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# Reversible Metal Hydride Thermal Energy Storage for High Temperature Power Generation Systems


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# Presentation Outline



- Objective and goal of our ARPA-E HEATS seedling project
- State of the art vs PNNL innovation
- Project team
- Approach
- Key technical results
- Key accomplishments
- Near term scope
- Path forward after seedling project

# Show Proof of Concept of High Temperature Reversible Metal Hydride for TES

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**Objective: Demonstrate Proof of Concept of a New Durable High-Energy Density Thermal Energy Storage (TES) for Efficient High-Temperature Applications**


**Motivation: High-temperature material for TES >600°C is needed with sufficient energy density, efficiency, lifetime and low cost**

**Quantitative Objectives:** Our Metal Hydride (MH) can increase energy density **10x** relative to molten salts and exceeds ARPA-E volumetric capacity **8x**

| ARPA-E targets: | Our metal hydride: |
|---|---|
| ✓ Temperature for power generation >600°C | 650°C |
| ✓ Charging time <6 hours | <6 hours |
| ✓ Volumetric capacity >25kWh/$m^3$ | 200kWh/$m^3$ (system) |
| ✓ Exergetic efficiencies >95% | |

**We have shown feasibility of our metal hydride for TES!**

# Our Metal Hydride TES vs State of the Art

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- State of the art is molten salt
- Our Metal Hydride (MH) operates at HIGHER TEMPERATURES than previously explored MHs, and LOWER PRESSURE

| TES Material | Operation Range | Gravimetric Energy Density | Volumetric Energy Density |
|---|---|---|---|
| PNNL MH | 650°C, 1 bar $H_2$ | 1200kJ/kg | 1000kWh/$m^3$ |
| Molten Salt | 565°C<br>670°C (Phase change) | 153kJ/kg | 100kWh/$m^3$ |
| $MgH_2$ | 450°C, >40 bar $H_2$ | 3000kJ/kg | 1000kWh/$m^3$ |

Note: Approximate energy densities for material (theoretical), not system

# Team and Project Tasks

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- **Task 1:** Materials Development & Characterization
- **Task 2:** Design & Build 3kWh TES Prototype
- **Task 3:** Demonstrate & Validate TES Prototype

ARPA-E HEATS Project start date: December 2011
-2 years seedling project

| Key Roles of Project Team |
|---|
| **Pacific Northwest National Laboratory**<br>❖Project Management<br>❖Client communications / interface<br>❖Cycle life, isotherms and kinetics studies at >600°C<br>❖Thermal management<br>❖System design and fabrication<br>❖Safety<br>❖System demonstration / validation |
| **University of Utah**<br>❖Materials synthesis<br>❖Materials performance optimization<br>❖Materials Characterization |
| **Heavystone Lab (Industry partner)**<br>❖Large scale materials synthesis |

