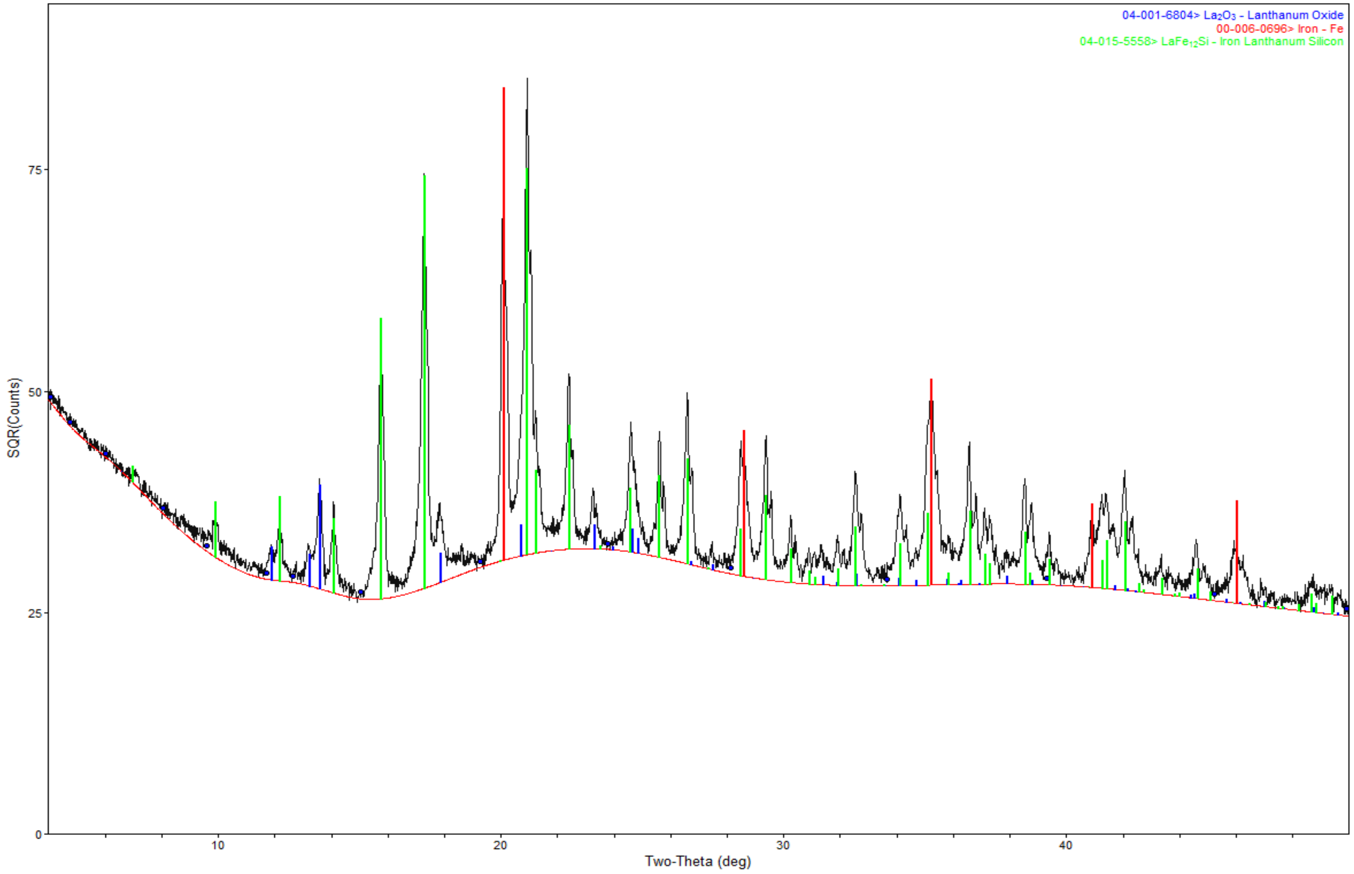
-Final densities of 97–99 % were achieved.

