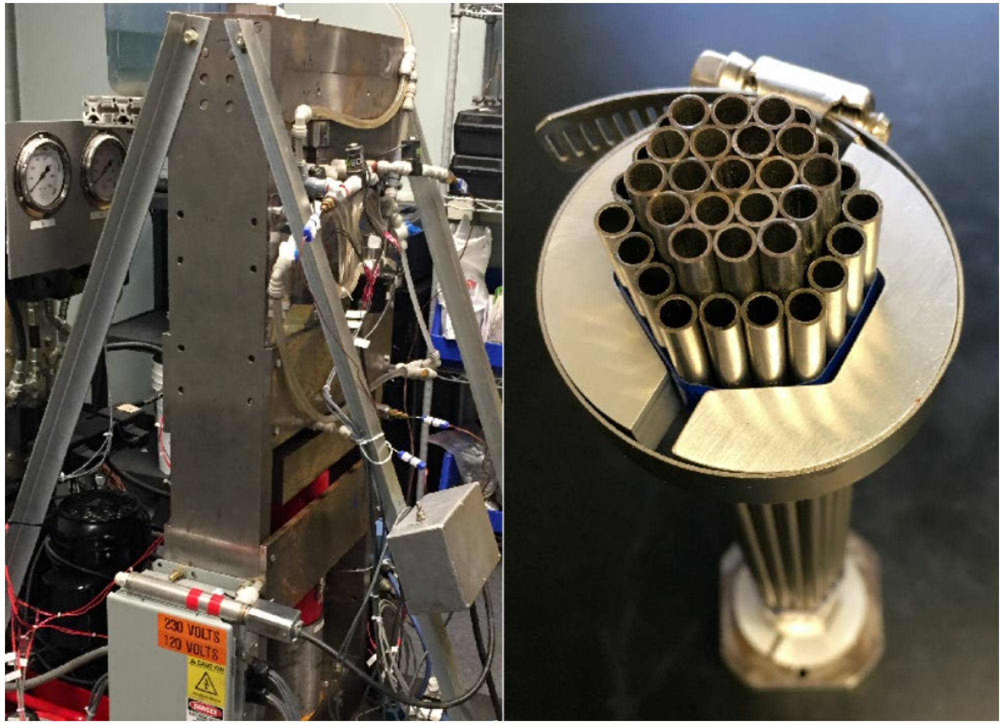
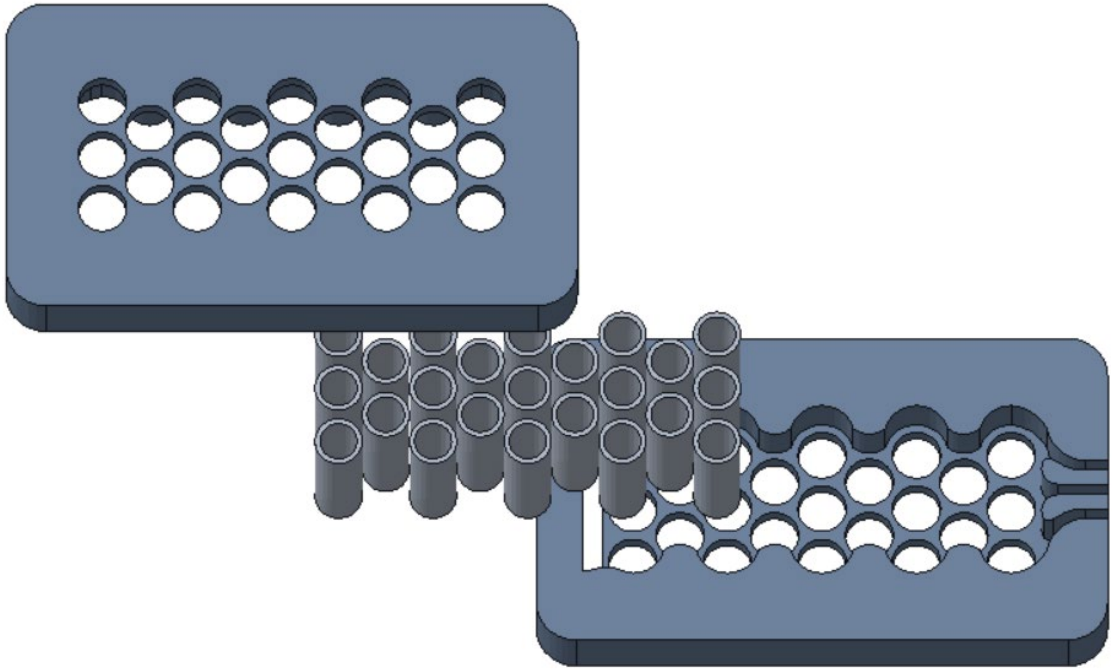
Thermoelastic Active Regenerators with Giant ΔT



Active Regenerator based on NiTi Tube Bundles



Cascade Regenerator

Performing Organization(s): University of Maryland, Maryland Energy & Sensor Technologies, LLC
PI Name and Title: Ichiro Takeuchi, Professor
PI Tel and/or Email: 301-405-6809, takeuchi@umd.edu

Project Summary

Timeline:

Start date: 04/02/2020

Planned end date: 03/31/2023

Key Milestones

- Demonstration of reciprocating active regenerator based on NiTi tube bundles; 06/30/2021
- Initial operation of cascade regenerator; 06/30/2021
- Cu-based thermoelastic materials identified; 04/30/21

Budget:

Total Project $ to Date:

- DOE: $ 342,416
- Cost Share: $115,693

Total Project $:

- DOE: $ 1,800,000
- Cost Share: $ 450,000

Key Partners

Maryland Energy & Sensor Technologies, LLC (Cu-based thermoelastic materials and systems)
University of North Texas (Tuned NiTi materials)

Project Outcome:

The proposed project aims to design, develop, demonstrate, and evaluate scalable thermoelastic Brayton-like active regenerator prototypes with system ΔT as large as 100 K. The systems will be based on NiTi tube bundles, and one of the designs will feature a novel multi-stage cascade regenerator. We will also demonstrate a compact regenerator based on novel Cu-based thermoelastic alloys.

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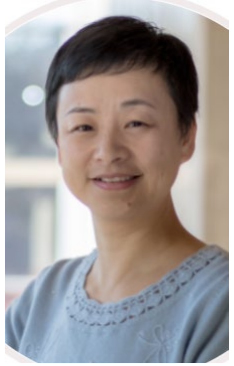
Team

- **PI: Ichiro Takeuchi**
- **Department of Materials Science and Engineering:** Functional materials, high-throughput materials science
- **Key Members:**
  - Takahiro Yamazaki (postdoctoral researcher)
  - James Shen (graduate student)

- **Co-PI: Reinhard Radermacher**
- **Director, Center for Environmental Energy Engineering**
- **Key Members:**
  - Prof. Yunho Hwang (Cooling devices)
  - Jan Muehlbauer (engineer)
  - Nehemiah Emaikwu (graduate student)



- **Co-PI: Sherry Xie (Chief Operating Officer)**
- **Maryland Energy & Sensor Technologies, LLC (MEST):** Start-up focused on commercializing thermoelastic cooling technologies
- **Key Member:**
  - Abimael Santos (engineer)

Challenge

Problem Definition: Thermoelastic cooling, which utilizes high latent heat of martensitic transformation for pumping heat, is one of the most promising alternative cooling technologies. Despite its potentials, there has not been demonstration of commercial-scale thermoelastic cooling devices.