# Metal Hydrides vs. Complex Metal Hydrides
# Materials Options

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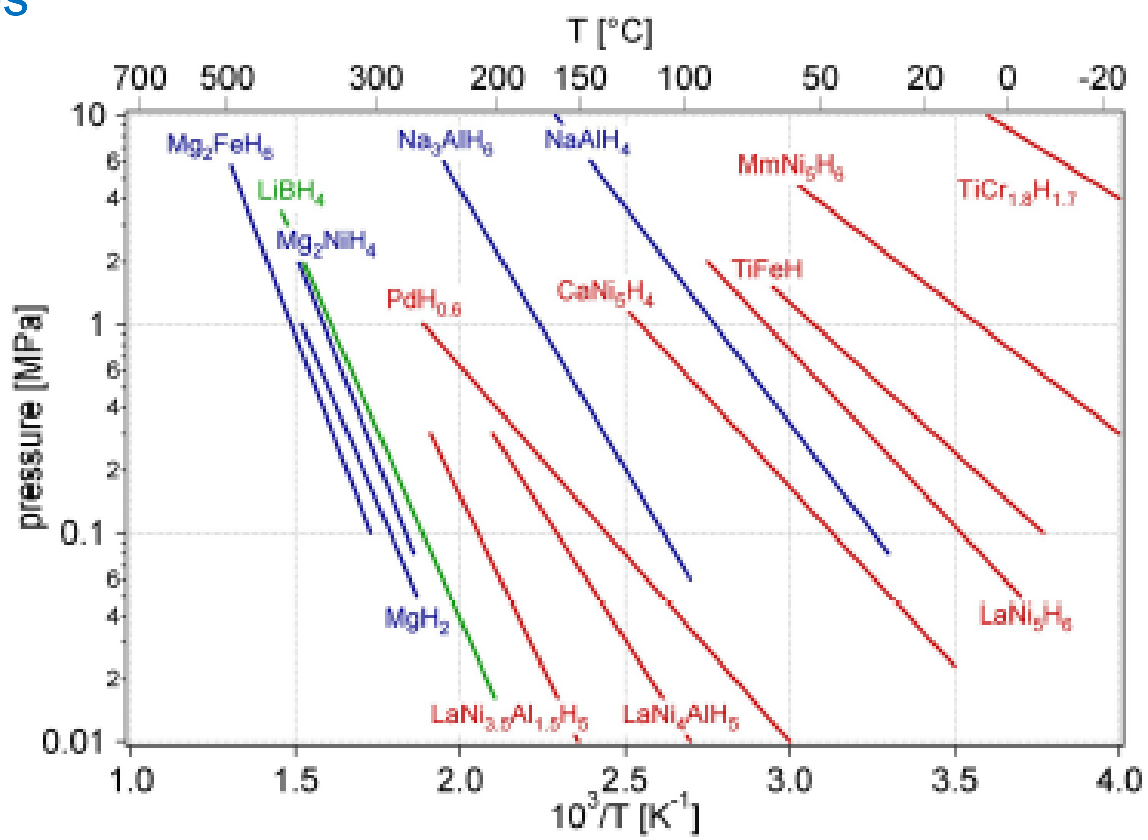
- **Complex metal hydrides**
  - high wt% $H_2$
  - high enthalpy
  - operation T typically <600°C
  - high pressures
  - complex reaction mechanism
  - seldom reversible
- **Metal hydrides**
  - low wt% $H_2$
  - can be tuned for T range >600°C
  - high enthalpy
  - low pressures
  - reversible




**Solution: Choose metal hydride that operates reversibly >600°C and at ambient $H_2$-pressure**

# Materials Development of High-T Alloys
# Materials Tuning

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- Explored high-temperature alloys in order to
  1) increase reversible hydrogen content, thus, increase thermal energy storage capacity
  2) decrease operation pressure to 1 bar $H_2$-pressure

- Results:
  - Synthesized several alloys
    - By alloying, plateau pressures can be shifted up or down as hydrogen content changes.
  - Optimized performance at 650°C and 1 bar $H_2$-pressure
  - Showed 60 cycles! Exceeded our initial target

# Materials Development – Break Through Performance of Reversible Metal Hydride



- **Performance goals:**
  - 10x higher gravimetric energy density than molten salt
    - Demonstrated feasibility for 1200-1600kJ/kg
  - Charge within 6 hours
    - Demonstrated feasibility to meet ARPA-E target < 6 hours

- **Experiments:**
  - Performed isotherms to determine best operation pressure and temperature
    - ~650°C and 1 bar established
  - Cycle life tests
    - ~60 cycles accomplished

# Approach to Design of Hydride Bed

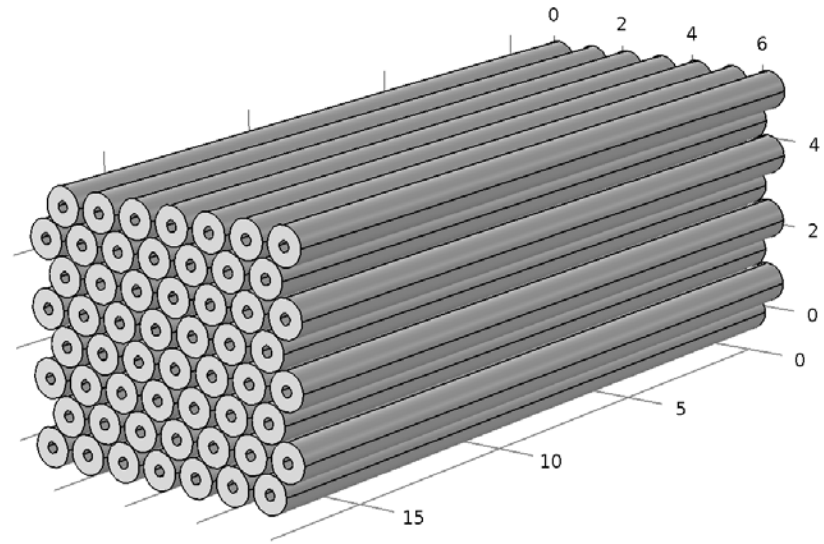


- Hydride powder is expected to size reduce over multiple hydride cycles
- Small particles lead to low bed thermal conductivity; two options examined for design
  - Use small diameter hydride beds (i.e. ¾")
  - Enhance the thermal conductivity of the bed
- Our approach is to enhance thermal conductivity using copper

