FueL Additives for Solid Hydrogen (FLASH) Carriers for Electric Aviation

Noemi Leick (P.I.)
National Renewable Energy Laboratory

DOE Hydrogen Program, Award # TCF-21-24761
2024 Annual Merit Review and Peer Evaluation Meeting – May 8th, 2024

AMR Project ID# ST243

Project Goal

Motivation:

- Most UAV technologies currently rely on (non-renewable) electric power.
- Fuel cells with material-based H_2 storage addresses this limitation and can be cost effective.

Project goals and outcomes:

- Develop FLASH formulation that can deliver 6g H_2/100g fuel
- Design, build and test fuel cell cartridge compatible with FLASH
- Test FLASH with 600 W fuel cell system and quantify cartridge and system specific energy

Optimization of fuel formulation for H_2-powered unmanned aerial vehicles (UAVs).

www.aerospace.honeywell.com

Overview

Technology Commercialization Fund

U.S. DEPARTMENT OF ENERGY | OFFICE OF Technology Transitions

Timeline

- Project Start Date:
  - NREL: 11/01/2022
  - Honeywell: 03/15/2023
- Project End Date: 06/14/2024

Barriers and Targets

Technical barriers addressed by the project	Project's key technical targets
Cost of borohydride fuel too high.	Max. $150/kg of fuel
Lacking assessment matrix for fuels is preventing efficient material screening.	Min. 6 wt% H_2 from total fuel
Impurities in H_2 stream: detrimental to fuel cells and toxic to living organisms.	Power a 600 W fuel cell system

Budget

- Total DOE Share: $250k
- Total Cost Share: $250k
- Total DOE Funds Spent*: $210k
- Total Cost Share Funds Spent*: $150k

* As of 03/15/2024

Partners

- N. Leick (PI, NREL)
- F. Harrington, R. Moen (Honeywell)
- N. Strange (consultant, SLAC)
- T. Gennett (advisor, NREL & Colorado School of Mines)

NREL Transforming ENERGY

Honeywell THE POWER OF CONNECTED

SLAC NATIONAL ACCELERATOR LABORATORY

COLORADO SCHOOL OF MINES

Potential Impact

Technology Commercialization Fund

U.S. DEPARTMENT OF ENERGY | OFFICE OF Technology Transitions

Project activity	Potential Impact	Relevance to DOE goals
Establish mixtures of borohydride and salts able to overcome current borohydride-related challenges.	$NaBH_4$-based fuels have the potential to meet the target of $150/kg, threshold to marketability. *(Honeywell's current material costs $600/kg).*	The project's materials were identified by DOE's HyMARC EMN. R&DD efforts are necessary to reduced costs, at the material-based, component, and system-level, which will provide pathways to private sector uptake.
Develop assessment matrix for fuels used in green UAV technologies.	The assessment matrix developed will enable a more efficient selection of fuels for H_2-fuels for drones.	This can in turn lower greenhouse gas emissions and criteria pollutants.
Quantification of impurities in H_2 stream for down selected fuels.	Understanding their impact in different environments (fuel cells, atmosphere, biosphere) is crucial for the advancement of green technologies in the drone industry.	This can support (and improve) energy, environmental, or social justice.

