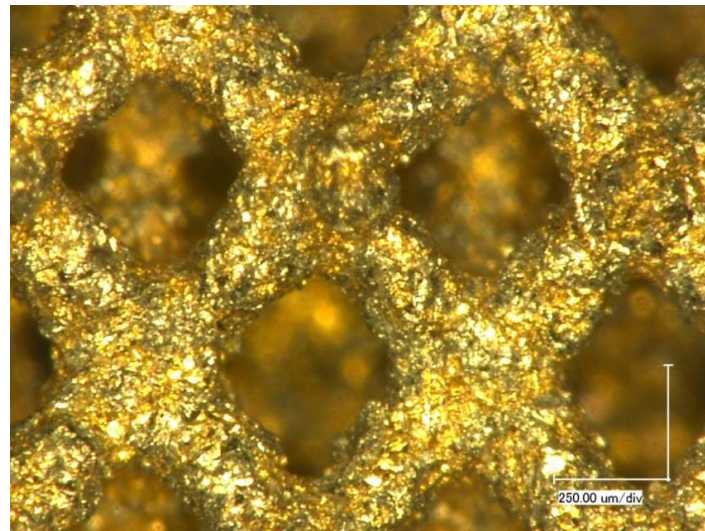
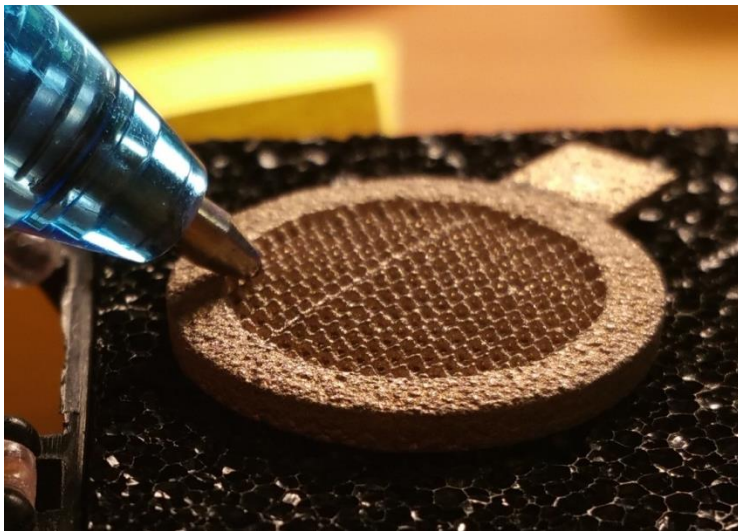


Magnetocaloric Refrigerator



Performing Organization(s): Oak Ridge National Laboratory

PI Name and Title: Ayyoub M. Momen, R&D Staff

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Project Summary

- **Timeline**

- Start date: 11/6/2017
- Planned end date: 11/6/2020

- **Key Milestones**

- Milestone 1; Reinstate 90% of magnetocaloric effect of the 3D printed microchannel, 11/6/2018
- Milestone 2; Fabricate and test 10 stage 3D printed Kagome microchannel 11/6/2020

- **Budget**

Total Project \$ to Date:

- DOE: \$0.2M
- Cost Share: \$0.2M

Total Project \$:

- DOE: \$1M
- Cost Share: \$0.6M

- **Key Partners**

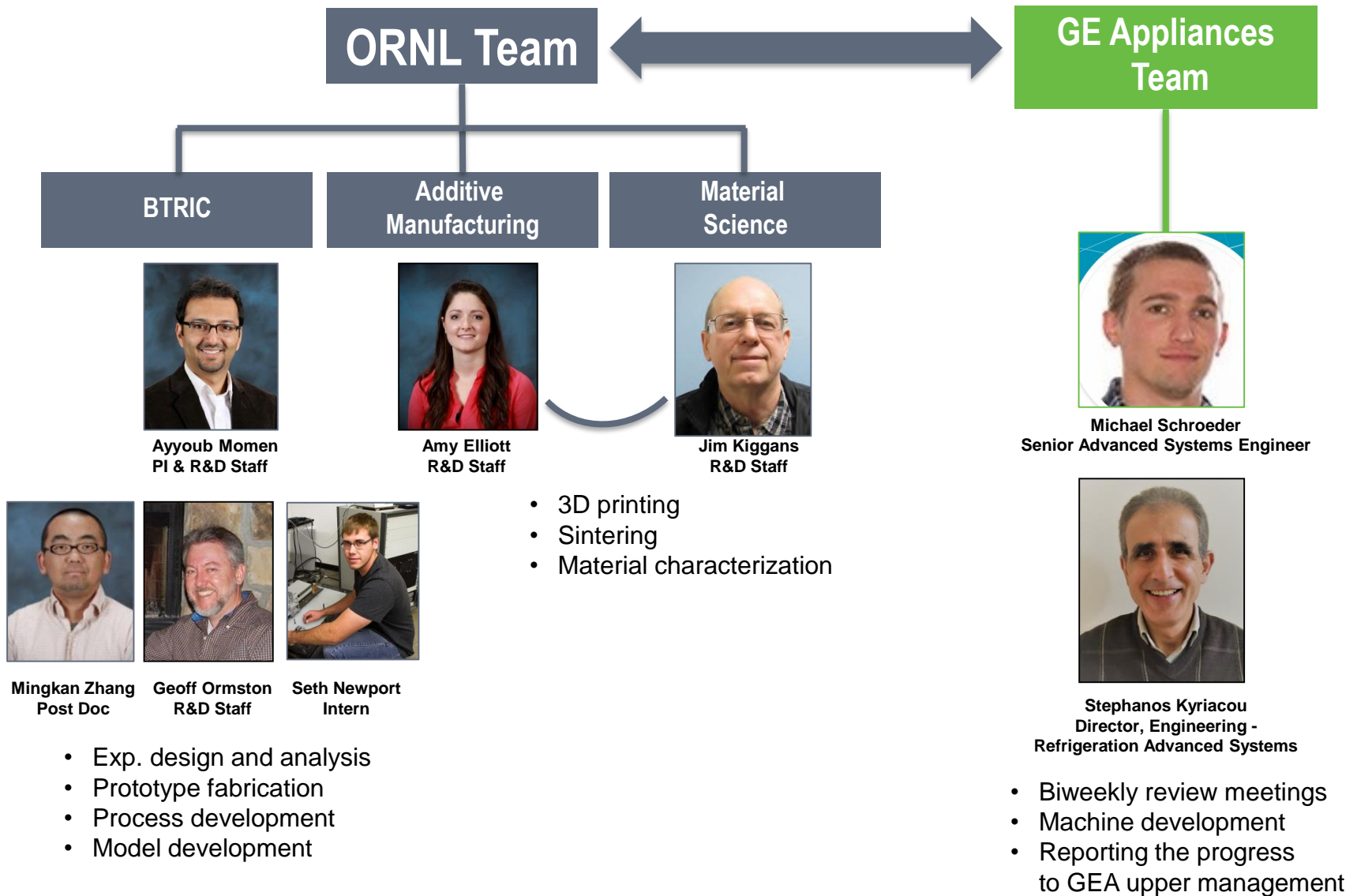
- General Electric Appliances and Haier Company



