# Atmospheric Water Extraction Enabled by Smart Moisture Absorbing Foams (SMAFs)

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Physical Sciences Inc. (PSI)

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**Physical Sciences Inc.**

Todd Emrick

**University of Massachusetts Amherst**

Ian Norris and Paul Smith

**Cascade Designs Inc.**

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# Our Team

Physical Sciences Inc.

VG-2021-197-1


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**TA1 Lead**
PSI


**Caitlin Bien**
**Mat. Dev. Lead**
PSI


**Bryan Sharkey**
**TA1 Team**
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**Russell Lambert**
**TA1/TA2 Team**
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**Zach Whitermore**
**TA1 Team**
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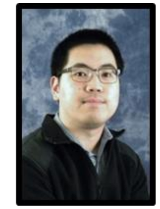
**Tiffany Yu**
**TA1/TA2 Team**
PSI


**Jeffrey Yee**
**TA1 Team**
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**Shaylee Sarmiento**
**TA1 Team**
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**Peter Warren**
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**Sean Torrez**
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**Deputy PM**
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**Travis Emery**
**Modeling Lead**
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**John Grimble**
**Prototyping Lead**
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**Heidi Reid**
**TA2 Team**
PSI


**Jacob Miske**
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**Paul Smith**
**Lead Engineer**
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**John Williams**
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Physical Sciences Inc.

UMass Amherst

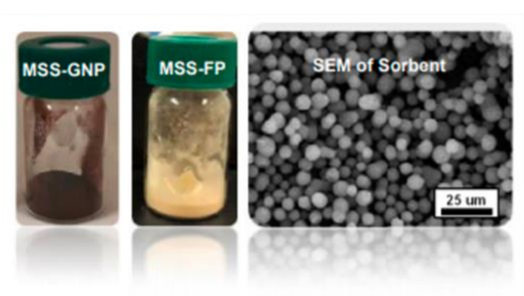
CASCADE DESIGNS®

Physical Sciences Inc.

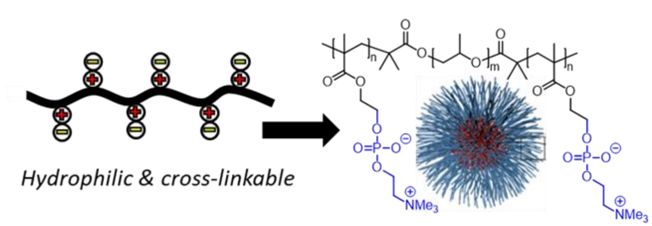
# Team Members and Roles



- **Physical Sciences Inc., PSI (Program Lead)**
  - **Program Role:** Sorbent development, evaluation and optimization (TA1). AWE system modelling, design, prototyping and evaluation (TA2). Management and reporting.
  - **Expertise:** Tech development for large government programs.
- **University of Massachusetts Amherst, UMass (TA1 Partner)**
  - **Program Role:** Sorbent material synthesis, characterization and scale-up.
  - **Expertise:** World class Polymer Science and Engineering program.
- **Cascade Designs, CDI (TA2 Partner)**
  - **Program Role:** Prototype system development, optimization and field testing. Commercialization partner, owner of Mountain Scientific Research (MSR) brand.
  - **Expertise:** Design and manufacture of individual sustainment gear.




PSI Smart Sorbent Platform




UMass Functional Materials

MSR/CDI Water Filtration Systems

# Program Summary



- **Team:**
  - Physical Sciences Inc. (PSI), Andover, MA (PI: Gamliel, PM: Warren)
  - University of Massachusetts Amherst, Amherst, MA (Co-I: Emrick)
  - Cascade Designs Inc (CDI), Seattle, WA (Co-I: Norris)

- **Primary Objective –** Develop a man portable system capable of extracting potable drinking water from air, obviating the need for costly and dangerous transportation (Expeditionary Track).
  - **TA1 Goal:** Create a new and revolutionary class of sorbents that have high capacity, rapid water uptake and release sorbed water by compression-enabled switching from hydrophilic to hydrophobic state.
  - **TA2 Goal:** Design, construct and optimize a system capable of meeting the DARPA SWaP and output requirements by leveraging the SMAF compressive release capability developed in TA1.

