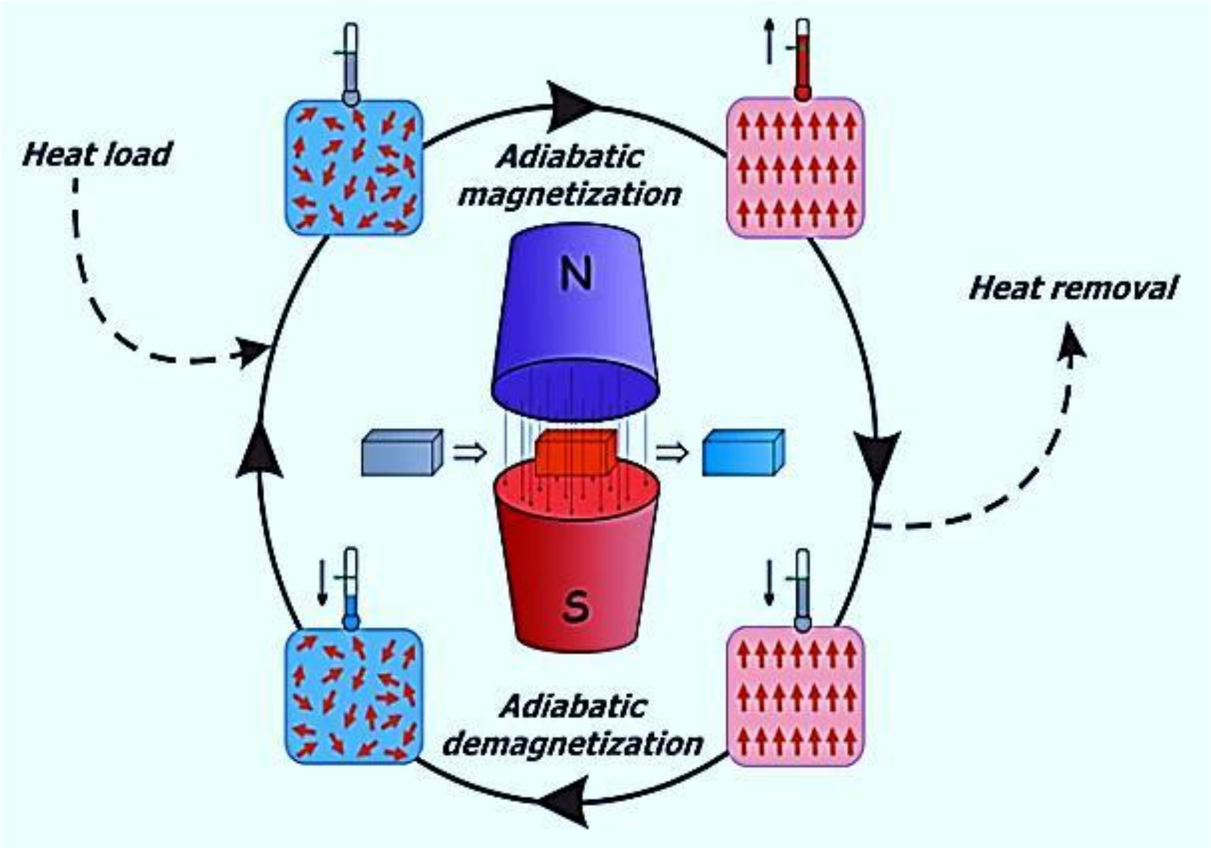
Magnetocaloric Refrigerator Freezer

2014 Building Technologies Office

Peer Review



CRADA PARTNER

General Electric

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: Aug 1st, 2013 (FY14)

Planned end date: Sept 30th, 2016

Key Milestones

1. Determine requirements for refrigeration circuit seals and hydraulics; 31-March-2014
2. Develop breadboard refrigerator-freezer design; Achieve target goals with breadboard design; 9/30/2014 (Go/No-Go)

Budget:

Total DOE $ to date: $450K (FY13-$450k Received)

Total future DOE $: $1,150 ($550k in FY15 and $600k FY16)

Target Market/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.

Key Partners:

CRADA project with General Electric

Project Goal:

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

Purpose and Objectives

Problem Statement: In the U.S., residential refrigerators employ vapor compression system and use approximately 1.4 kWh/day. According to the BTO Market Definition Calculator, the projected residential refrigeration market for 2030 is 1,537 TBtu/year, plus an additional 1,590 for commercial, for a total of 3,128 TBtu/year.

Magnetocaloric refrigeration is a promising alternative to vapor compression systems and has the potential to reduce energy consumption of cooling units by 25%.

The main challenges for developing magnetocaloric cooling systems are:
a) producing low cost, stable, high magnetocaloric effect material (MCE);
b) designing a low cost, high efficiency heat transfer system;
c) producing low cost, strong magnets.
This project will mainly focus on item **a** and **b**.