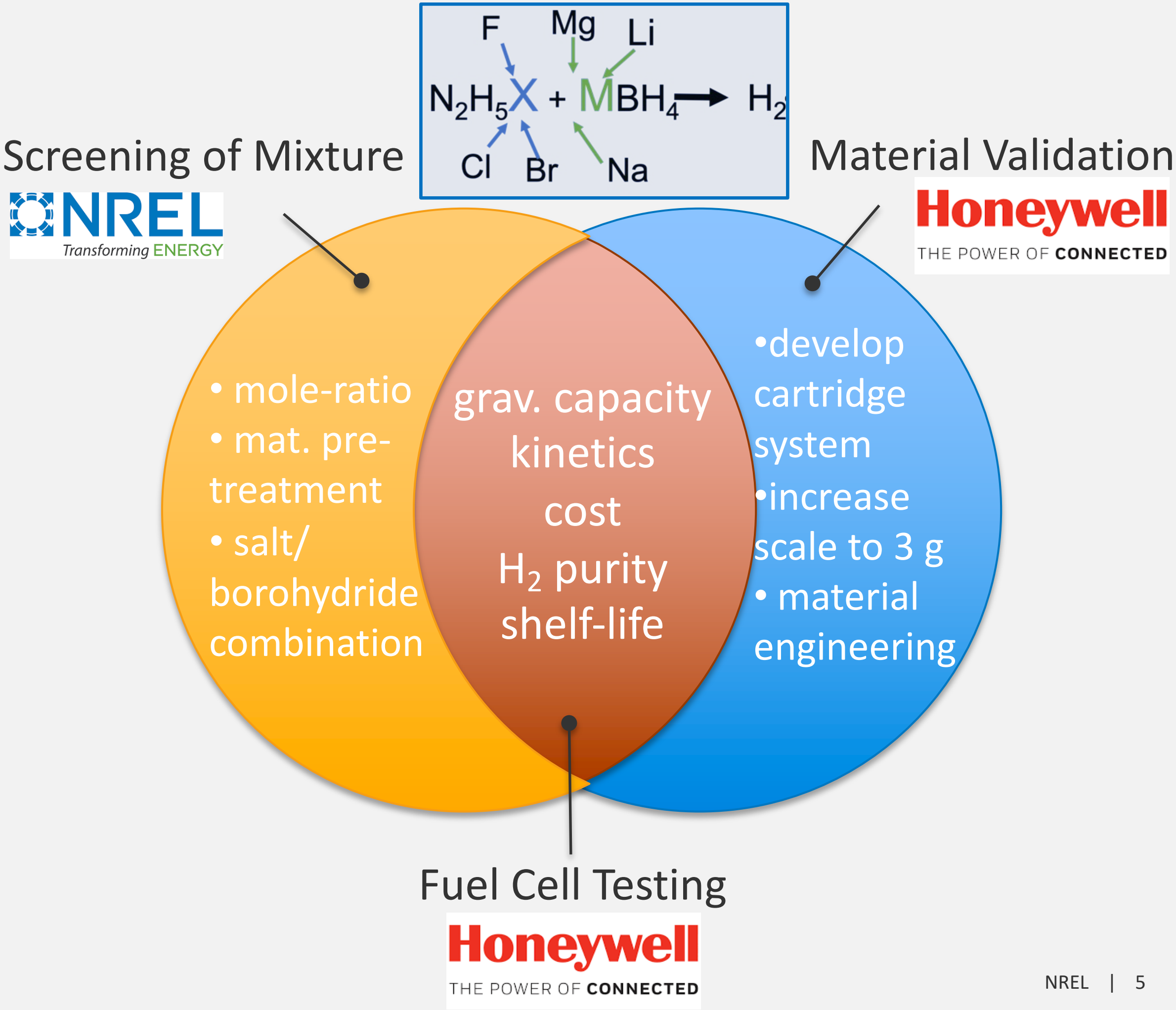
Approach

1. Screening of Mixture (small scale – 100s mg)

2. Material Validation (medium scale – 3 g and more)
   – grav. capacity
   – kinetics
   – cost assessment
   – H_2 purity
   – shelf-life

3. Fuel Cell Testing

If material performance is validated, they proceed to fuel cell testing.



Safety Planning and Culture

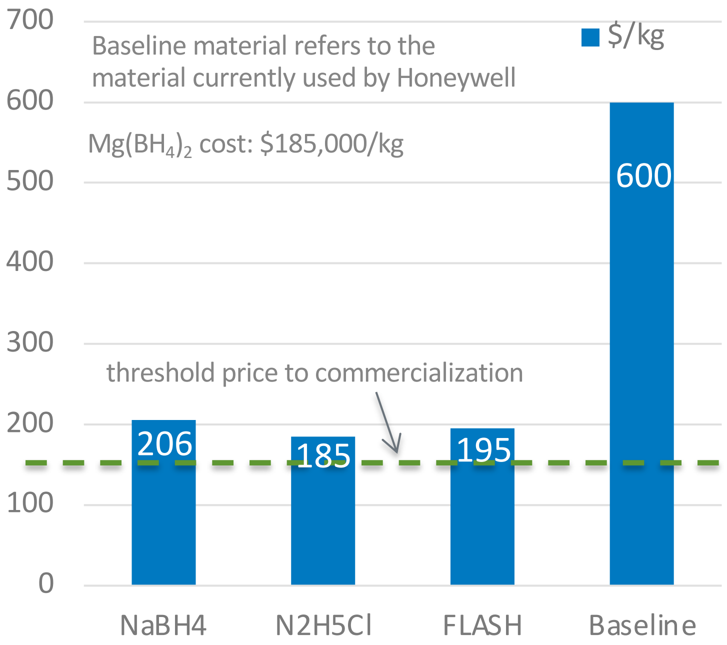
- **Safety plan:** This project was **not** required to submit a safety plan to the Hydrogen Safety Panel (HSP)
- **Incidents and near misses:** procedures for this project are aligned with NREL's and Honey-well's practice of tracking and reporting any near misses. So far, none have occurred.
- **Best practices and lessons learnt:** from the decade-long expertise from the NREL team working on hydrides and metal-hydrides, a list of best practice exists and is followed. This list will be amended to reflect lessons learnt from incidents and/or near misses. This exercise is supported by NREL's health and safety team. The same is true for Honeywell's policy.