# TES 3kWh Prototype Design Concept Selected



- Accomplished numerical modeling of physical properties and hydrogen uptake data based on experimental data
- Provided performance predictions with COMSOL Multiphysics




**Design 1**: Close-packed array of 56 tubes for storage

Chosen Design


**Design 2**: Storage cylinder with internal structure of Cu-foam

Volumetric energy density is 200kWh/$m^3$ for system (ARPA-E target is 25kWh/$m^3$)

# Copper Foam Fill for Hydride Cylinder



- Use open cell Duocel copper foam with interstitial spaces filled with hydride powder.
  - Allows simple construction of test cylinder
  - Easy to fill with hydride powder
  - Low sensitivity to errors in estimate of hydride bed thermal conductivity
  - Foam enhances conductivity in both radial and axial directions.

# Modeling of Bed Cycling to Determine Loading Swing for Bed Sizing

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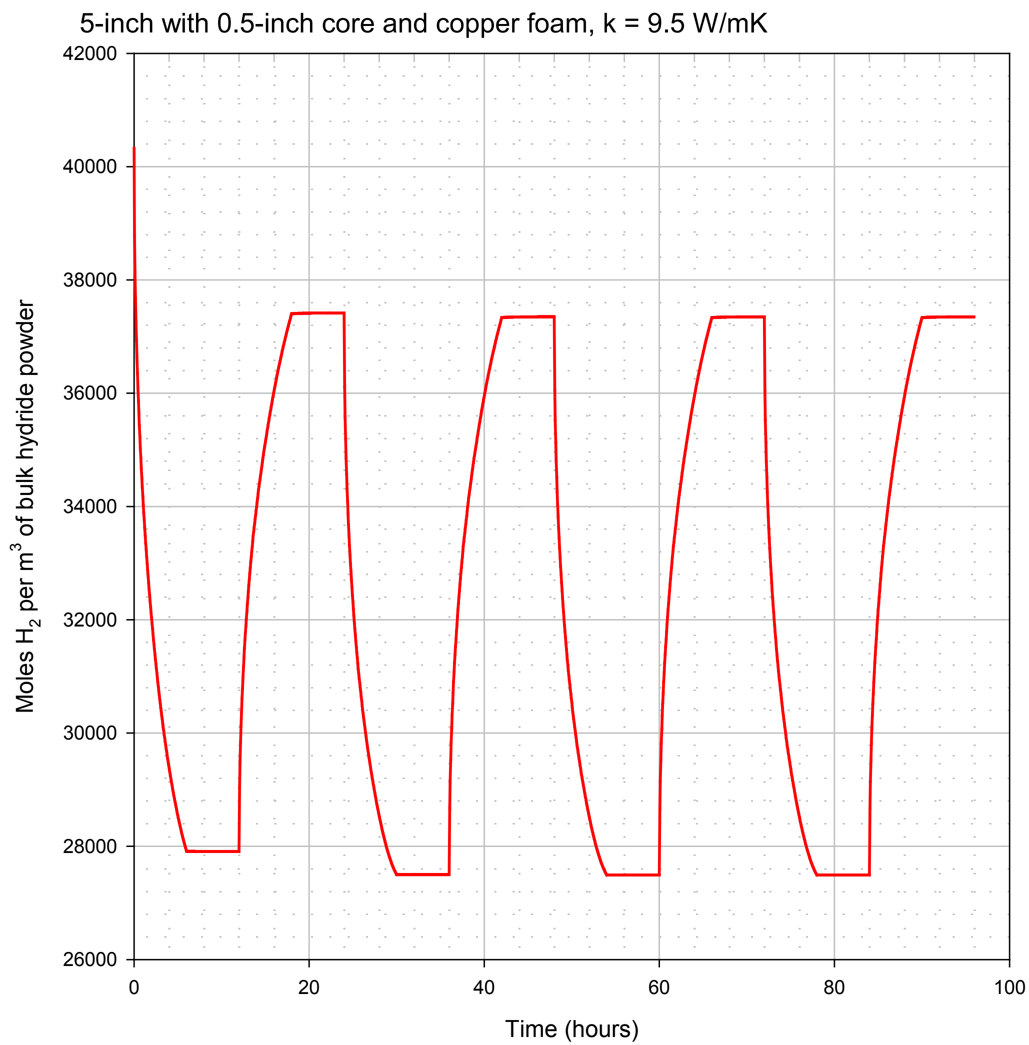
- Repeating Cycle:
  - 6h accept heat
  - 6h rest
  - 6h return heat
  - 6h rest