Project Goals: Our project aims to design, develop, demonstrate, and evaluate scalable thermoelastic Brayton-like active regenerator prototypes with system ΔT as large as 100 K.

- Implementation of NiTi tube bundles for active regeneration scheme with 400 W operation with $\Delta T > 50$ K
- Develop giant ΔT regenerators using multilayered NiTiX materials stack with cascade designs
- Demonstration of active regenerators based on Cu-based thermoelastic materials for compact table-top operation

Approach - Overview

Year-1: Develop and optimize NiTi tube bundle regenerator and simulations

- *Demonstration of active regenerator based on tube bundles*
- *Investigate feasibility of giant ΔT using multilayered stack*
- *Synthesize/obtain Cu-based thermoelastic materials*
- *Simulation of thermoelastic active regenerator*
- *Market transformation plan*

Year-2: NiTiX cascade regenerator for giant ΔT

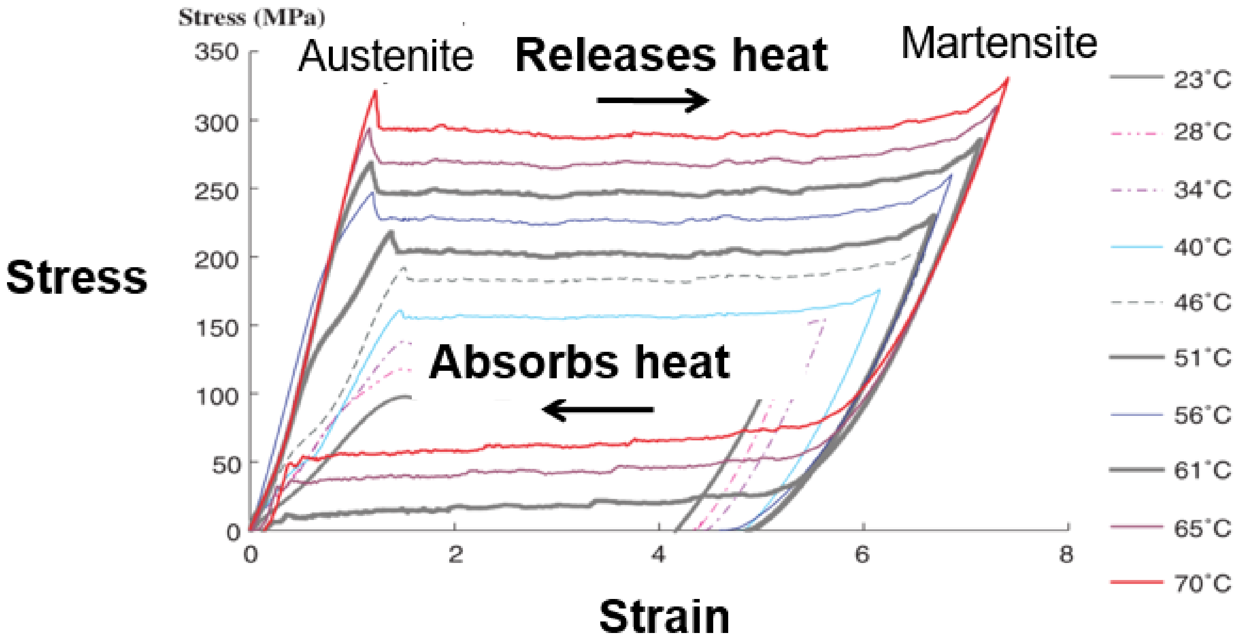
- *Tube bundle regenerator with ΔT > 50 K and 400 W*
- *Design and construct cascade regenerator with giant ΔT*
- *Initial design and construction of regenerator with Cu-based materials*
- *Improvement of systems*
- *Market transformation plan*

Year-3: Table-top operation of the Cu-based regenerator

- *Finish optimization of tube bundle regenerator; evaluate system COP*
- *Optimize operation of giant ΔT cascade regenerator*
- *Stand-alone operation of 25 W Cu-based table-top regenerator*
- *Market transformation plan*
- *Develop commercialization plans*

Approach - Thermoelastic Active Regeneration

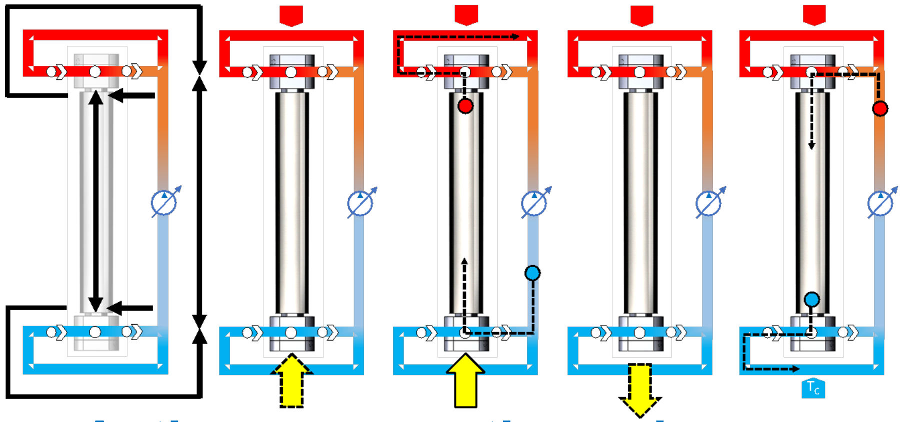
- Latent heat of martensitic transformation is used to pump heat from superelastic shape memory alloy
- Materials temperature lift can be as large as ΔT > 20 K
- Materials COP can be as high as 80% of the Carnot limit



Stress- strain curves at various temperatures

Superelasticity of shape memory alloys

- Active regeneration can be used to boost ΔT
- Each thermoelastic material can operate over 140 K span
- In compression mode, thermoelastic materials have been shown to survive over 1 million cycles



Single tube bundle regenerator operation steps (from left to right)