- **Prioritizing Safety & Analyzing Hazards for FLASH Materials.**
  - ➢ Because they are/they have:
  - – moisture sensitive,
  - – pyrophoric because they are nano-size,
  - – enhanced reactivity of the borohydride/salt mixtures,
  - – release of toxic reaction products,
  - ➢ handling and testing occurs in:
  - – air-free environments,
  - – small quantities first,
  - – sealed and air-tight containers.
  - ➢ Online and in-person training sessions occur for every new user who are shadowed until the understanding of safety procedures for this project are demonstrated.

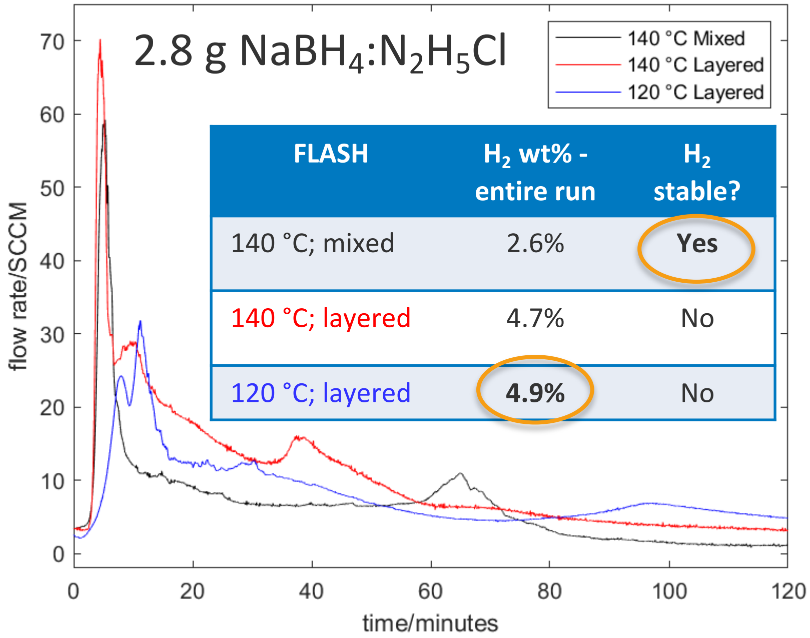
Accomplishments and Progress - FLASH cost and performance

Technology Commercialization Fund
U.S. DEPARTMENT OF ENERGY | OFFICE OF Technology Transitions

Cost-effective FLASH: $NaBH_4$:N_2H_5Cl in 1:1 mole ratio



Hydrogen release: Competition between wt% and stability

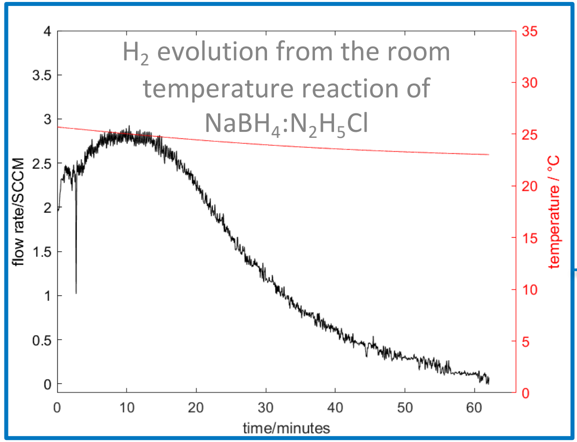


FLASH	H_2 wt% - entire run	H_2 stable?
140 °C; mixed	2.6%	**Yes**
140 °C; layered	4.7%	No
120 °C; layered	**4.9%**	No