Target Market and Audience: Principal audience is residential/commercial refrigeration OEMs; secondary target is small commercial refrigeration or cooling systems. It has the potential to be used in larger scale HVAC, drying, industrial heating/cooling applications as well.

Purpose and Objectives

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 is to achieve 100 F temperature span and approximately 100 watts of cooling capacity.

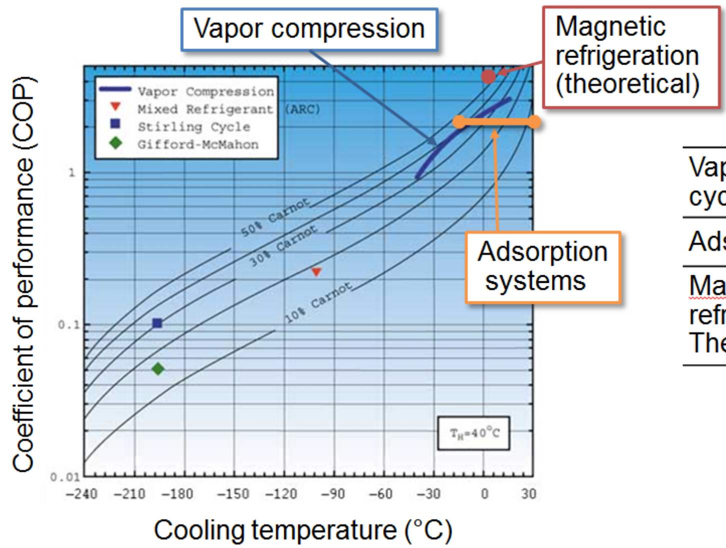
Goals:

a) Near-term:
Develop a feasible design with emerging MCE materials.

b) Intermediate-term:
Design a magnetocaloric refrigerator-freezer

c) Long-term:
Introduce a unit to the market

Theoretical performance limit for cooling systems: $COP_{Carnot} = T_C/(T_H - T_C)$



	Carnot COP
Vapor compression cycles	30–40%
Adsorption systems	5–40%
Magnetocaloric refrigeration: Theoretical limit	60%

Approach

Approach: efforts are concentrated in three categories:

a) Develop a modeling tool with optimization capabilities;

b) Address the challenges facing magnetocaloric hydraulic system and material stability

c) Develop a high efficiency magnetocaloric system design.

Key Issues:

1) optimization of utilization factor and other non-dimensional parameters of the system for different magnetocaloric materials, 2) rotating valve leakage, 3)dead-volume, 4)low heat transfer rate (limits the frequency), 5) corrosion, 6)MCE material carry-over, 7) large pressure drop, and 8) cost reduction

Distinctive Characteristics:

Approach "a" resolves issues #1

Approach "b" resolves issues #2&3

Approach "c" resolves issues #2 to 8

Progress and Accomplishments

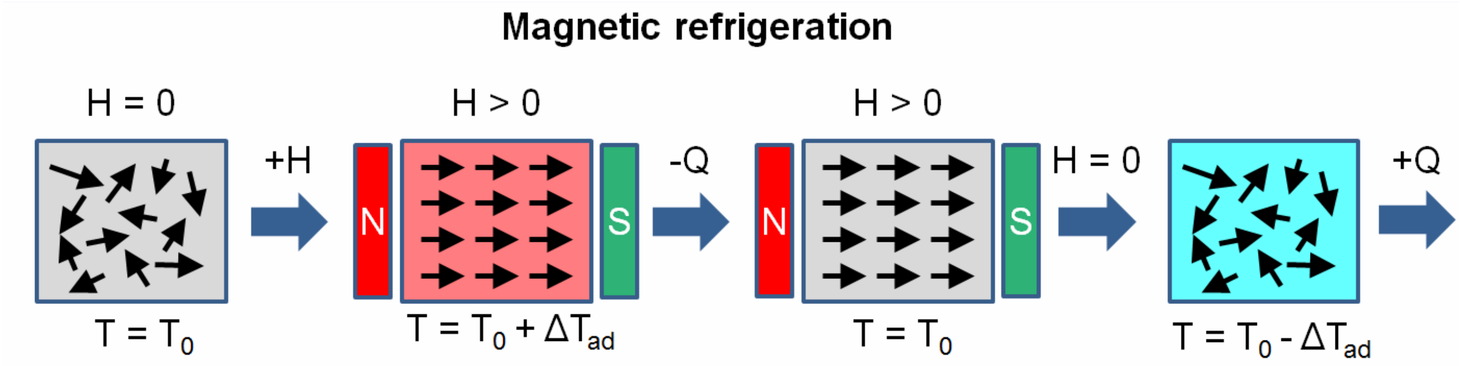
Brief Summary of Accomplishments:

- A novel idea of "leak-less rotary valve" has been conceived, fabricated and tested that may result in a long life, and low leak fluid control valve. ***ORNL Invention Disclosure*** **201403265 (DOE S-Number# S-124,876).**
- The novel idea of "Magnetocaloric Refrigeration using ****(intentionally removed)", ***ORNL Invention Disclosure 201403263*** **(DOE S-Number# S-124,874)** has been conceived which can potentially reduce the cost of system and at the same time enhance the performance of the system.
- A refrigerator-freezer design specifications has been completed.
- A model for multi-objective optimizations of active magnetic refrigeration (AMR) system has been developed.
- A bench scale prototype has been developed and initial testing has been performed.
- Two manuscripts have been submitted to Thermag VI, ASME IMECE 2014 conferences.

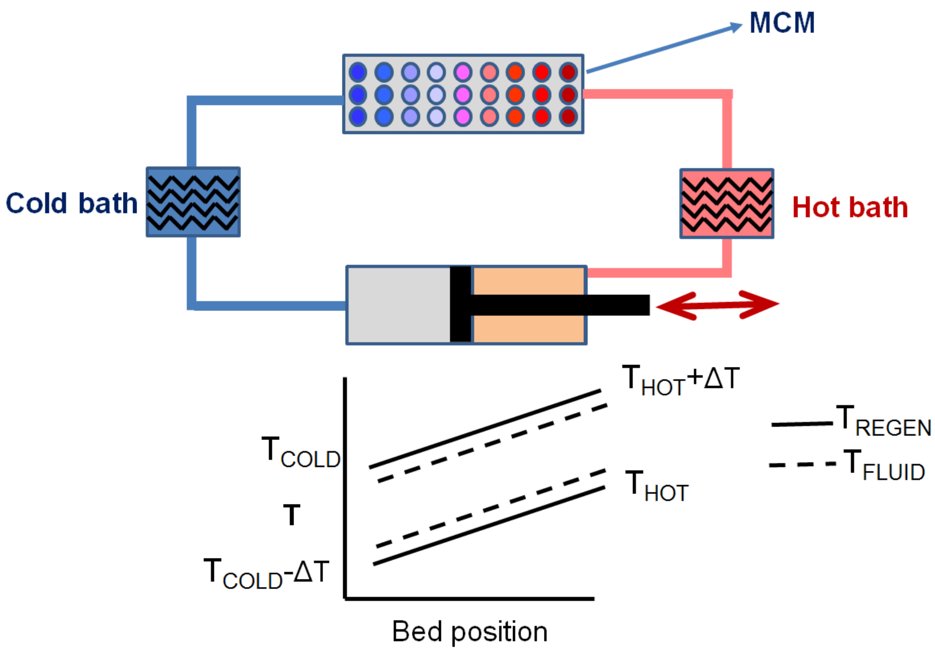
Progress on Goals:

- Requirements for refrigeration circuit seals and hydraulics has been determined.
- Refrigerator-freezer design specifications have been determined.

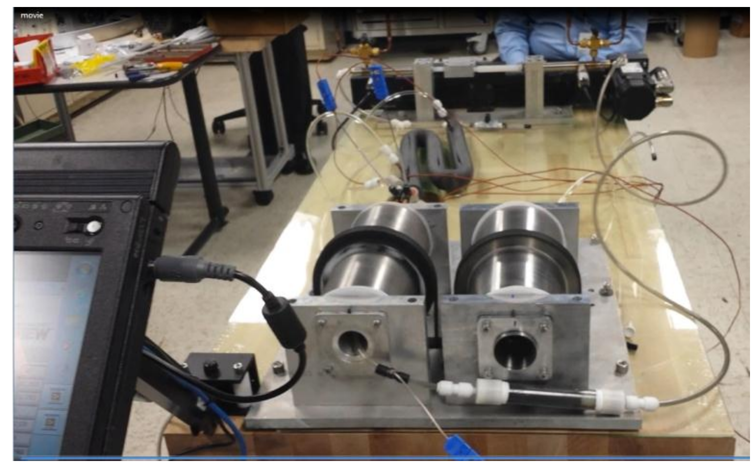
Brief Description of Basic Principal



Active Magnetic Refrigeration (AMR)