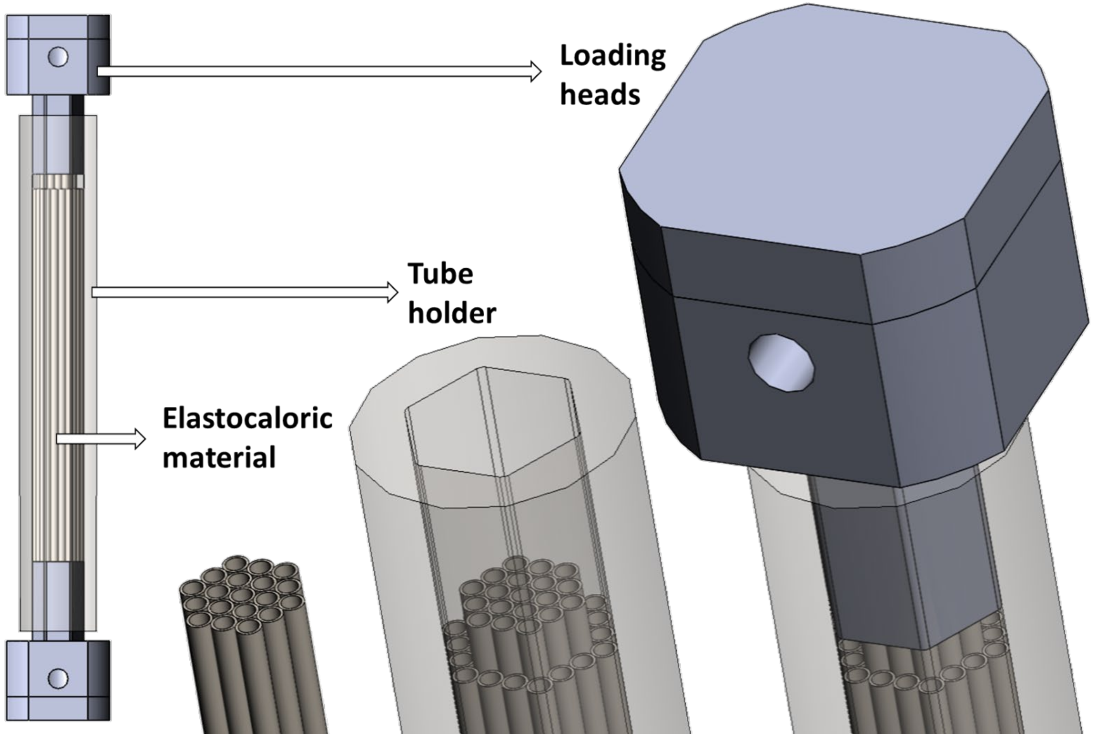
Active regeneration scheme

Impacts

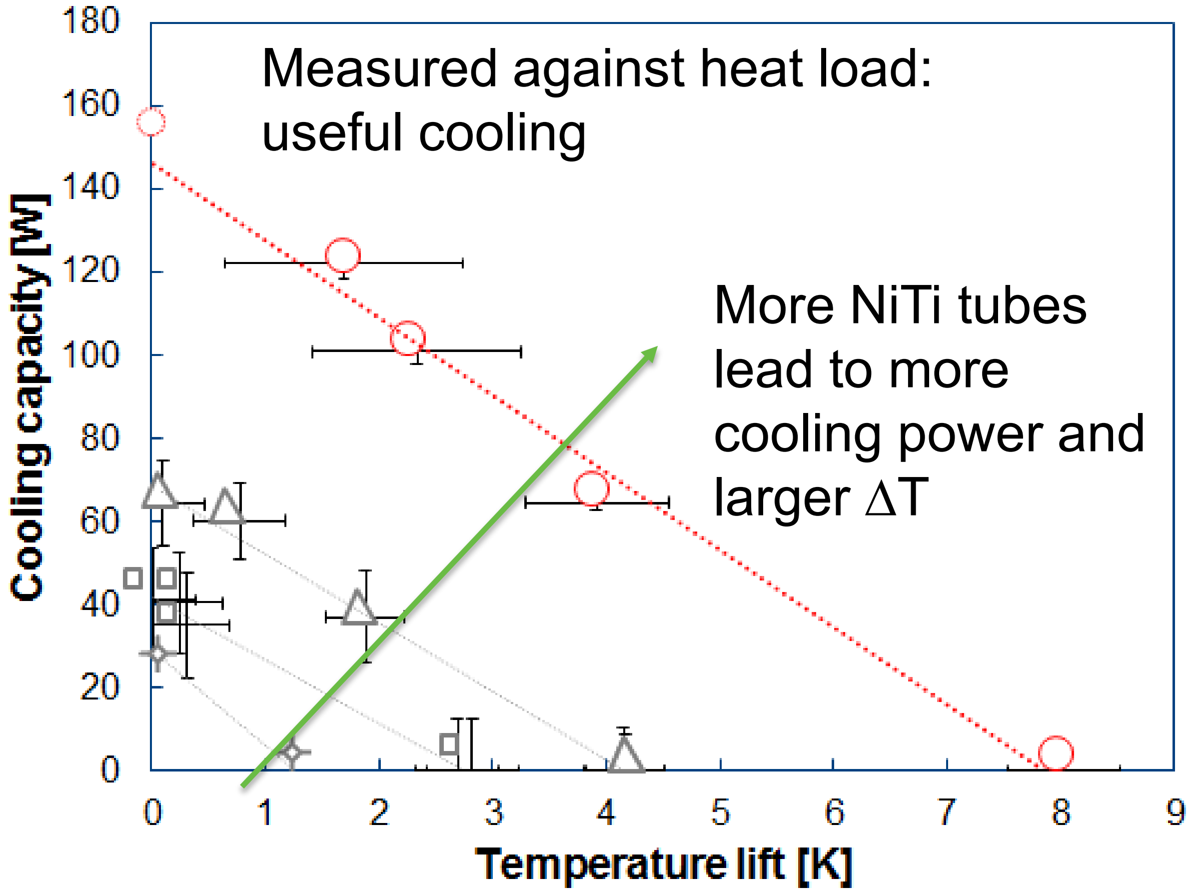
- **Technology Advancement**
  - Thermoelastic cooling device with 400 W in delivered cooling
  - Cascade regeneration implementing materials for attaining giant ΔT across system
  - Novel Cu-based thermoelastic materials requiring low critical stress for compact device configuration using small actuators
- **Air conditioning Industry Impact**
  - Development of zero GWP cooling device with potential for high system COP
- **Energy Saving**
  - Targeted system COP of > 4
  - Applicable to residential and commercial building in all climate zones
  - Primary energy saving potential (nationally): 437 TBtu

Progress 1 – NiTi tube bundle based regenerators

Largest useful cooling power (140 W) and the largest regenerator ΔT (22.5 K) for thermoelastic (elastocaloric) cooling have been achieved to date