# DARPA BAA Requirements



- **Topic** – DARPA BAA HR001120S0014 Atmospheric Water Extraction (AWE)
- **Broad Need** – Water transport to the warfighter is mission-critical but logistically challenging, requiring equipment, fuel, and personnel that limits tactical maneuver and decision space. Warfighter requires 3-7 L/day of drinking water.

| Metrics | Phase I Objective | Phase II Objective |
|---|---|---|
| Water Production Rate | ≥1 L/day @ ~4 °C, 50% RH<br>≥1 L/day @ ~27 °C, 10% RH<br>≥1 L/day @ ~43 °C, 60% RH | ≥5.5 L/day @ ~4 °C, 50% RH<br>≥5.5 L/day @ ~27 °C, 10% RH<br>≥7.5 L/day @ ~43 °C, 60% RH |
| System Dry Weight | ≤7 kg | ≤2.5 kg |
| Power | Must be contained onboard | Must be contained onboard |
| Volume | 6 L (0.21 $ft^3$) | 1.5 L (0.05 $ft^3$) |
| Desired Properties | - | Water meets TB-Med-577 potability standards,<br>Operational for >30 days at 24 hr runtime |

- *"The world's ultimate weapon runs on water; everything else runs on fuel"*

# Key Innovation – Compressive Release

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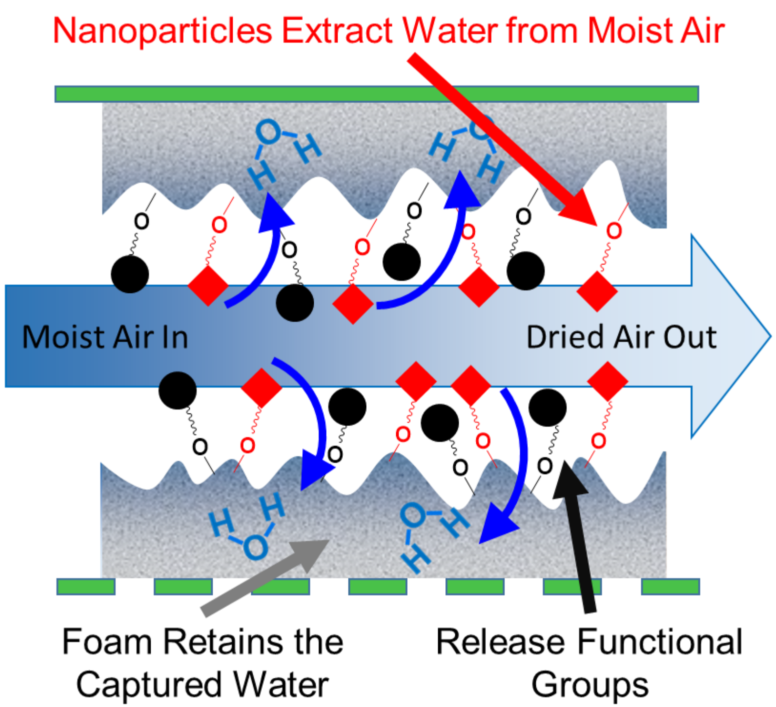
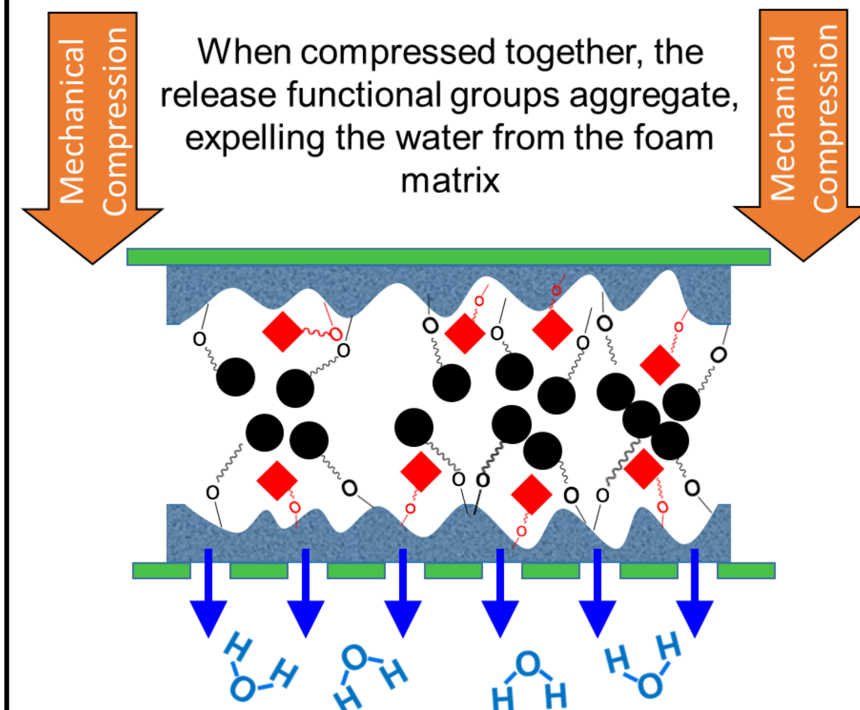