- **Project Outcome**

- Harnessing the MCE to achieve cooling is among the most promising of the emerging non-vapor-compression technologies. MCE has the potential to reduce energy consumption by 20–30% beyond vapor compression while also eliminating any risk of direct refrigerant emissions to the atmosphere.
- This technology's primary energy savings technical potential is 0.20 quad/yr in 2030, per DOE-BTO's P-Tool.

Team



Magnetocaloric Effect

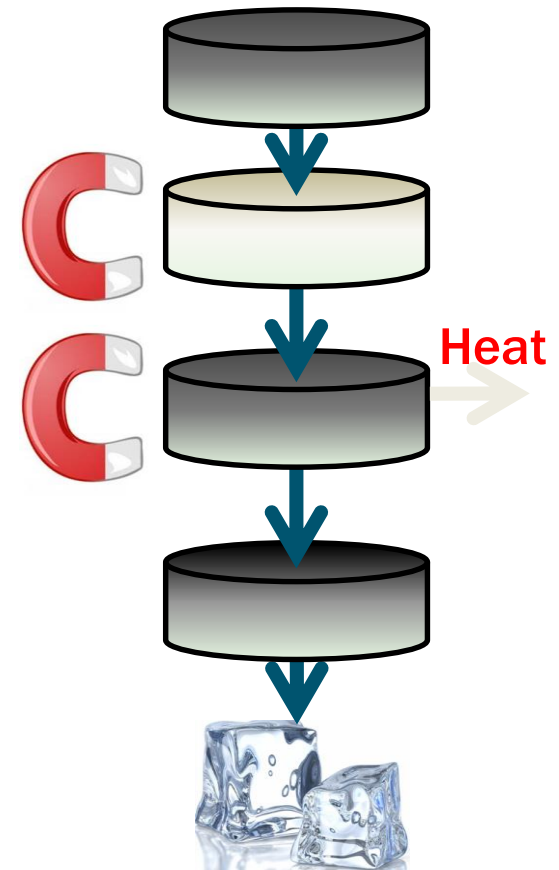
The Magnetocaloric Material are sensitive to the magnetic field:

The alloy starts at room temperature

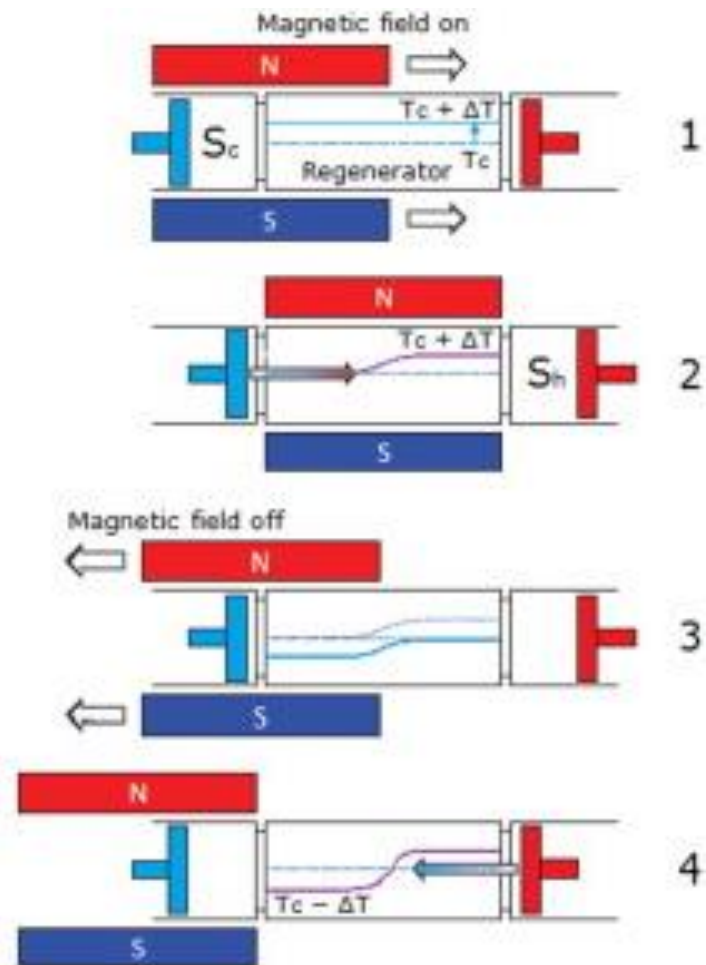
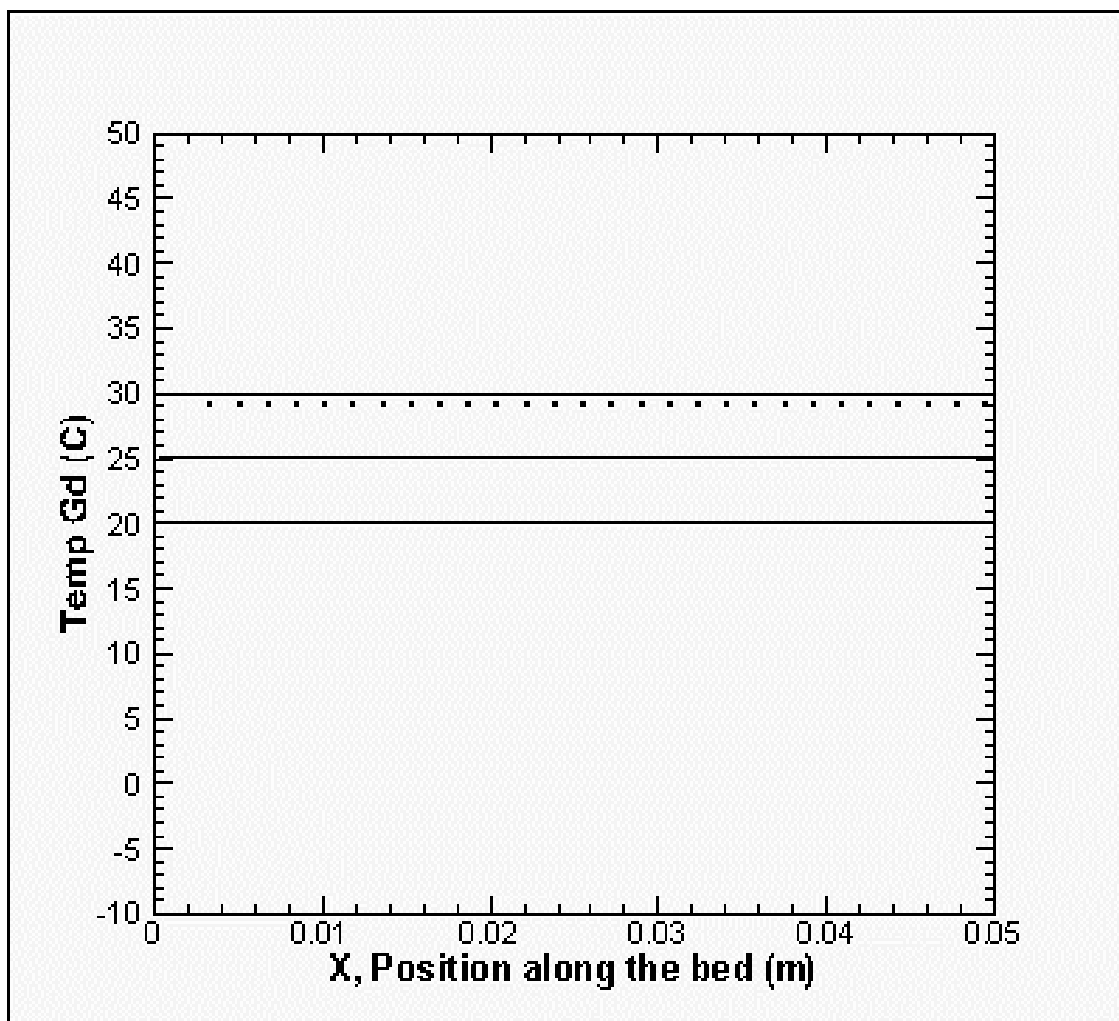
A magnetic field is applied causing the material temperature to go up

Heat is removed, material returns to room temperature

Magnetic field is removed, material gets colder than its started Useful for refrigeration



How the MC system operates



Significance

Technology Potential:

- There are >200M refrigerators units in U.S.A. In most homes refrigerator is the second largest user of electricity (13.7%) right after air conditioning (14.1%).
- Magnetocaloric refrigeration has the potential to be 20% more efficient than the conventional vapor compression systems.
- According to the recent DOE study on 17 non-vapor compression HVAC technologies, Magnetocaloric refrigeration technology ranked as “very promising” alternatives because they exhibit moderate-to-high energy savings potential, offer significant non-energy benefits, and/or fit well with the BTO mission.

Note:

Early stage R&D is needed to fully utilize the recent and future emerging MCMs. Developing a high performance Magnetocaloric refrigeration system is a very challenging task from system development perspective.