# High Temperature Test Bed Design

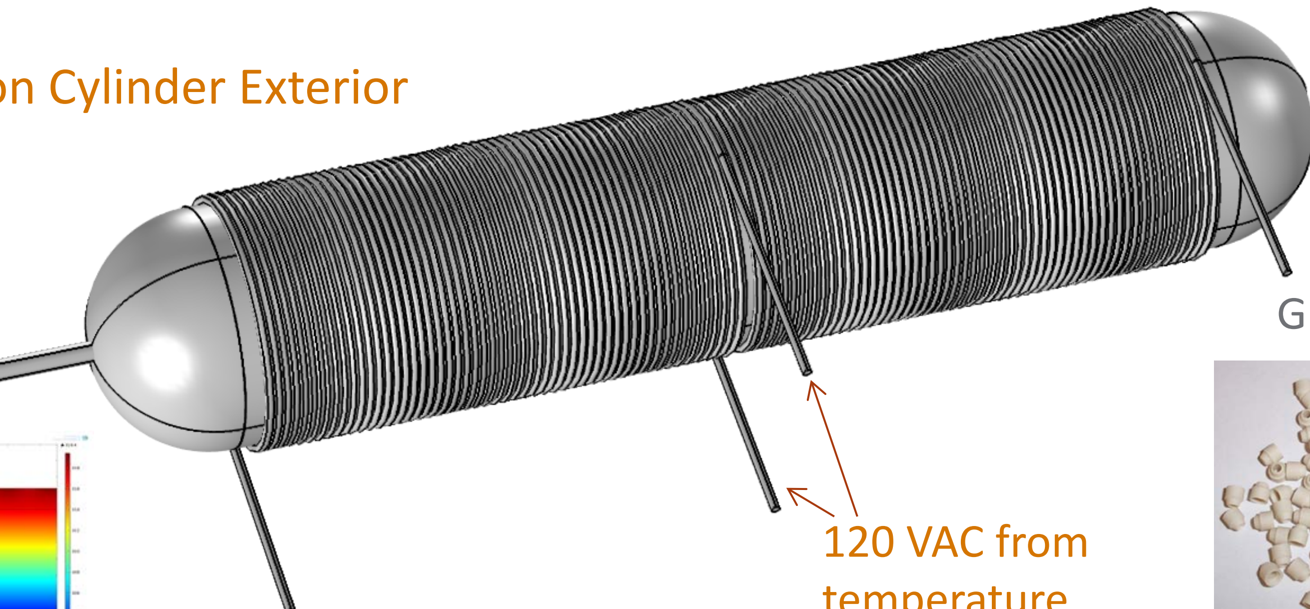


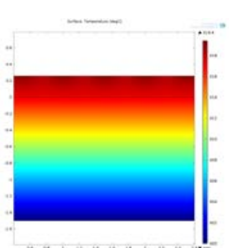
- Control shell temperature by balancing heat loss with heat input via electrical heater.
- Heat/cool cylinder by adjusting heat input
  - Heat loss through insulation ~constant
    - Temperature change on plateau region is very small
  - Heating accomplished by increasing power input to level above steady-state heat loss
  - Cooling accomplished by reducing heat input to a level below steady state heat loss.

# Hydride Test Bed Design Details



- Column is made from S40 pipe (316SS)
- Bed consists of Copper Foam, filled wtih metal hydride powder
- Cylindrical section is wrapped with a Ni-80 heater insulated with ceramic “Salamander” beads.
- Heater is covered by controlled thickness insulation layer,  ends well insulated
- Porous metal tube at bed centerline to add/remove $H_2$ from bed