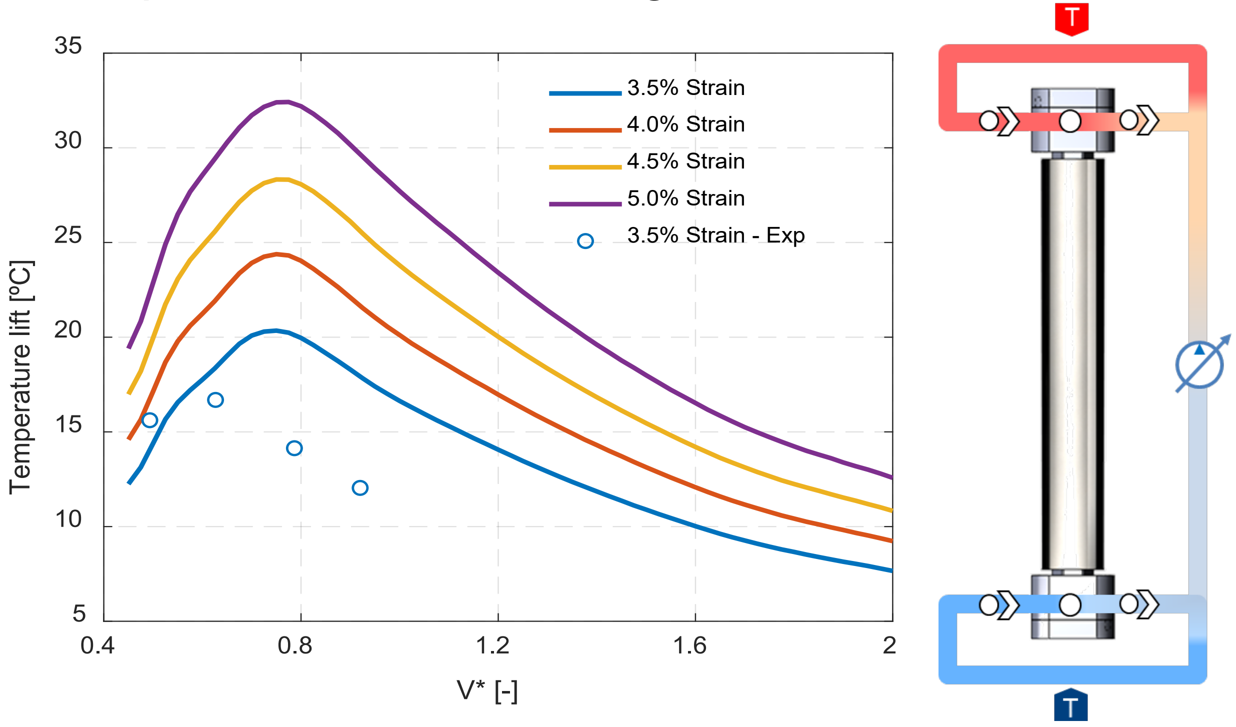
NiTi tube bundle compression configuration



Progress 1 – NiTi tube bundle based regenerators

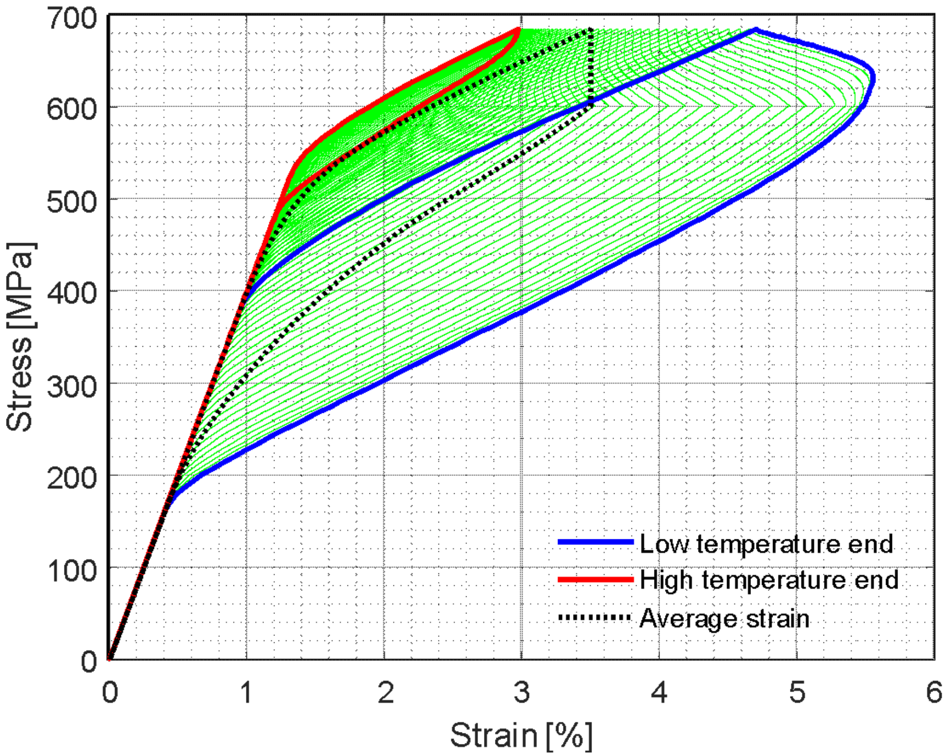
Simulation tools have been developed which guide us in optimizing the system operation performance

Simulation (curves) vs experiment (points): temperature lift across regenerator vs V*



V* (utilization factor): fraction of cooling fluid (water) which circulates in regenerator