Accomplishments and Progress - Fuel Evaluation Score Card

Low-Temperature Thermolysis Reaction:

$$NaBH_4 \cdot N_2H_5Cl \rightarrow NaCl + N_2H_4BH_3 + 2\ H_2$$

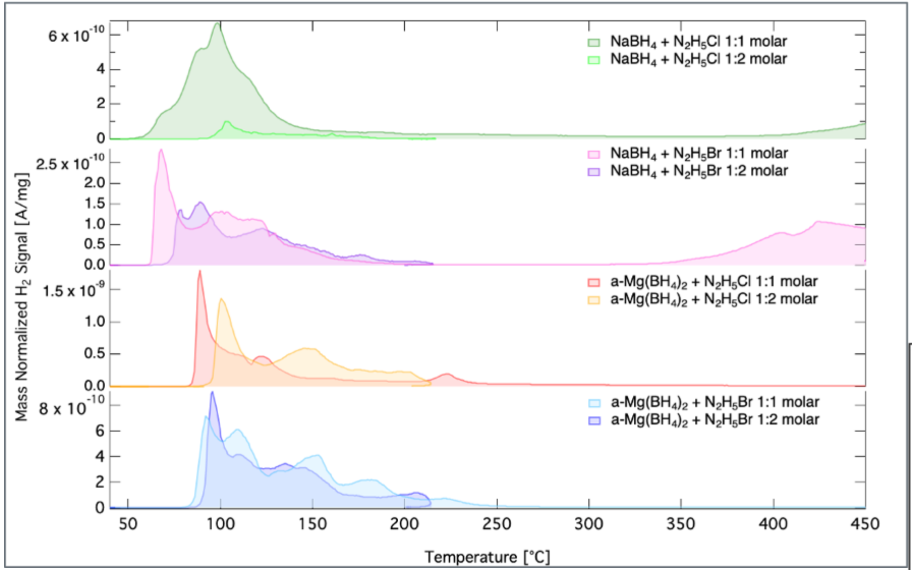


	Threshold target	$NaBH_4 \cdot N_2H_5Cl$
Hydrogen storage density	6 wt%	5 wt% ★
Safety	No health hazards or acute toxicity	Acute oral, dermal, and inhalation toxicity; Health hazard: Cat 1B (H350) presumed human carcinogen ☆
Storage	No venting	Venting required if fuel is stored together ★
Transport	Air transport permitted	Air transport permitted; two components may need to be shipped in separate containers ★
Material compatibility	Compatible with common lightweight aerospace materials such aluminum	Contains chloride, incompatible with aluminum ★
Hydrogen contaminants	Meets SAE J2719 and ISO 14687 requirements	N_2, NH_3 and N_2H_4 may pose a risk ★

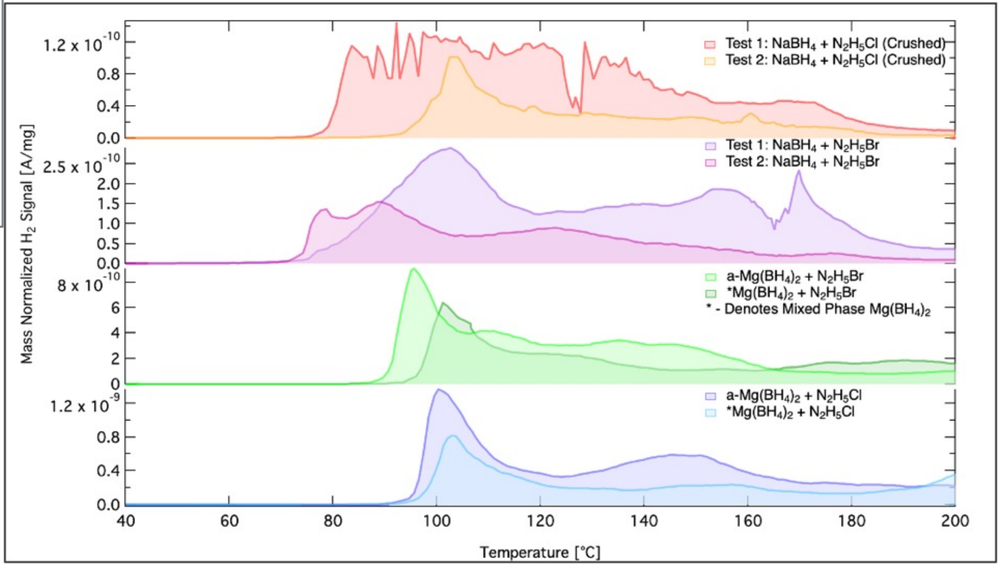
★ Path to addressing concern (see Future Work) ☆ Potential engineering control to put in place

Pathways to address insufficient requirements are in place. Current score of our FLASH material: B

Accomplishments and Progress - Impact of ratio and reproducibility



Amount of H_2 released highly depends on the molar ratio of $NaBH_4$ and N_2H_5Cl.