General Electric's Prototype



Video

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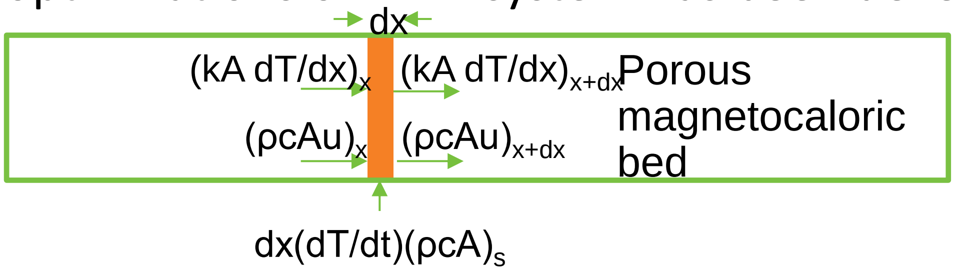
Progress and Accomplishments

Accomplishment 1 (satisfies Milestone Q1): A fast/accurate model for multi-objective optimizations of AMR system has been developed:

1D energy equations



$$(1-\varphi)(\rho c)_s \frac{\partial T_s}{\partial t} = (1-\varphi)k_s \frac{\partial^2 T_s}{\partial x^2} - hA_{fs}(T_s - T_f) + (1-\varphi)q_s^{'''}$$ Energy equation for solid phase

$$\varphi(\rho c)_f \frac{\partial T_f}{\partial t} + (\rho c)_f u \frac{\partial T_f}{\partial x} = \varphi k_f \frac{\partial^2 T_f}{\partial x^2} + hA_{fs}(T_s - T_f) + \varphi q_f^{'''}$$ Energy equation for fluid phase

$$h = \frac{Nuk_f}{D_h}, \qquad Nu = f(\mathrm{Re})$$ Fluid-solid coupling

$$u = \frac{-k}{\mu}\nabla P,$$ Darcy law for fluid flow

16 independent variables, Running thousands cases for optimization is very time consuming

Local thermal equilibrium approximation ($T_s = T_f = T$)

Accurate for Particle Diameter <2 mm or System Frequency <2 HZ

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c)_f u \frac{\partial T}{\partial x} = k_m \frac{\partial^2 T}{\partial x^2} + q_m^{'''} \qquad [1]$$

- **8** independent variables (compared to original**16** independent variable)
- Computationally less expensive
- Running thousands cases for optimization purposes is feasible

[1] D. a. Nield and A. Bejan, "Convection in Porous Media," pp. 31–47, 2013.

Progress and Accomplishments

- **Accomplishment 1 cont.**:

Dimensionless variables: $x^+ = \frac{x}{L},\ t^+ = \frac{t}{\tau}\ , u^+ = \frac{u\tau}{L}, T^+ = \frac{T - T_i}{\Delta T_{adi-c}}\ , q^+ = \frac{q_m''' \forall}{\dot{q}_{cooling}}$

$$\dot{q}_{cooling} = u\varepsilon A_c (\rho c)_f (T_{amb} - T_{cold\_bath})$$

$$\frac{\partial T^+}{\partial t^+} + \Phi \frac{\partial T^+}{\partial x^+} = \lambda_1 \frac{\partial^2 T^+}{\partial x^{+2}} + \lambda_2 q^+$$

Similar to utilization factor $\frac{\dot{m}_f c_f \tau}{m_s c_s}$

Dimensionless Parameters :

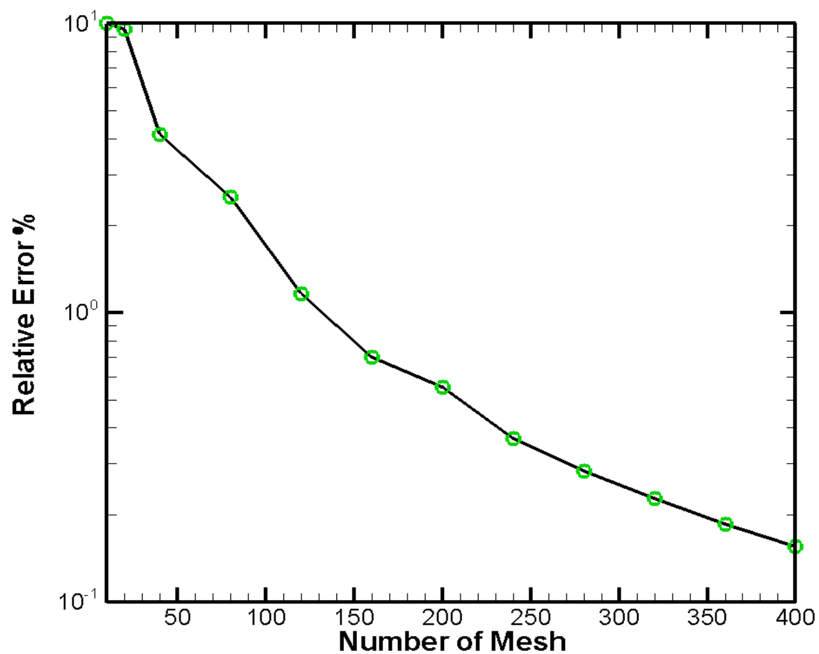
$$\Phi = \frac{(\rho c)_f}{(\rho c)_m} u^+,\ \lambda_1 = \left(\frac{k_m \tau}{L^2 (\rho c)_m}\right), \text{ and } \lambda_2 = \left(\frac{\Phi \varepsilon (T_{amb} - T_{cold\_bath})}{\Delta T_{adi-c}}\right).$$