**Water Capture:**
Atmospheric $H_2O$ is captured by the nanoparticles and transferred to the foam matrix.




**Water Release:**
Externally-applied mechanical compression makes all internal surfaces hydrophobic, releasing liquid $H_2O$

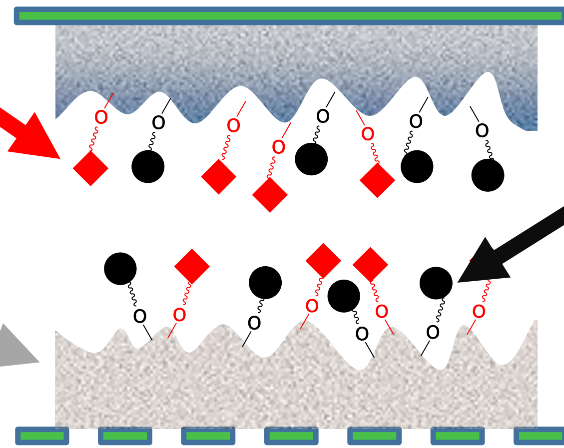
TA1 Smart Moisture Absorbing Foam (SMAF) designed to have **water capture**, **storage** and **release** functionality (non-thermal release mechanism)

# TA1: Material Level Concept



**Water Capture**: Ionic grafting, polymers, and microporous materials

## SMAF Construction



**Water Release**: Hydrophilic/Hydrophobic Organo-Silicate

**Water Storage**: Biopolymer Foam Matrix

| Exp. Results | Milestone 1.1 Metric | Matrix 1 | Matrix 2 |
|---|---|---|---|
| Water Uptake at 100% RH ($g_{H2O}/g_{foam}$) | > 10 | **12.5** | **11** |