Challenges

Magnetocaloric Refrigeration Challenges

New Material discovery

Not addressed under this project

Processing the material

High performance MCM are difficult to be formed, because they are:

- Heat sensitive
- Very reactive
- Brittle

System integration

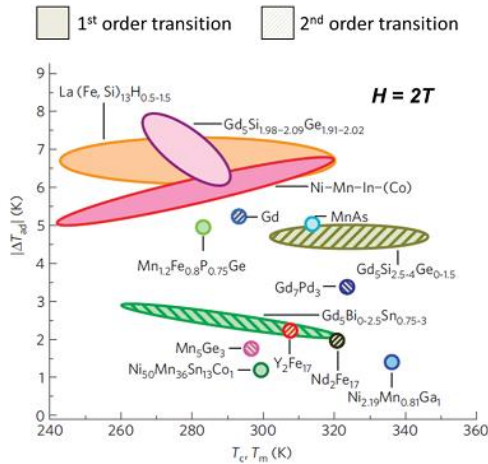
In the system level Pressure drop across MCM heat

exchanger is the main challenge:

- Excessive pressure drop hurting the performance 2 folds
- Limits the operating frequency
- Limits the cooling/heating capacity

Reducing cost

Cost reduction is inversely proportional to system cooling power density



Source: J. Liu *et al.* Nat. Mater. 2012

Approach

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

$$COP = \frac{Q_{cool}}{W_{in}}$$

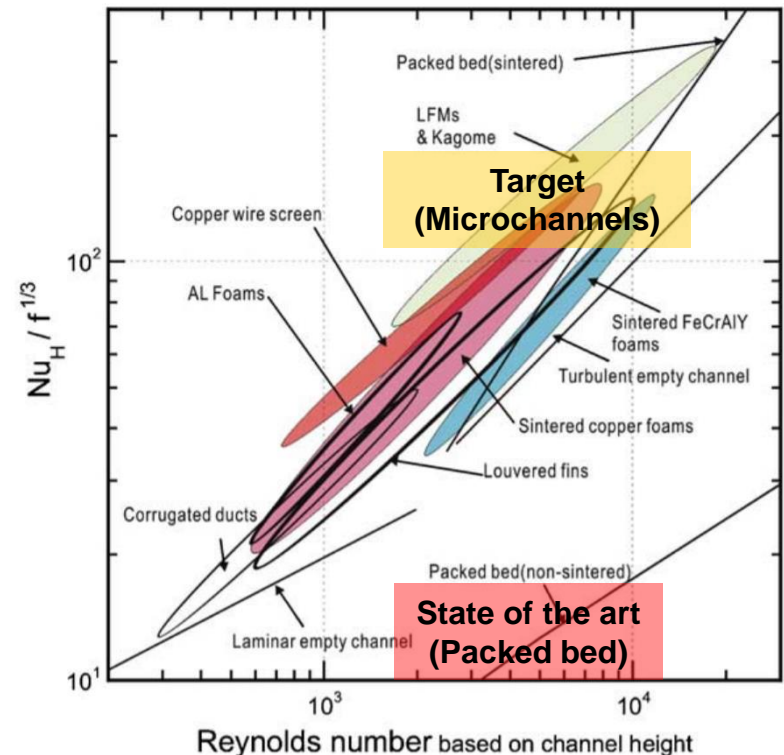


$$COP = \frac{Q_{cool} - \text{Pump power heat}}{W_{in} + \text{Pump power heat}}$$

To depart from the state of the art, we need to find develop manufacturing processes to make Microchannels from MCM.

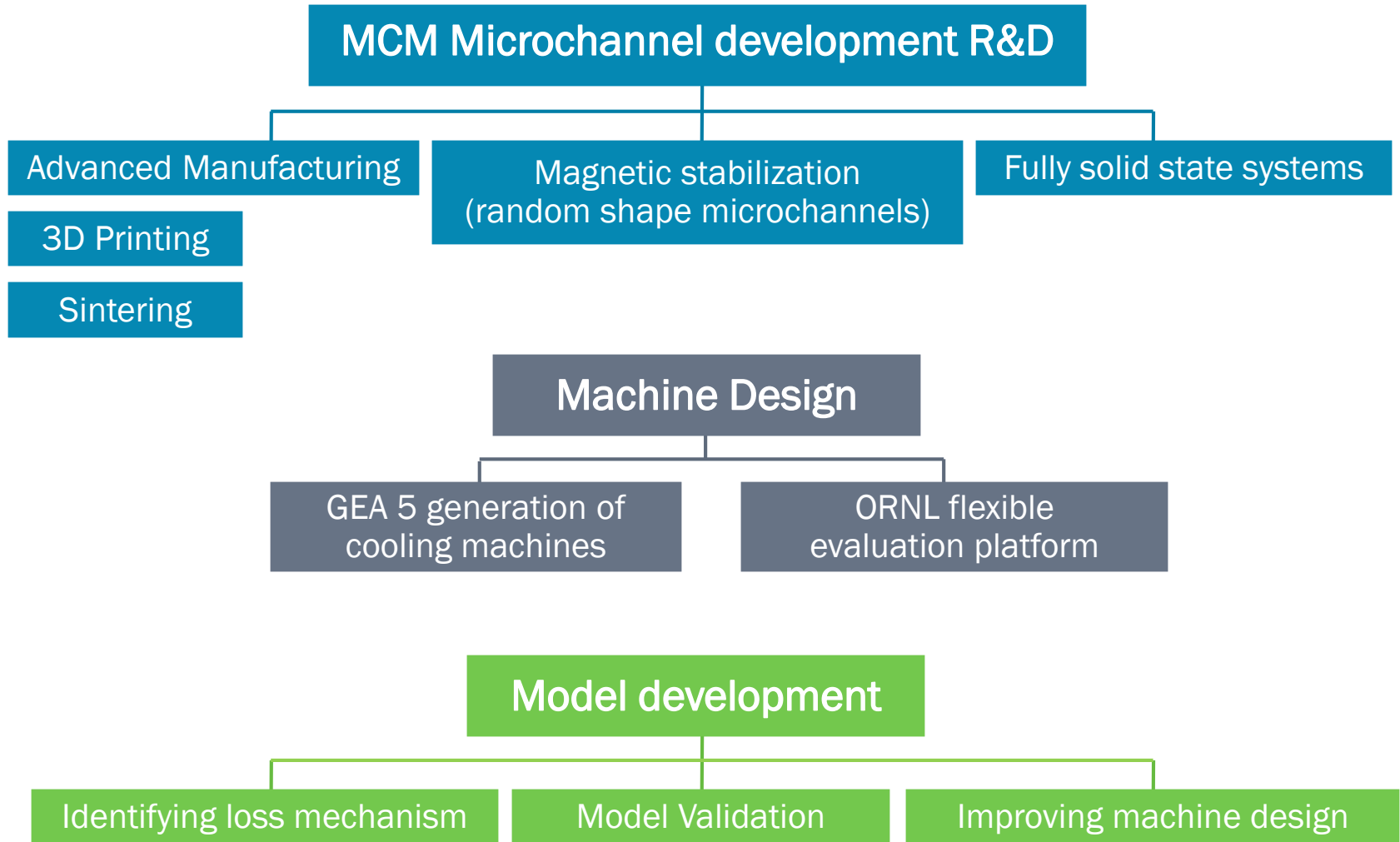
High performance MCM are difficult to be formed or manufactured in shapes (i.e. Microchannel), because they are:

- **Heat sensitive**
- **Very reactive**
- **Brittle**



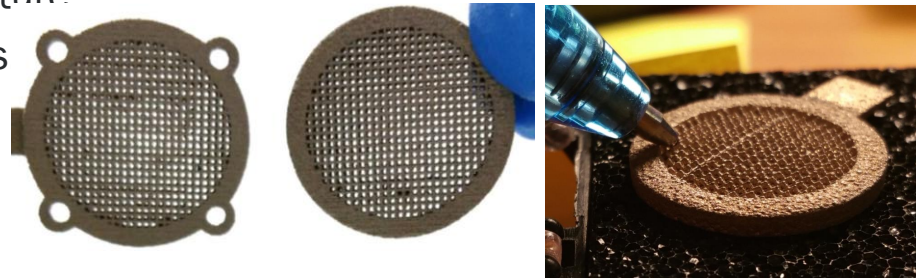
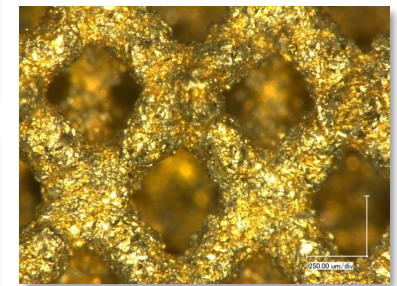
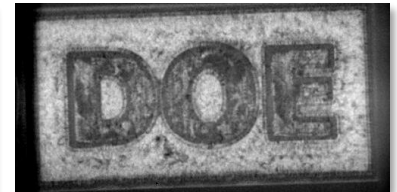
Source: J. Tian, T. Kim, T.J. Lu, H.P. Hadson, D. T. Qucheillit, D.J. Sypeck, H.N.H. Hadky.

Approach



Progress: Advanced Manufacturing

- 3D printing of the heat exchangers is a new field and very challenging.
- Additional, complexity is added when we want to do this on the new material (MCM) that does not like to cooperate (reactive, heat sensitive and fragile)!!
- After 18 months of early stage R&D, we fabricated MCM microchannels of 150 μm at 100% MCM full density.
- Variable Parameters Investigated:
 - Particle diameter
 - Binder saturation
 - Print orientation
 - Type of binder
 - Cleanability
 - Curing temperature
 - Pixilation issues



Progress: Advanced Manufacturing

- Developed MCM 3D printing process
- Developed sintering process
- Identified the flaw in the process
- Currently working to eliminate the C and O₂ pickup during the process

**Big challenge to be resolved:
Carbon and Oxygen pickup during process**

2016

Learn how to print MCM

2016-17

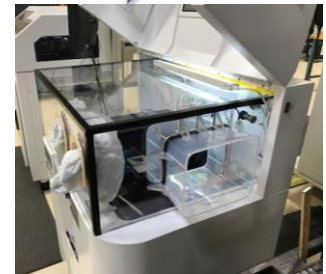
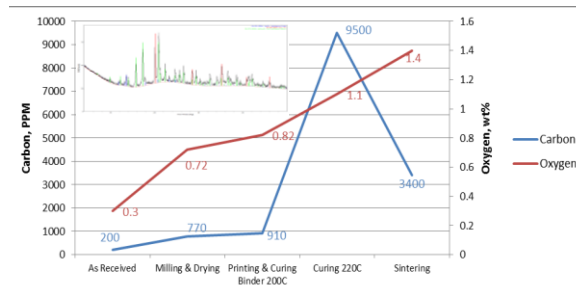
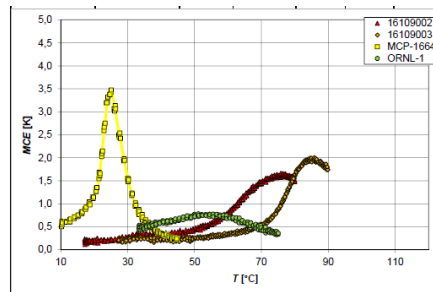
Learn how sinter MCM 3D printed part