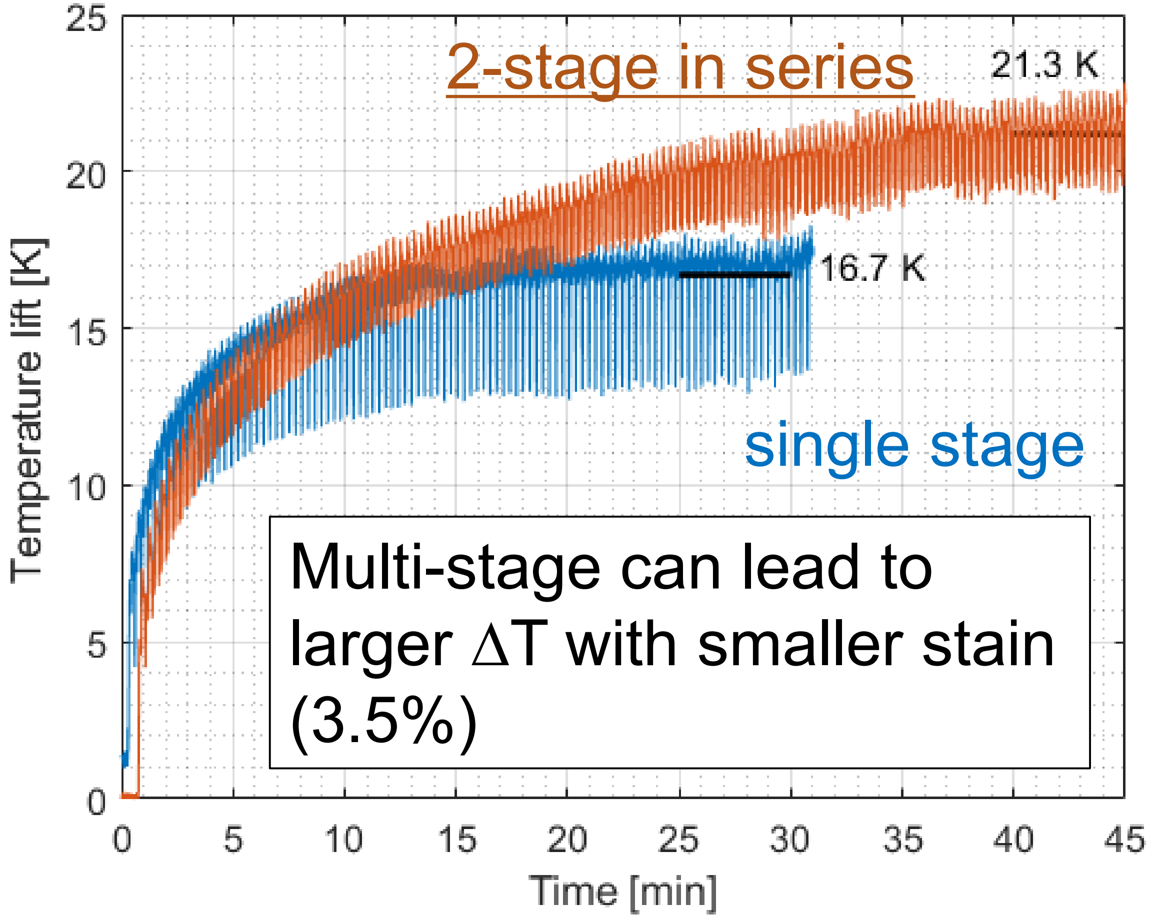
Simulation of stress-strain at different positions within one single-stage regenerator



Temperature lift leads to unbalanced strain across regenerator

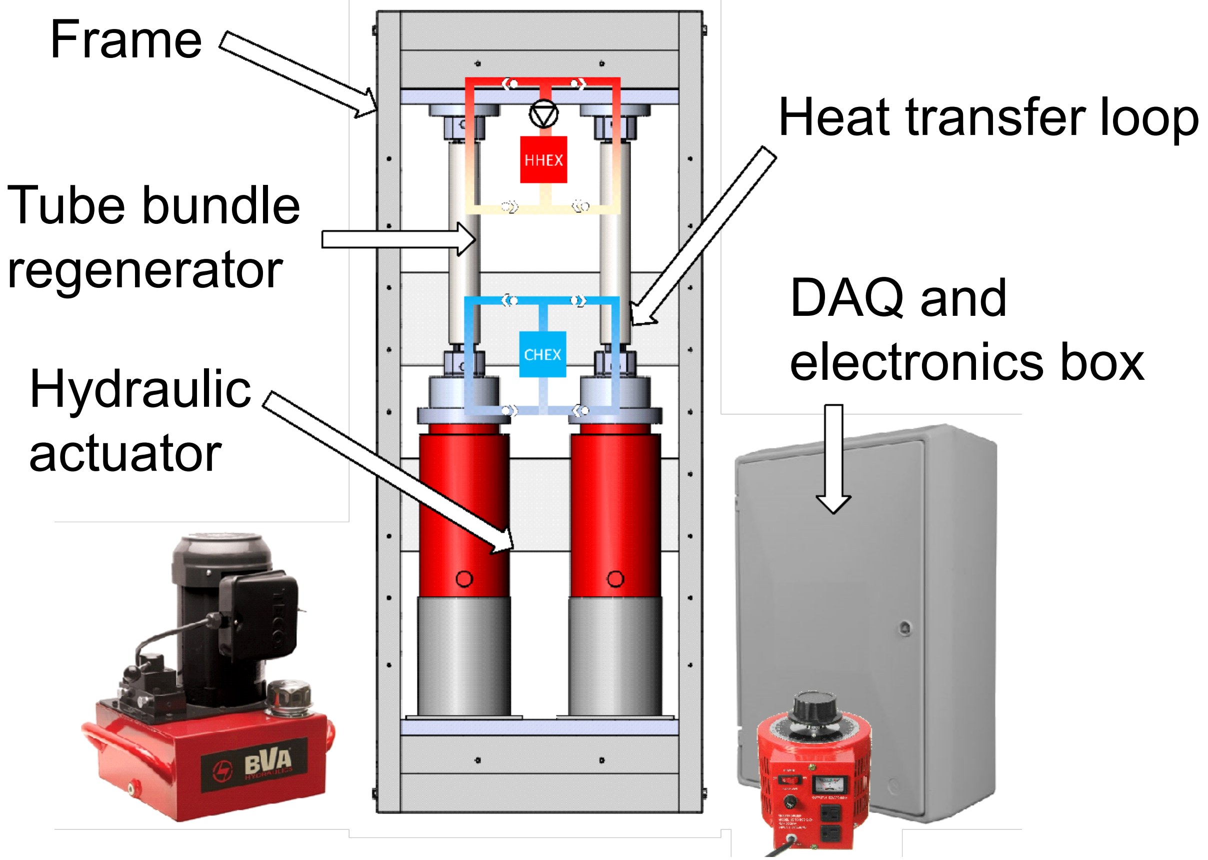
Progress 1 – NiTi tube bundle based regenerators

Various multi-stage configurations have been developed and are being tested



Experiment: ΔT develops over ~ 20 min.