Utilization factor | Importance of axial thermal diffusion | Cooling load vs. magnetocaloric cooling potential

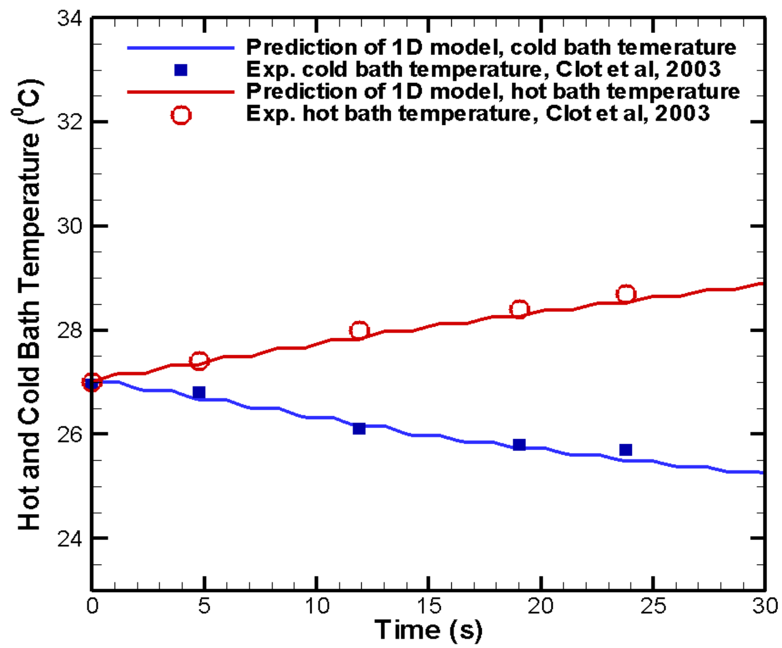
Progress and Accomplishments

- **Accomplishment 1 cont.:**

1st order upwind	Courant number <0.05	400 grids	Computational time ~ 2 s/cycle



Relative numerical error of modeling with respect to number of elements along regenerator



Model validation with experimental results [Clot et al. (2003)]

Video of a sample simulation

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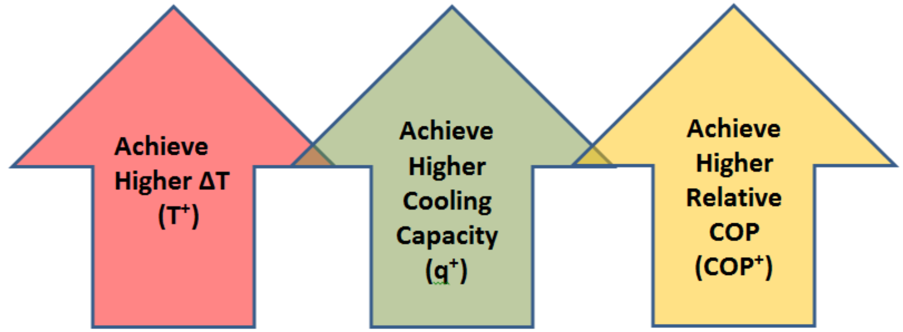
Progress and Accomplishments

- **Accomplishment 1 cont.**:

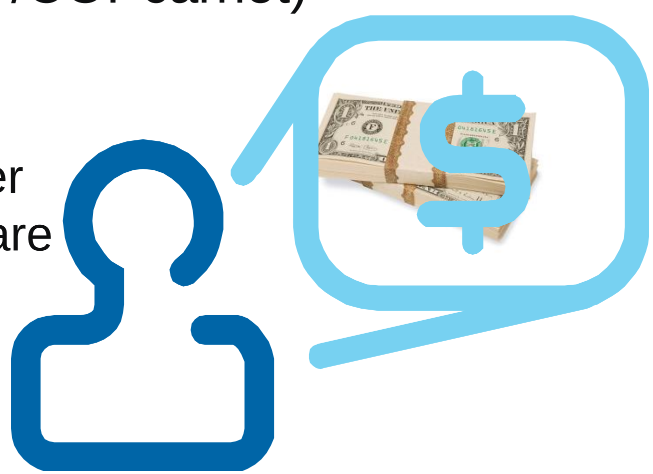
Multi Objective Optimization:

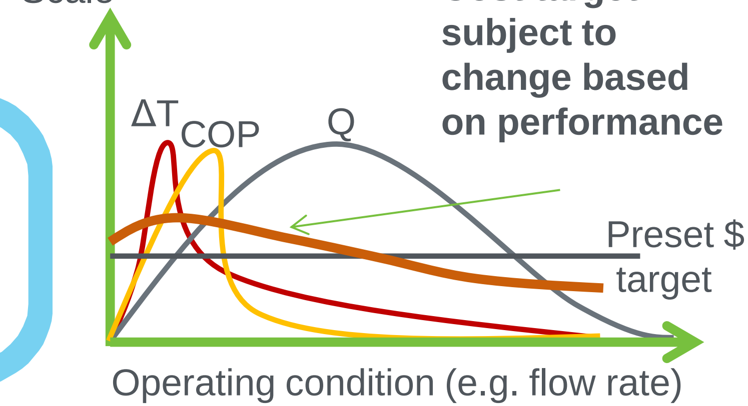


Technically there are three competing parameters:

The goal is:
-higher temperature span
-higher cooling capacity
-higher COP^+ (=COP/COPcarnot)

What industry cares about:
Consumer cost in order to maintain market share





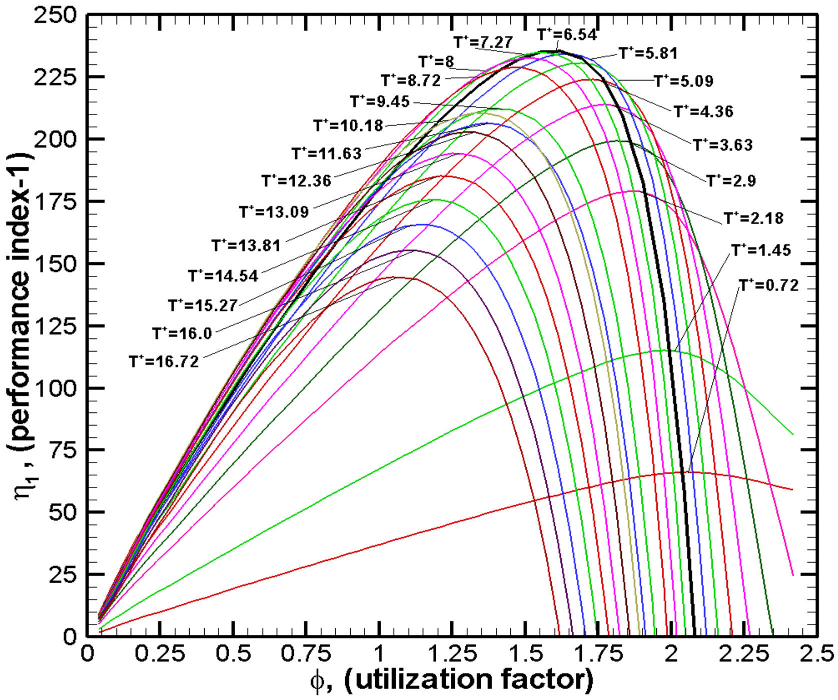
Cost target subject to change based on performance

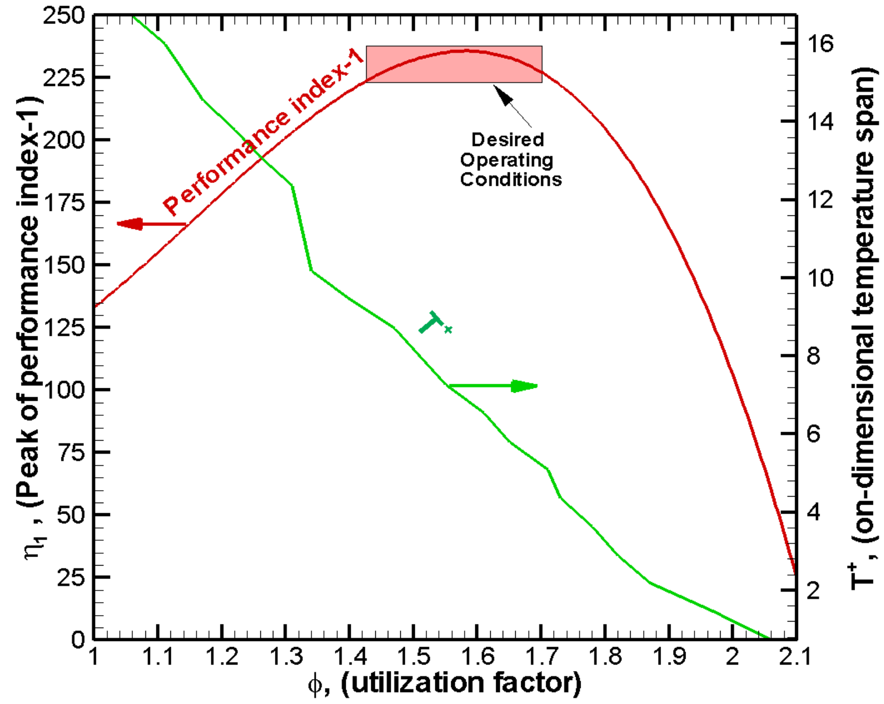
Progress and Accomplishments

- **Accomplishment 1 cont.**:
- Let's define "performance index 1":