Heat input modeled; sufficiently uniform at wall interior

“Salamander” Beads

# Design Concept: If Copper Foam Cost Is Too High for Commercial Application

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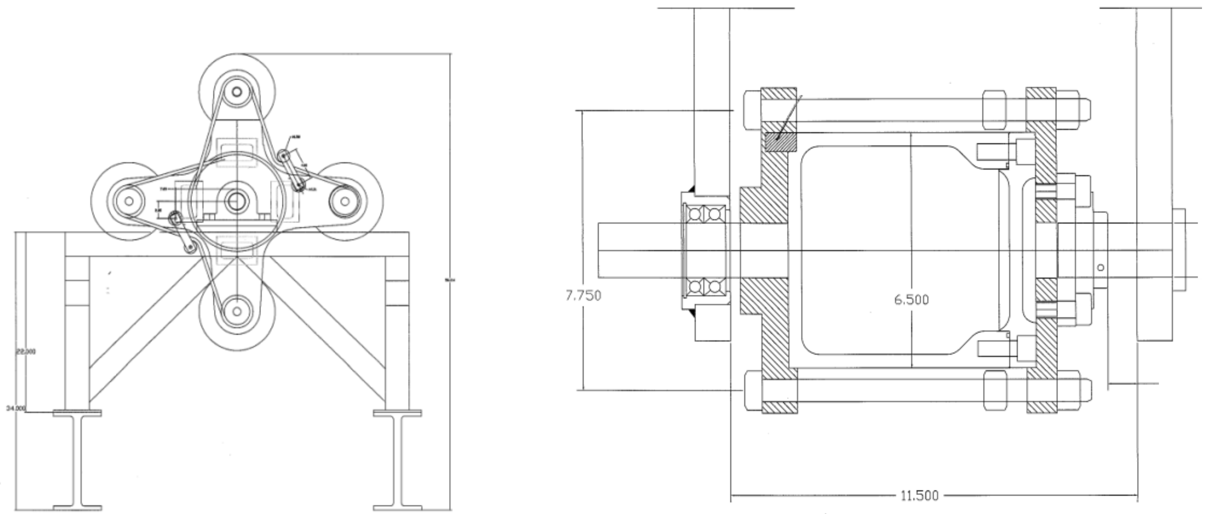
- Use thin copper disks with Hydride powder filling the space between disks.
- Conduction in radial direction dominated by copper, axial conduction must occur in powder
- Advantages
  - Material cost of sheet copper is lower than foam
- Disadvantages
  - More difficult to fabricate bed compared to foam

# Scale-Up of Hydride Powder Industry Partner: Heavystone Lab



- Designed and fabricated new planetary milling machine for preparation of kilograms of metal powders

Drawing of milling machine



# Summary
# Key Results in Year 1

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- **Task 1:** Materials Development & Characterization

  **Demonstrated metal hydride's feasibility for high-T TES**

  - 10x higher energy density than molten salt
  - Volumetric energy density 200kWh/$m^3$ for system, *i.e.*8x ARPA-E target
  - Established operation range of ~650°C and ~1 bar $H_2$ pressure
  - >60 cycles demonstrated: exceeded goal

- **Task 2:** Design & Build 3kWh TES Prototype
  - Two design concepts evaluated by COMSOL modeling
  - Recommend a stainless steel cylinder with Cu-foam
  - Build prototype in Year 2

# Decisions Made for Go/No-go Decision December 2012



- **Go on optimized hydride as TES material**
  - Hydride exceeds ARPA-E performance targets on gram size scale
  - Operation range: 1 bar and 600-800°C
- **Go on scale up of hydride powder**
  - Heavystone Lab to make ~15kg for 7.4 liter container
  - Verify scale up reproducibility
- **Go on building 3kWh prototype**
  - Design: Stainless steel container with internal Cu-structure for enhanced heat transfer
- **Go on build thermal diffusivity device**
  - Study thermal conductivity during cycling in hydrogen atmosphere
  - Study cycle life and oxidation mitigation if needed
  - Study materials engineering properties

# Year 2 ARPA-E HEATS Scope



- **Design and build bench-scale TES of ~3kWh** (PNNL)
  - One bed, “half”, system is the current scope
  - Final drawing of high-T prototype accomplished
  - Fabrication in progress
- **Scale up to kilogram quantities of TES material** (Heavystone Lab)
  - Confirm reproducibility (U. of Utah and PNNL)
- **Demonstrate and validate prototype** (PNNL)
  - Evaluate concept and calculate efficiencies
  - Obtain ‘one day-one night’ cycles at 650°C and 1 bar $H_2$-pressure
  - Show proof of concept and feasibility for meeting ARPA-E targets of 95% exergetic efficiencies

# Path Forward after ARPA-E HEATS Seedling



- Next step is to accomplish a full dual bed system with both a HT-hydride and a LT-hydride
  - Need to explore interplay between HT and LT hydrides to optimize performance
  - Demonstrate full system with on-sun testing

# Path Forward for Metal Hydride TES



## Phase 1: Proof of concept of HT-hydride for TES

- Metal Hydride exceeds ARPA-E targets

## Phase 2: Design, build, demo TES system

- Demonstrate efficiencies and cycle life of full system

## Phase 3: Integrate TES system with end application

- On-sun testing for high-T power generation

Phase 1 funded by ARPA-E HEATS. Phase 2 and 3 future funding TBD

## Acknowledgement:
## Award from ARPA-E HEATS program