2017

Process evaluation Identify the processes flaws

2018-19

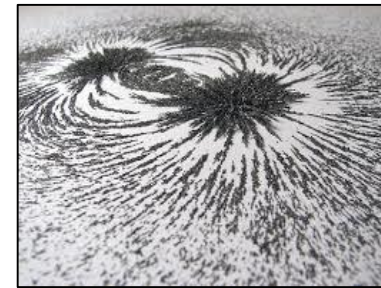
Resolving remaining issues
10 stage 3D MCM microchannels for testing in AMR



Progress: Magnetic Stabilization

We invented MCM magnetic stabilization process in 2016.

- No heating is involved
- Scalable process (compared to additive manufacturing)
- Simple and low cost solution
- Significantly reduces the pressure drop
- Provides very high interstitial heat transfer rates
- Random microchannels as small as 20–100 μm
- Enhance magnetization of particles by 10%
- MCE properties intact



2015

Idea developed

2016

Process developed
(binder, fluidization, magnetization,
curing, pressure drop)

2017

3 Stage AMR
developed, evaluated

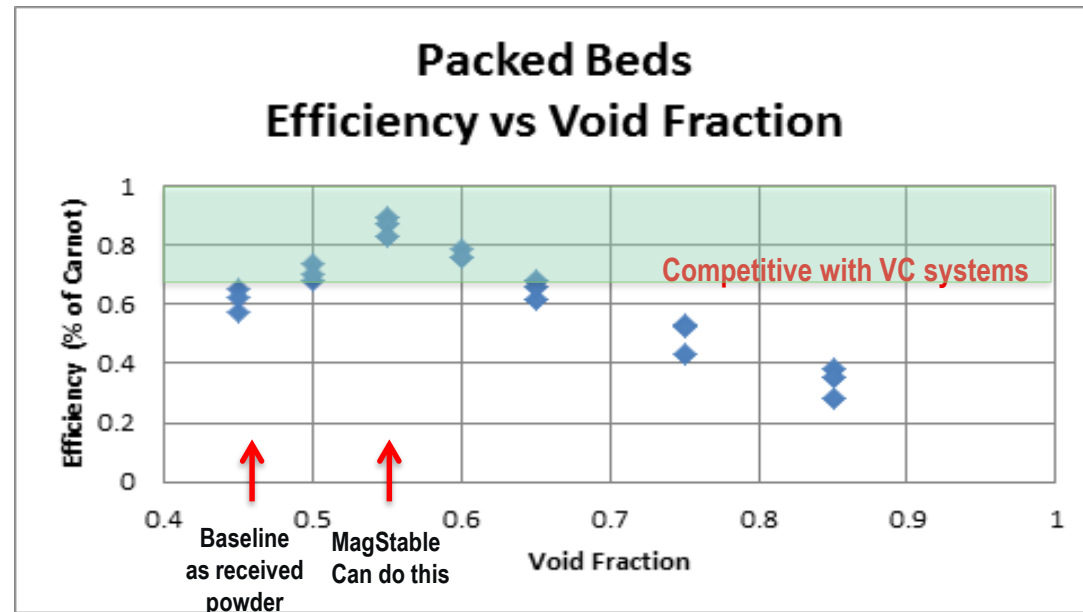
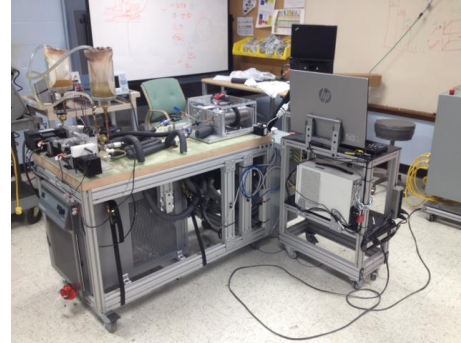
2019

10 Stage AMR
Evaluation and fine
tuning the process

Progress: Magnetic Stabilization

The process will be refined in FY18-19:

- Improving fabrication process
- Evaluating the performance of the multistage regenerator
- Hydrodynamic, HT, Physical inspections
- Evaluate the performance of 10 stage AMR
- Finalize the recipe for the Magstable manufacturing process



Progress: Multistage AMR Model Development

Model development: A paper was published in a Nature family journal on 16-layer regenerator.

www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN A numerical analysis of a magnetocaloric refrigerator with a 16-layer regenerator

Mingkan Zhang, Omar Abdelaziz, Ayyoub M. Momen & Ahmad Abu-Heiba

Received: 29 June 2017
Accepted: 25 September 2017
Published online: 25 October 2017

A numerical analysis was conducted to study a room temperature magnetocaloric refrigerator with a 16-layer parallel plates active magnetic regenerator (AMR). Sixteen layers of LaFeMnSiH having different Curie temperatures were employed as magnetocaloric material (MCM) in the regenerator. Measured properties data was used. A transient one dimensional (1D) model was employed, in which a unique numerical method was developed to significantly accelerate the simulation speed of the multi-layer AMR system. As a result, the computation speed of a multi-layer AMR case was very close to the single-layer configuration. The performance of the 16-layer AMR system in different frequencies and utilizations has been investigated using this model. To optimize the layer length distribution of the 16-layer MCMs in the regenerator, a set of 137 simulations with different MCM distributions based on the Design of Experiments (DoE) method was conducted and the results were analyzed. The results show that the 16-layer AMR system can operate up to 84% of Carnot cycle COP at a temperature span of 41 K, which cannot be obtained using an AMR with fewer layers. The DoE results indicate that for a 16-layer AMR system, the uniform distribution is very close to the optimized design.