$$\eta_1 = T^+ . q^+$$ Or in dimensional form $$\eta_1 = \Delta T . q_{cooling}$$

Summary results of more than **3500** runs.





e.g. Think as Mass Flow Rate

Progress and Accomplishments

Accomplishment 2 (satisfies Milestone Q2):
Developing a solution for problematic rotating valve. The challenges were 1) expense, 2) leakage 3) high torque requirement 4) wear and life time.

- Proposed Solution 1: Leak-less Rotating Valve Utilizing ***** (intentionally removed) ***, ***ORNL Invention Disclosure 201403265,*** **DOE S-Number# S-124,876**.

low cost solution prevents leakage, and gap or wear over time
(further investigation is required)

Video of rotating valve

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Progress and Accomplishments

Accomplishment 3 (novel solutions- beyond Milestones):

- Proposed Solution 2: Magnetocaloric Refrigeration using ****(intentionally removed), ***ORNL Invention Disclosure 201403263,*** **DOE S-Number# S-124,874**.

- Typical magnetocaloric refrigerator components:

1. Magnet
2. Generators
3. Motor

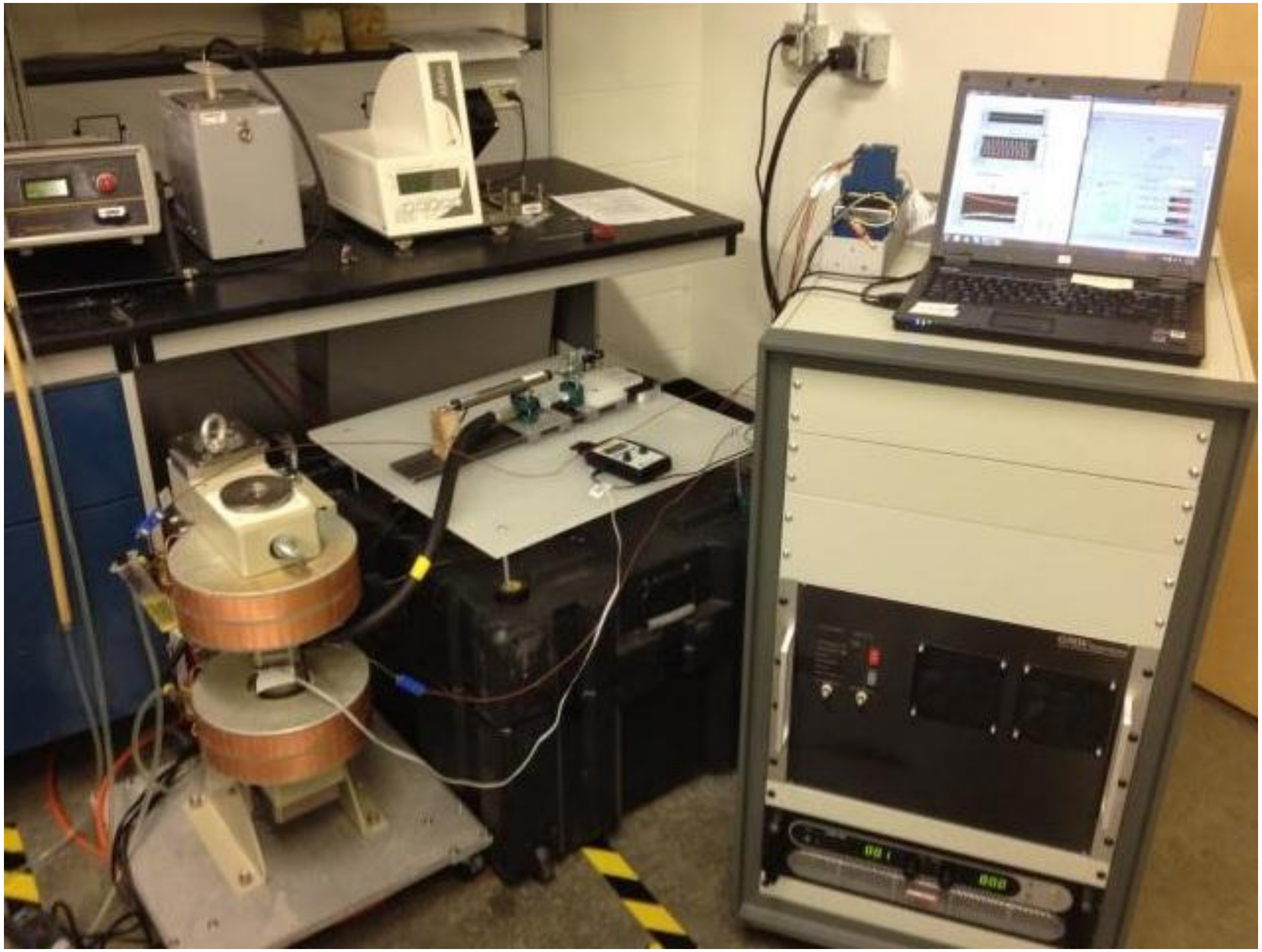
4. Pump
5. Heat exchangers
6. Plumbing
7. Leak less rotating valve