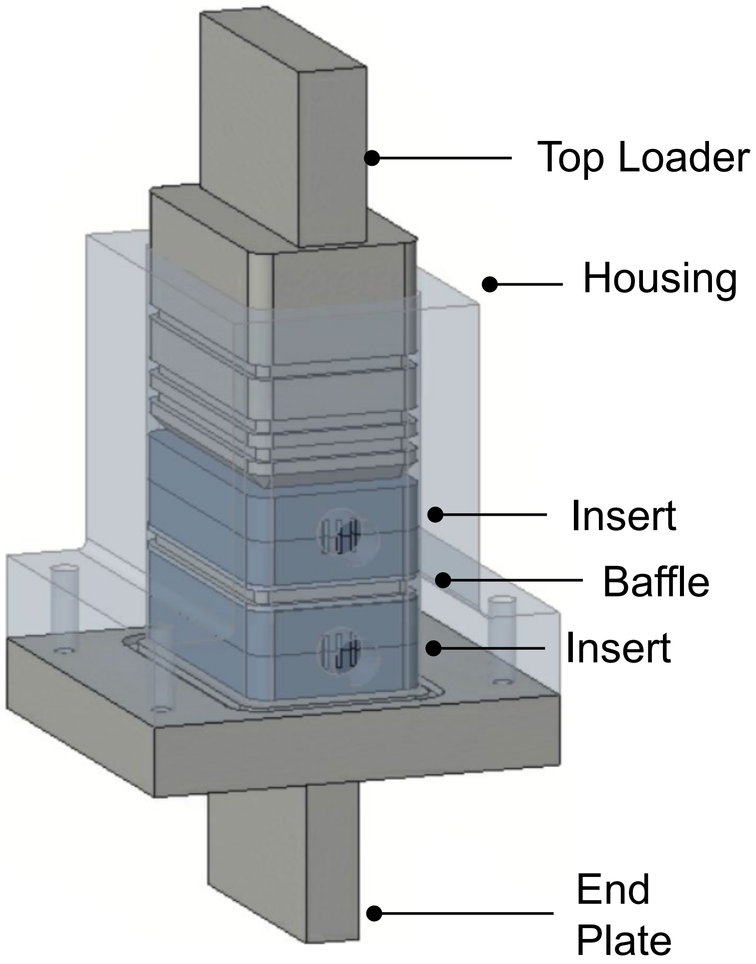
2-stage in parallel



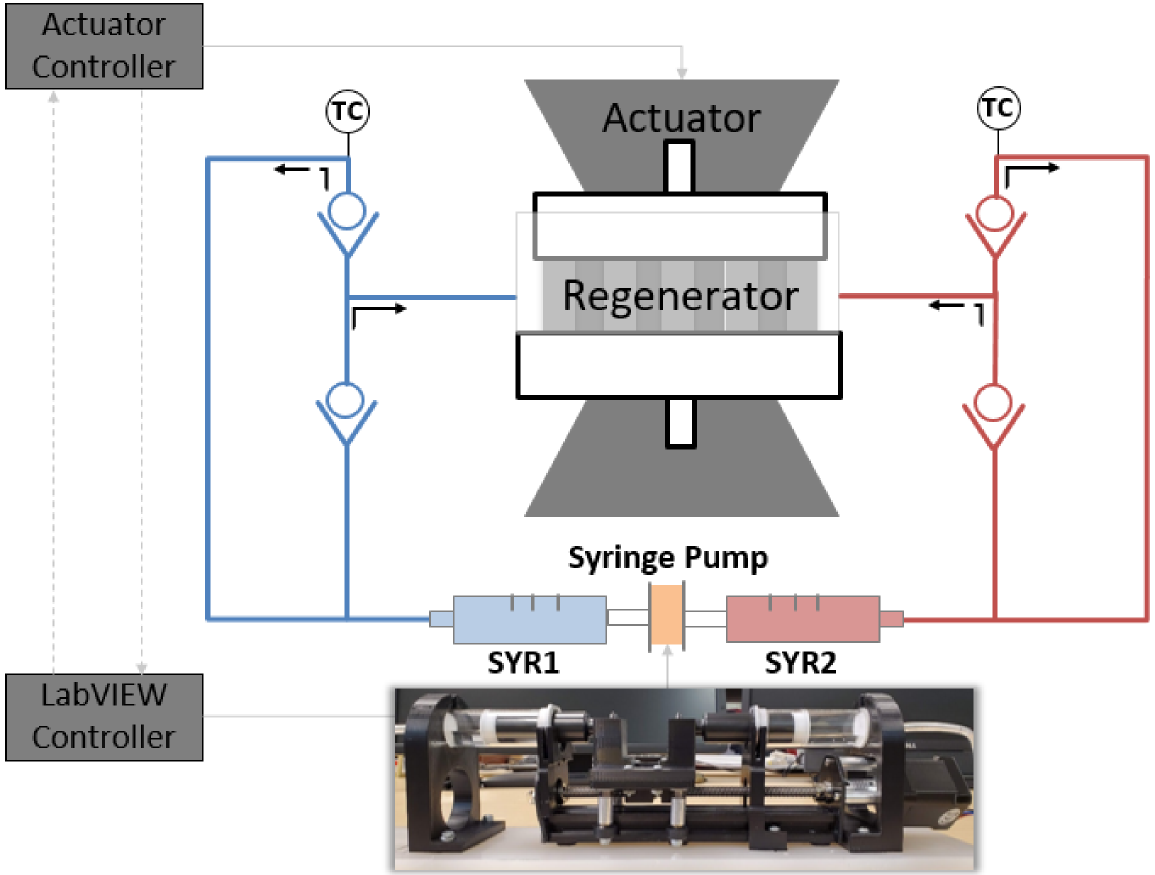
Reciprocating 2-stage (parallel) set-up can work on both ends of regenerator at the same time

Progress 2 – Cascade regenerator for giant ΔT

Cascade regenerator design and experimental measurement setup



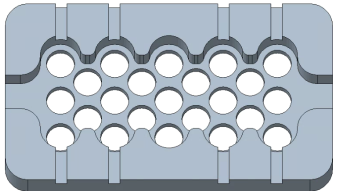
2-stage cascade regenerator[1]

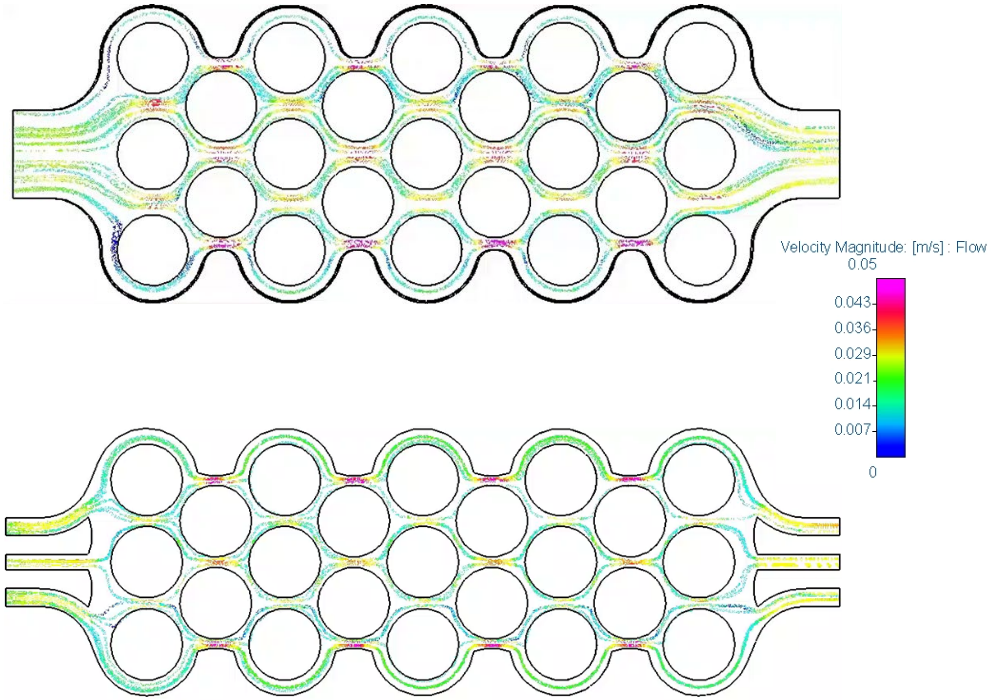


In addition to the potential for giant ΔT, the cascade design allows simpler regenerator housing

