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

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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

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/m³: 200kWh/m³ (system)
- Exergetic efficiencies >95%

We have shown feasibility of our metal hydride for TES!
State of the art is molten salt

Our Metal Hydride (MH) operates at HIGHER TEMPERATURES than previously explored MHs, and LOWER PRESSURE

<table>
<thead>
<tr>
<th>TES Material</th>
<th>Operation Range</th>
<th>Gravimetric Energy Density</th>
<th>Volumetric Energy Density</th>
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<tbody>
<tr>
<td>PNNL MH</td>
<td>650°C, 1 bar H₂</td>
<td>1200kJ/kg</td>
<td>1000kWh/m³</td>
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<tr>
<td>Molten Salt</td>
<td>565°C</td>
<td>153kJ/kg</td>
<td>100kWh/m³</td>
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<td>670°C (Phase change)</td>
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<tr>
<td>MgH₂</td>
<td>450°C, &gt;40 bar H₂</td>
<td>3000kJ/kg</td>
<td>1000kWh/m³</td>
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Note: Approximate energy densities for material (theoretical), not system
### Team and Project Tasks

**Task 1:** Materials Development & Characterization

**Task 2:** Design & Build 3kWh TES Prototype

**Task 3:** Demonstrate & Validate TES Prototype

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<table>
<thead>
<tr>
<th>Key Roles of Project Team</th>
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<tr>
<td><strong>Pacific Northwest National Laboratory</strong></td>
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<tr>
<td>- Project Management</td>
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<td>- Client communications / interface</td>
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<td>- Cycle life, isotherms and kinetics studies at &gt;600°C</td>
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<tr>
<td>- Thermal management</td>
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<td>- System design and fabrication</td>
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<td>- Safety</td>
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<td>- System demonstration / validation</td>
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<th><strong>University of Utah</strong></th>
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<tr>
<td>- Materials synthesis</td>
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<td>- Materials performance optimization</td>
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<td>- Materials Characterization</td>
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<tr>
<th><strong>Heavystone Lab (Industry partner)</strong></th>
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<tr>
<td>- Large scale materials synthesis</td>
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ARPA-E HEATS Project start date: December 2011
-2 years seedling project
Complex metal hydrides
- high wt% H₂
- high enthalpy
- operation T typically <600°C
- high pressures
- complex reaction mechanism
- seldom reversible

Metal hydrides
- low wt% H₂
- 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 H₂-pressure
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 1200-1600 kJ/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
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. $\frac{3}{4}''$)
- 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

**Chosen Design**
Cu foam and hydride powder

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

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

Volumetric energy density is 200kWh/m³ for system (ARPA-E target is 25kWh/m³)
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

Repeating Cycle:
- 6h accept heat
- 6h rest
- 6h return heat
- 6h rest
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 with 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 $\text{H}_2$ from bed

Heater on Cylinder Exterior

Heat input modeled; sufficiently uniform at wall interior
Design Concept: If Copper Foam Cost Is Too High for Commercial Application

- 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
Summary
Key Results in Year 1

► 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/m³ for system, i.e. 8x ARPA-E target
- Established operation range of ~650°C and ~1 bar H₂ 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