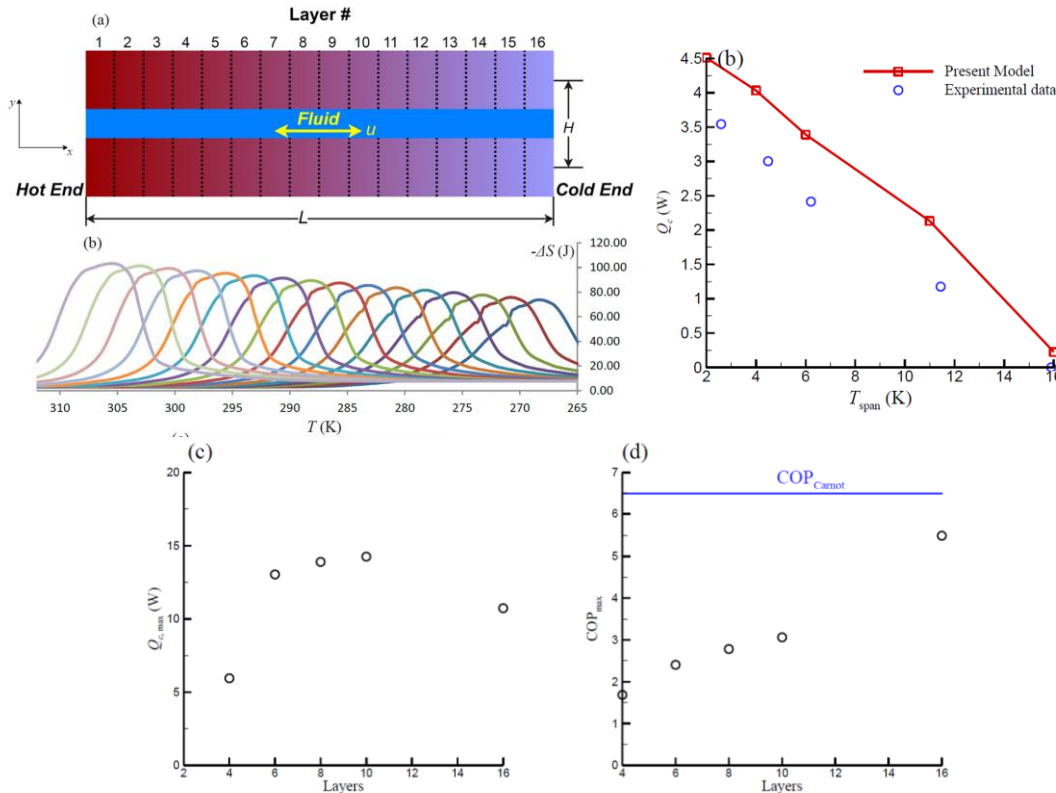
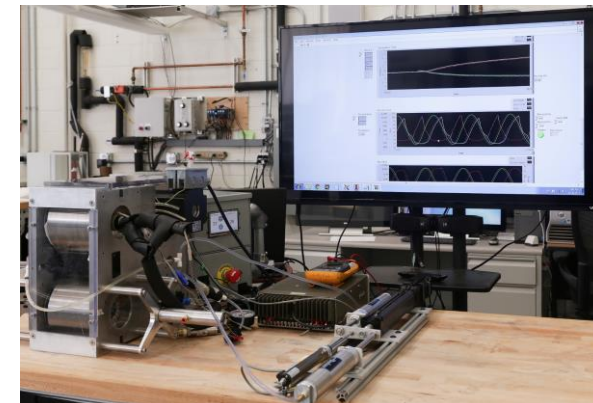


Figure 5. Q_c (a), COP (b), $Q_{c,max}$ (c), and COP_{max} (d) variations with utilization for different N_{layer} .