# Printed MCM microchannel was successfully sintered to high densities



The sintered structure is very strong and robust

# XRD (X-ray Diffraction) analysis indicated that crystalline structures were maintained during sintering




For the phase identification procedure, a search match was conducted using the Jade software and the ICDD database



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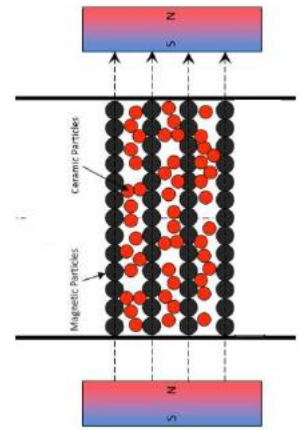
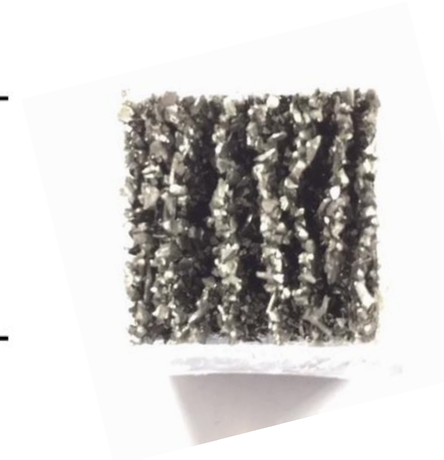
# Magnetically stabilized MCM microchannels

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

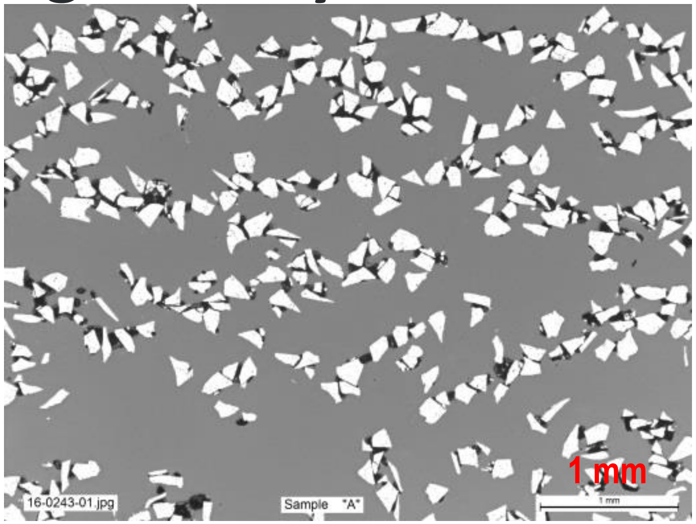
This solution significantly reduces the pressure drop and provides very high interstitial heat transfer rates. It has the potential to produce random microchannels as small as 20–100 µm, which cannot be achieved by other manufacturing processes.