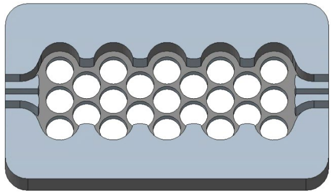
Progress 2 – Cascade regenerator for giant ΔT

1S-4



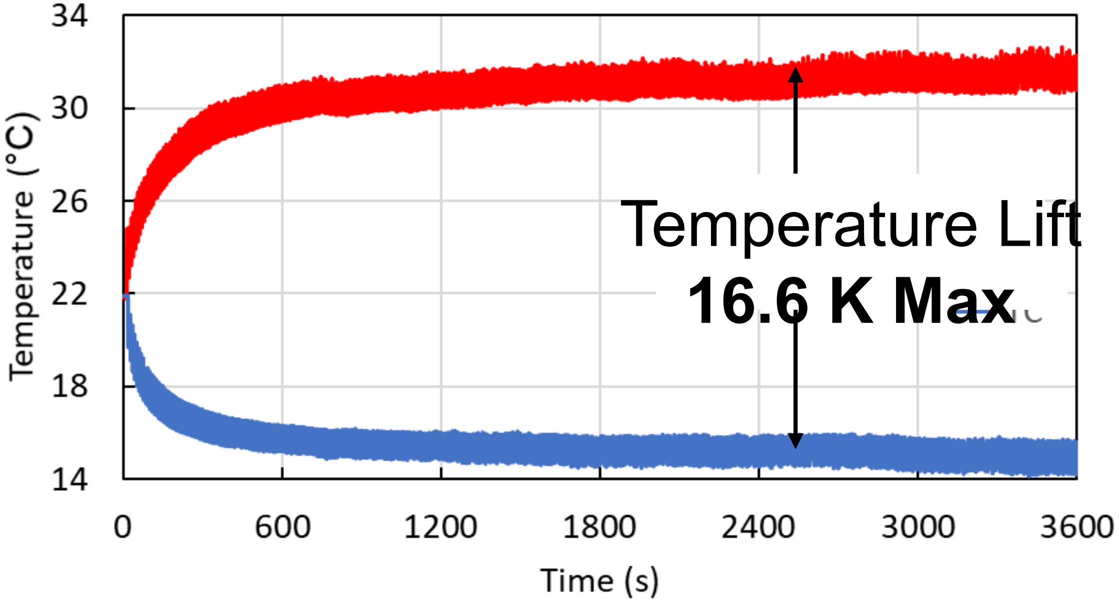


1S-6 (28%↓)
Added Distributor
Decreased S_T

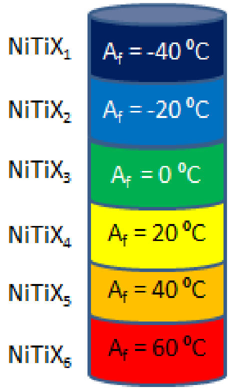


Simulation on medium flow around NiTi tubes is carried out to optimize the heat exchange with tubes

The largest ΔT across 2-stage cascade observed to date is 16.6 K



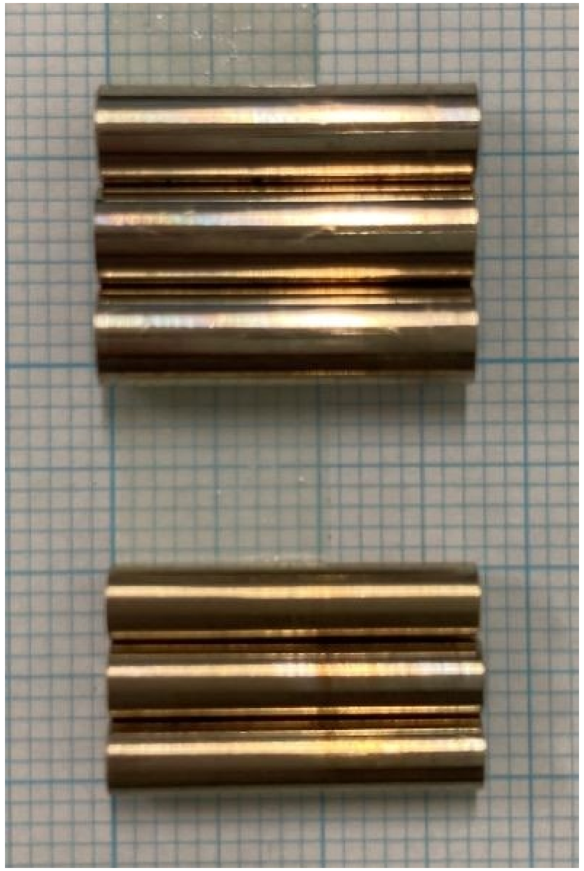
Effort to develop NiTiX materials with tuned transformation temperature for multi-level cascade is under way



Conceptual schematic of cascade stack

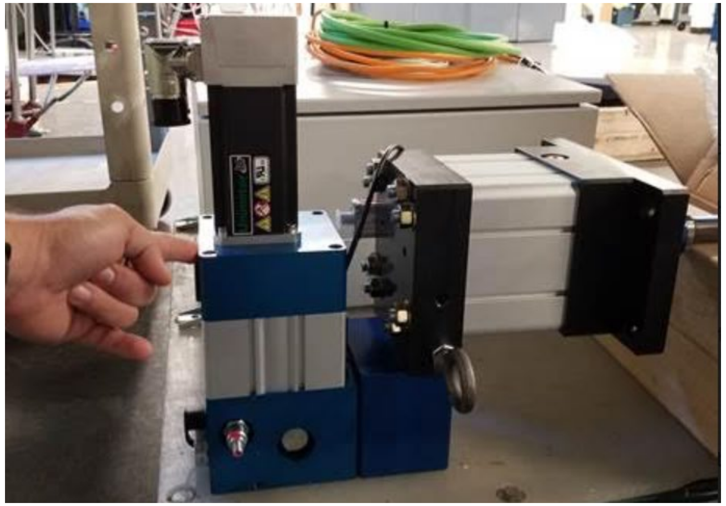
Progress 3 – Compact regenerator using Cu-based materials

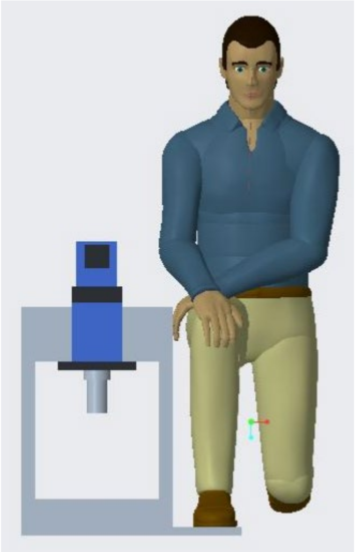
Cu-based thermoelastic materials require much smaller stress than NiTi, and thus can be used to construct regenerators with more compact actuators: the goal is to develop 25 W system with $\Delta T > 25$ K



Cu-Mn-Al and Cu-Zn-Al thermoelastic materials have been machined for implementation in cascade devices

Initial Cu-based regenerator construction and operation has commenced





Design of the frame and the overall active regenerator based on Cu-based thermoelastic materials

Stakeholder Engagement

- **Team Partner:**
  - Maryland Energy & Sensor Technologies, LLC (MEST) is the exclusive licensee of the thermoelastic cooling technology from the University of Maryland. They have helped developed the Cu-based thermoelastic materials.