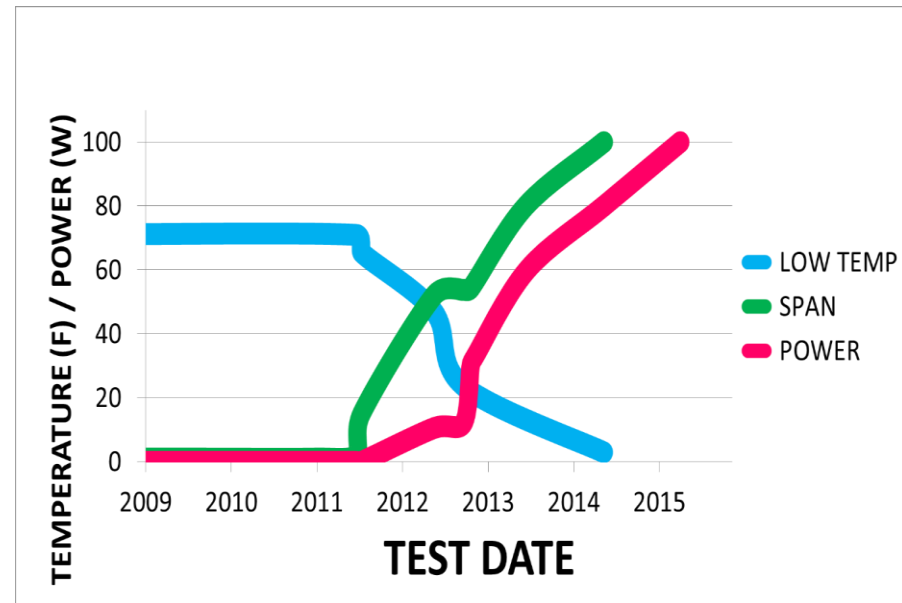
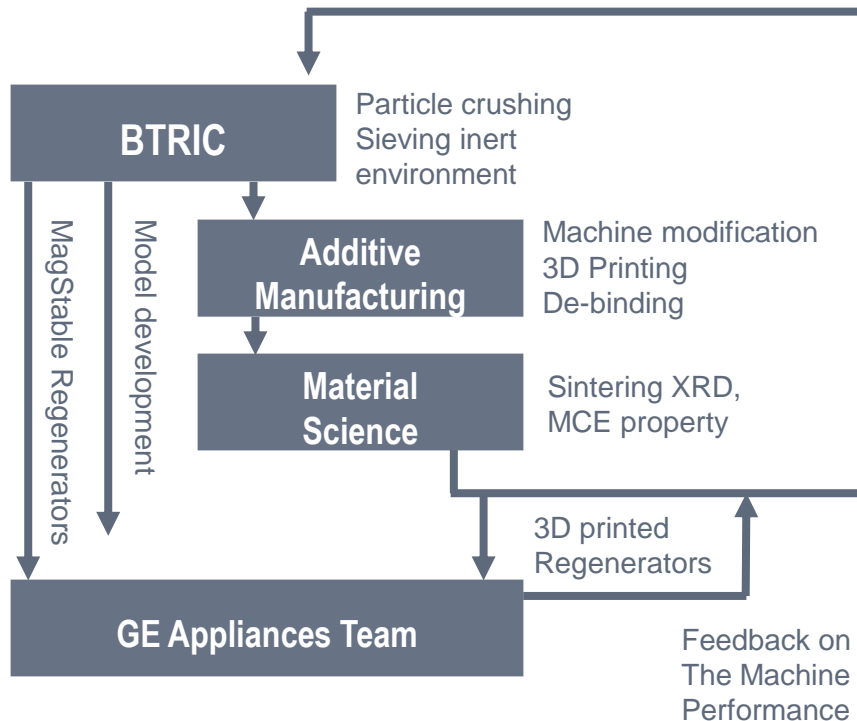
Currently the model is further developed to identify the main loss mechanisms in the system and being able to be validated against the Magnetically stabilized structure results.



Flexible Characterization Platform for Magnetocaloric Regenerator Performance Evaluation

Stakeholder Engagement

- ORNL staff have weekly internal meeting
- ORNL and GEA has bi-weekly meeting
- ORNL and GEA have quarterly site visits
- ORNL submit Quarterly progress report to DOE



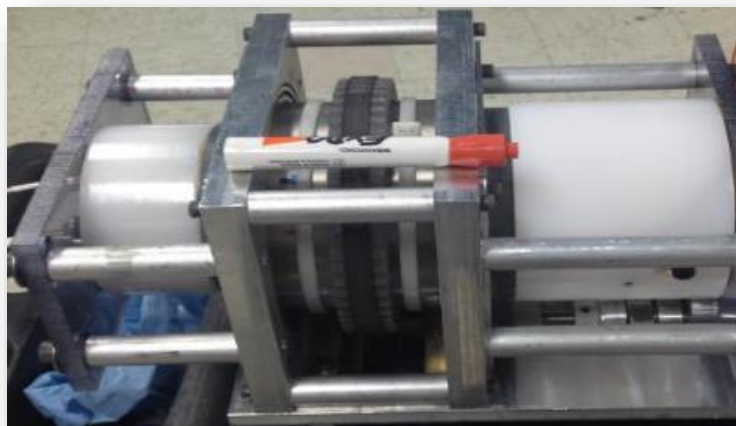
Prototyping: GEA's Prototype Development Progress



Prototype 1—early 2014



Prototype 2- 2014



Prototype 3- 2015



Prototype 4- 2016

Remaining Project Work

- **Modeling:**
 - Quantify the loss mechanisms for magnetized and 3D printed regenerators.
- **Magnetic stabilization:**
 - Refine the process, develop 10 stage regenerator, and improve the performance.
- **Parameters under investigation:**
 - Particle diameter, optimum bed expansion, binding process, draining process, Curing process.
- **3D printing, Sintering:**
 - Eliminate the introduction of the C and O₂ into the process.
- **Parameters under investigation:**
 - Type of binder, type of furnace, process atmosphere.
- **COP evaluation:**
 - Evaluate the COP of 10 stage magnetic stabilized structure and 10 stage 3D printed regenerator.
- **Detailed Cost Model Development by Manufacturer :**
 - Develop consumer cost model, Develop manufacturing cost model, market risk and mitigation strategy

Note: Preliminary cost model is currently available.

Thank You

Performing Organization(s): Oak Ridge National Laboratory

PI Name and Title: Ayyoub M. Momen, R&D Staff

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BTRIC