Reproducibility of H_2 release is variable, due to arbitrary mixing:
- localized reaction zones
- variable viscosity of the mixture

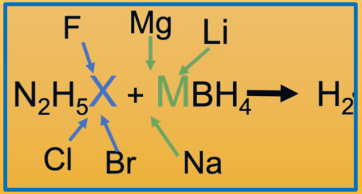
Responses to Previous Year's Reviewer Comments

This project was not reviewed last year

Collaboration and Coordination

Technology Commercialization Fund
U.S. DEPARTMENT OF ENERGY | OFFICE OF Technology Transitions

FLASH carriers



for UAVs

- FLASH formulations — Prime – National Lab: NREL Transforming ENERGY
- Characterization — NREL Transforming ENERGY; No cost partners – consultants: Colorado School of Mines, SLAC National Accelerator Laboratory
- Project management — NREL Transforming ENERGY
- Cartridge & fuel cell build — Cost Share Sub – Industry: Honeywell THE POWER OF CONNECTED
- Scale up — Honeywell THE POWER OF CONNECTED

DEIA / Community benefit plan

- This project did not have a DEIA or community benefit plan
- This slide shows what the TCF – Phase II proposal will include

https://www.msudenver.edu/chemistry/msu-denver-postbaccalaureate-bridge-program-projects/

Megan Lazorski, Ph.D.
Assistant Professor
at MSU Denver

- MSU Denver, a minority serving institution, has built a postbaccalaureate bridge program.
- NREL is already a collaborator in this program.
- The program includes industrial partners who are willing to host interns.
- In Phase II, we plan to include internships at NREL and Honeywell for students from MSU Denver.

Remaining Challenges & Barriers

Technology Commercialization Fund

U.S. DEPARTMENT OF ENERGY | OFFICE OF Technology Transitions

	Challenges and Barriers for $NaBH_4 \cdot N_2H_5Cl$	Potential Solutions
Hydrogen storage density	5 wt%	• Optimized stacking of the materials • Exchange N_2H_5Cl for NH_3BH_3
Safety	Acute oral, dermal, and inhalation toxicity; Health hazard: Cat 1B (H350) presumed human carcinogen	Potential engineering principle to minimize health and safety concerns: • Handling only in air-free environments • In case of cartridge being compromised, a water reservoir could be engineered to react the fuel before it can affect the environment
Storage	Venting required if fuel is stored together	Physical barrier between borohydride and salt, e.g. carbon
Transport	Air transport permitted; two components may need to be shipped in separate containers	Physical barrier between borohydride and salt, e.g. carbon
Material compatibility	Contains chloride, incompatible with aluminum	Exchange N_2H_5Cl for NH_3BH_3 to remove the chloride
Hydrogen contaminants	N_2, NH_3 and N_2H_4 may pose a risk	• Fuel cells often have a N_2 purification system to extract O_2 from the air, which could be integrated into the H_2 stream as well • The above-mentioned changes (e.g. NH_3BH_3, addition of carbon) could change the reaction mechanism and the reaction products

Future Work

Technology Commercialization Fund
U.S. DEPARTMENT OF ENERGY | OFFICE OF Technology Transitions

- Implement and test the potential solutions to address the remaining challenges:
  - replace N_2H_5Cl with NH_3BH_3
  - add a material between the borohydride and the salt to form a physical barrier, e.g. carbon black
  - optimize the material stacking

- Remaining work in Phase I:
  - modeling of the cartridge
  - fuel cell test
  - final report

Summary

- Due to high cost and supply chain issues, $Mg(BH_4)_2$ has been discarded.
- Current estimates put the $NaBH_4 \cdot N_2H_5Cl$ at $195/kg (target: $150/kg, baseline: $600/kg).
- Test at 100 mg and 2.8 g using mixing of $NaBH_4 \cdot N_2H_5Cl$ yield ~2.5 wt% of stable H_2 delivery to the fuel cell.
- Implementing strategic stacking of the materials led to ~5 wt% of H2, but the delivery is sporadic and unstable.
- Partial dehydrogenation leads to hazardous NH_3, N_2H_4 impurities.