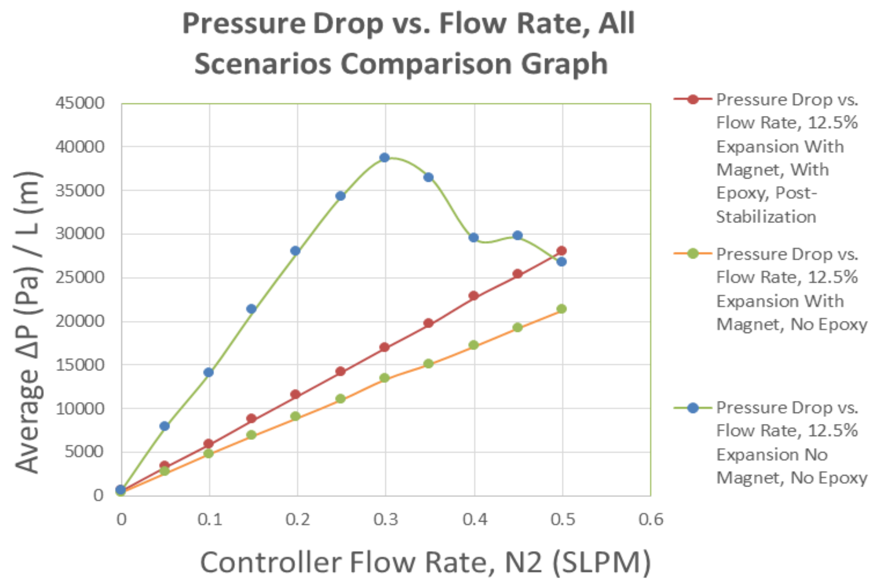



**Ayyoub M. Momen, Magnetically Stabilized Magnetocaloric Microchannel** ,” US Provisional Patent Application, ID DOE S-138,206, Feb 4th, 2016

# Magnetically stabilized MCM microchannels

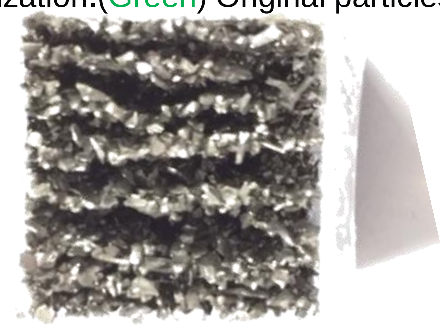



A slice of the fabricated structure.




Pressure drop across the MCM (Red) After magnetic stabilization and adding epoxy. (Orange) After magnetic stabilization.(Green) Original particles.

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



**Ayyoub M. Momen, Magnetically Stabilized Magnetocaloric Microchannel** ," US Provisional Patent Application, ID DOE S-138,206, Feb 4th, 2016

# Project Integration and Collaboration

## Project Integration:

1) GEA requested to be the lead on patenting the 3 inventions (out of 5) proposed by ORNL
2) Weekly meetings between ORNL team members
3) Biweekly meeting between ORNL and GEA
4) ORNL-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

## Communications:

- Conference Paper No. IMECE2014-38928,
- Conference Paper No. IMECE2015-53428,
- ASHRAE Presentation 2016
- Google Hangout http://www.youtube.com/watch?v=uDF_COU1OJI
- Several visitors from public, private, media, industry, DOE

# Next Steps and Future Plans

**Next Steps and Plans**:

1. Evaluation of MCM microchannels through collaboration with GEA (6/30/2016)

2. Improve the regenerator structure (9/30/2016)

3. Final optimization and testing and drafting the final report (12/30/2016)

# Acknowledgment

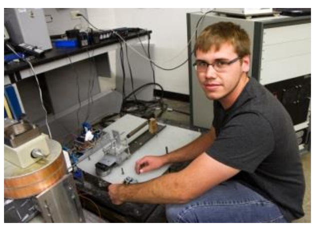
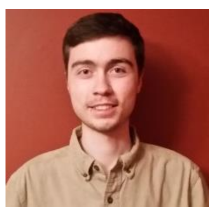
## ORNL Team

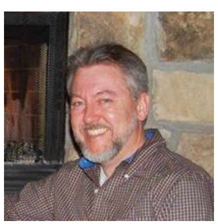
- Building Eqpt. Res. Center
- Additive Manufacturing
- Material Science

## GE Appliances Team








# REFERENCE SLIDES

# Project Budget

**Project Budget**: DOE total $1,600K FY 13-16
**Variances**: None.
**Cost to Date**: ~$1150K as today
**Future Funding**: $0

| Budget History | | | | | |
|---|---|---|---|---|---|
| FY 2015 | | FY 2016 | | FY 2017 | |
| DOE | Cost-share | DOE | Cost-share | DOE | Cost-share |
| $550K | * | $600K | * | NA | * |

# Project Plan and Schedule

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

| | FY2015 | | | | 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) | 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. | | | | | | | | | | | |
| Current/Future Work | | | | | | | | | | | |
| Indentify testing procedures for comparable bed testing | | | | | | | | | | | |
| Testinf, fabrication MCM microchannels by collaborating with GEA | | | | | | | | | | | |
| Improve preformance of regenerator strructure | | | | | | | | | | | |
| Final optimization, testing and drafting the final report | | | | | | | | | | | |