- **Industrial Partners:**
  - We have regular update meetings with several major HVAC companies who have expressed interest in thermoelastic cooling.

- **Others:**
  - We regularly present our work at international HVAC conferences and symposia
  - We hosted THERMAG IX, the largest international conference on caloric cooling technologies at the University of Maryland, June 7-11, 2021 (online).
  - We have been interviewed by multiple media outlets recently, and news articles on thermoelastic cooling have appeared on Physics.org, MIT Technology Review, Quanta Magazine, Science Magazine, etc.

Remaining Project Work (BP2 and BP3)

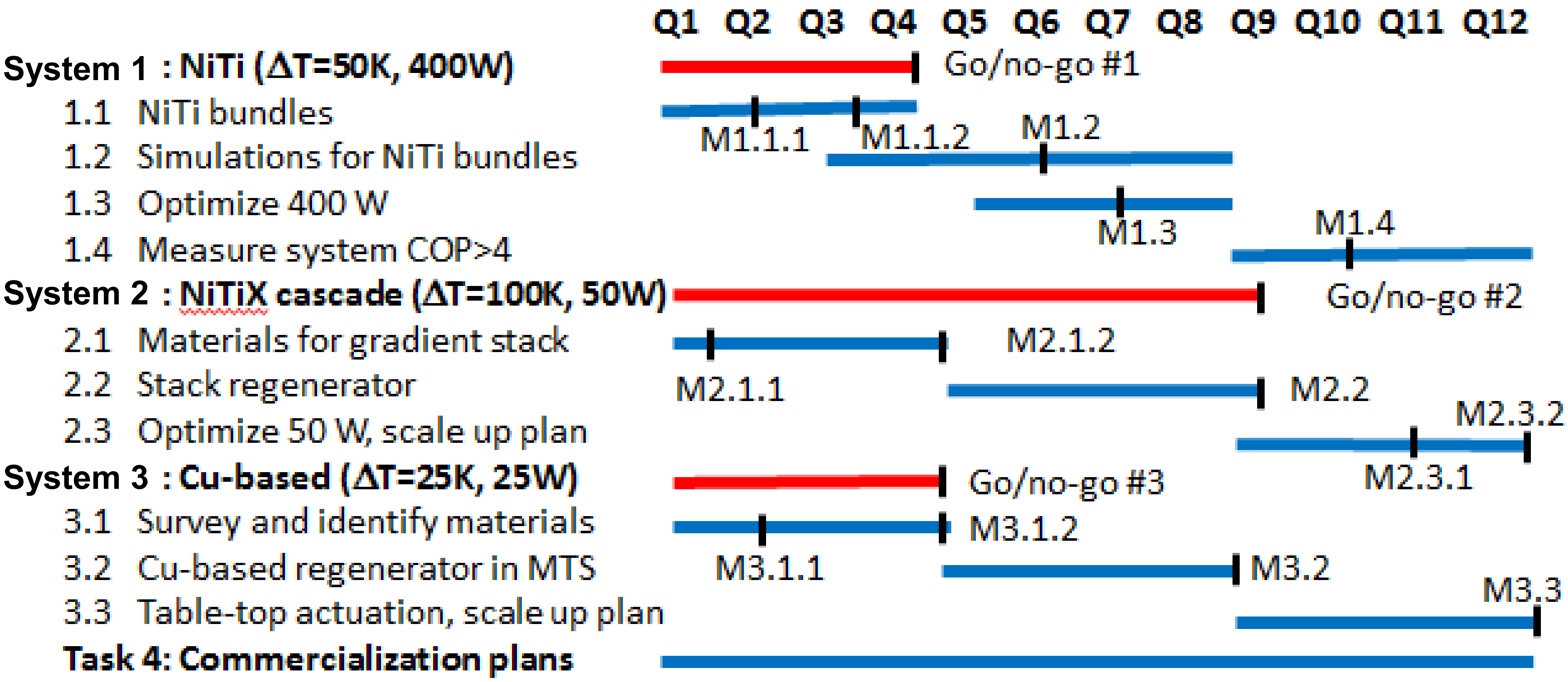
- **Task 5: Active regenerator based on NiTi tube bundles, BP2 (In progress, 50%)**
  - Perform simulations for feasibility of ΔT > 50 K with 400 W operation; complete by March 2022
- **Task 6: Multilayered NiTiX stack for cascade with giant ΔT, BP2 (In progress, 50%)**
  - Complete development of tuned NiTiX and develop cascade regenerator; complete by March 2022
- **Task 7: Design and initial construction of Cu-based regenerators, BP2 (In progress, 50%)**
  - Down select materials; build a regenerator with compact actuator; complete by March 2022
- **Task 8: Market analysis and commercialization plan (In progress, 25%)**
  - Performed on continual basis; expect full completion by late March 2023
- **Task 9: Active regenerator based on NiTi tube bundles, BP3**
  - Achieve ΔT > 50 K with 400 W operation; measure system COP; complete by March 2023
- **Task 10: Multilayered NiTiX stack for cascade with giant ΔT, BP3**
  - Optimize operation of giant ΔT (~ 100 K) cascade regenerator with 50 W; complete by March 2023
- **Task 11: Design and initial construction of Cu-based regenerators, BP3**
  - Demonstrate compact regenerator operation with ΔT > 25 K and 25 W; complete by March 2023
- **Task 12: Market analysis and commercialization plan; final report, BP3**
  - Performed on continual basis; expect full completion by June 2023

Project Budget

Project Budget: DOE 1,800,000, Cost share: 450,000
Variances: Our expenditure was low in BP1 due to COVID-19 closure in 2020 and until recently; we were unable to hire, etc. It has been ramped up in BP2
Cost to Date: DOE 342,416, Cost share: 115,693
Additional Funding: None.

Budget History					
04/2020 – 03/2021 (BP1, past)		04/2021 – 03/2022 (BP2, current)		04/2022 – 03/2023 (BP3, planned)	
DOE	Cost share	DOE	Cost share	DOE	Cost share
< 600,000	<150,000	600,000	150,000	600,000	150,000

Project Plan and Schedule



Thank You

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