In this novel design, these components may not be required

Progress and Accomplishments

Accomplishment 4:

ORNL bread-board prototype for validation.



Progress and Accomplishments

Market Impact:
This project can potentially save 0.75 Quad of energy and be the first commercialization of magnetocaloric refrigeration in the world

Awards:
None

Recognition/Publication/Inventions:

1. "Magnetocaloric Refrigeration using ******", **INVENTION DISCLOSURE NUMBER:** 201403263, DOE S-Number# S-124,874.
2. "Leak Less Rotating Valve Utilizing ****", **INVENTION DISCLOSURE NUMBER: 201403265,** DOE S-Number# S-124,876.
3. "Thermofluid Analysis of Magnetocaloric Refrigeration", Ayyoub Mehdizadeh Momen, Omar Abdelaziz, Kyle Gluesenkamp, and Edward Vineyard and Michael Benedict, TherMag VI, 7-10 Sept 2014, 1534.
4. "Multi-Objective Optimization of Magnetocaloric Refrigeration", Ayyoub Mehdizadeh Momen, Omar Abdelaziz, Kyle Gluesenkamp, and Edward Vineyard and Michael Benedict, ASME IMECE, Montreal, Canada, Nov. 14-20 2014, IMECE2014-38928.

Project Integration and Collaboration

Project Integration: The project is based on a collaborative R&D agreement (CRADA) with General Electric (US Appliances OEM).

a) ORNL-GE have bi-weekly technical phone call meetings.

b) ORNL-GE working on join patents/publications and try to explore all the pre-planed and novel solutions.

c) ORNL-GE have quarterly site visits.

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

Partners, Subcontractors, and Collaborators:

General Electric

Communications:

- GE's recent live public press-Google Hangout

Video is available at:

http://www.youtube.com/watch?v=uDF_COU1OJI

Next Steps and Future Plans

Next Steps and Future Plans:

Next steps:

Assess components and material requirements for refrigeration system

Develop bread-board refrigerator freezer design. This includes:

- Number of generators
- Hydraulic circuit design
- Material compatibility
- Heat exchanger sizing
- Pump sizing
- Utilization factor/Frequency/Mass of material/Porosity of material
- Magnet selection based on the geometry of the generators

Future plans:

Develop a prototype for the novel system described in INVENTION DISCLOSURE NUMBER: 201403263 and compare its performance with conventional systems. This solution may provide a breakthrough in magnetocaloric refrigeration and not only lead to 50% cost reduction, but also enable the Active Magnetic Refrigeration (AMR) system to run at one order of magnitude higher frequency (higher cooling capacity).

REFERENCE SLIDES

Project Budget

Project Budget: DOE total $1,600k FY 13-16
Variances: None.
Cost to Date: ~$198k through February 2014 (FY13~$77k, FY14~121k)
Additional Funding: None expected.

Budget History					
FY2013		FY2014		FY2015 – F2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$450k	*	$0	*	$1,150	*

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Project Plan and Schedule

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 missed
	◆	Milestone/Deliverable (Actual) use when met on time

	FY2013				FY2014				FY2015			
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)	Q4 (Jul-Sep)
Past Work												
Determine refrigerattor-freezer design specifications					◆							
Determine requirements for refrigeration circuit seals and hydraulics						◆						
Current/Future Work												
Assess component and material requirements for refrigeration circuit							◆					
G/NG (Q4): Develop breadboard refrigerator-freezer design; Achieve target goals with breadboard design								◆				
Explore properties of feasible MCE material									◆			
Review appropriate manufacturing processes and identify the most promising for material selection										◆		
Design the layered material and initiate fabrication											◆	
Performe initial testing on the material												◆