**Functional groups selected based on experimental evaluation**

# TA2: System Level Concept

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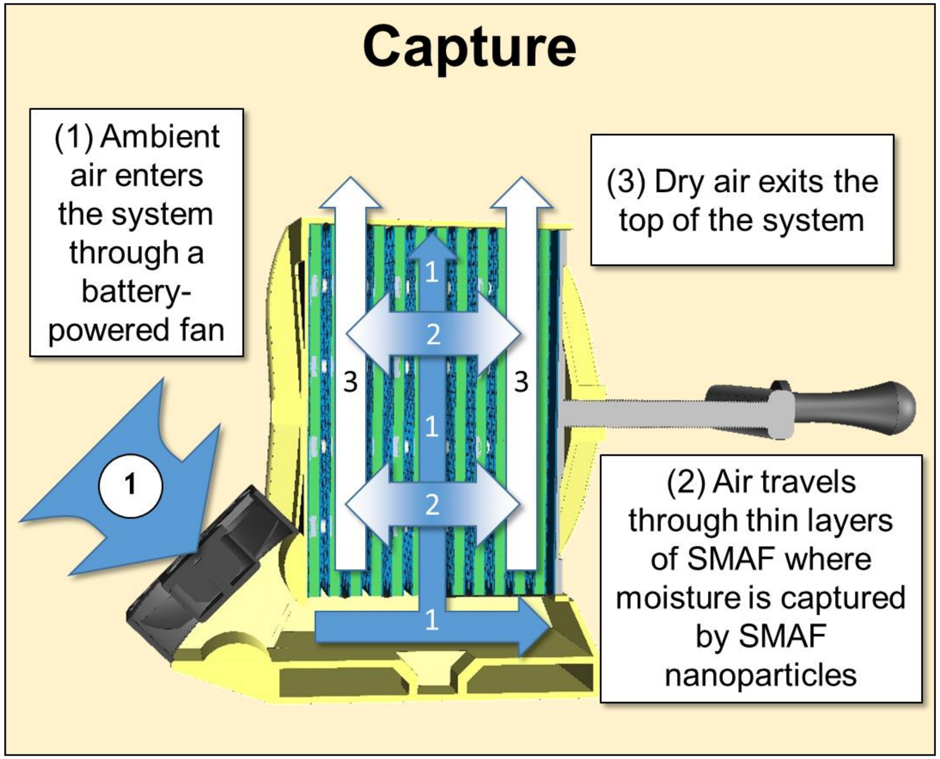
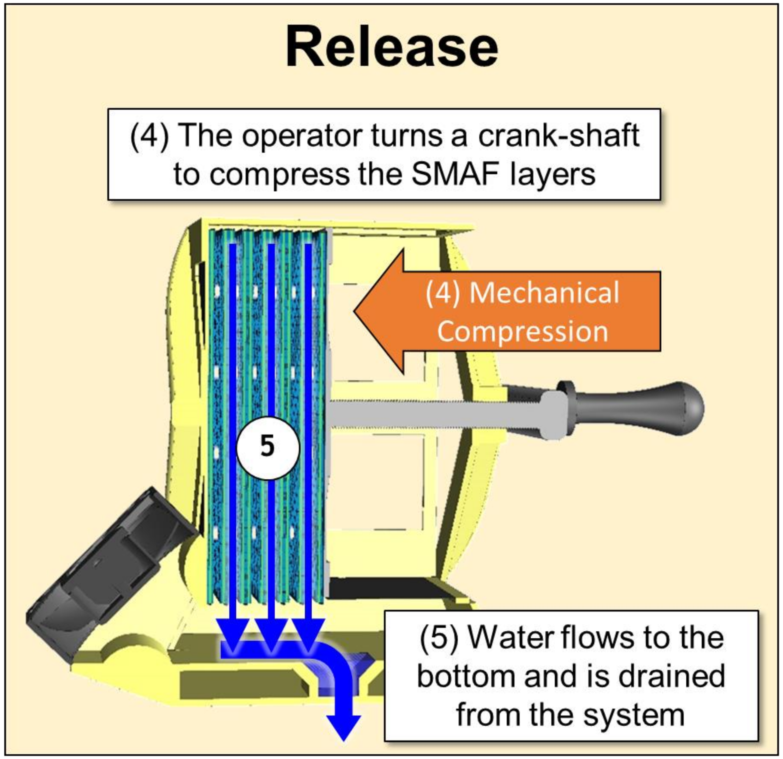


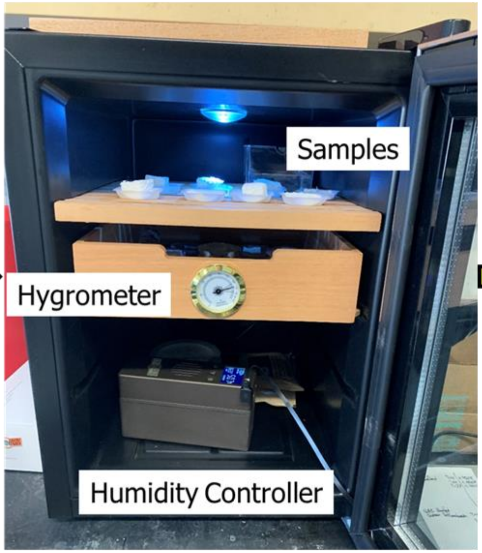



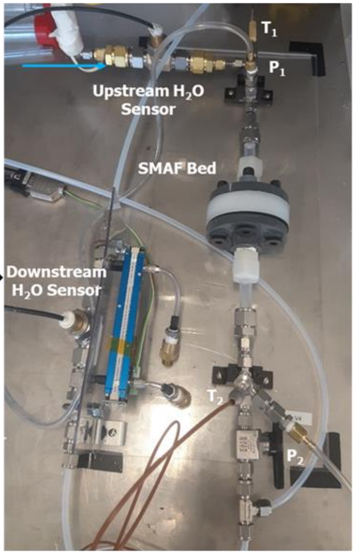

**TA2 design leverages high SMAF capacity and mechanical release to drastically reduce system SWaP**

# TA1 - Screening Methods



| Water Capture | | | Water Release |
|---|---|---|---|
| Dynamic Vapor Sorption (DVS) | Humidity Chamber | Fixed-bed | Compression Test |


**Measurement:** Water Uptake Isotherm (mg scale)

**Measurement:** Single-Point Uptake (100 mg scale)

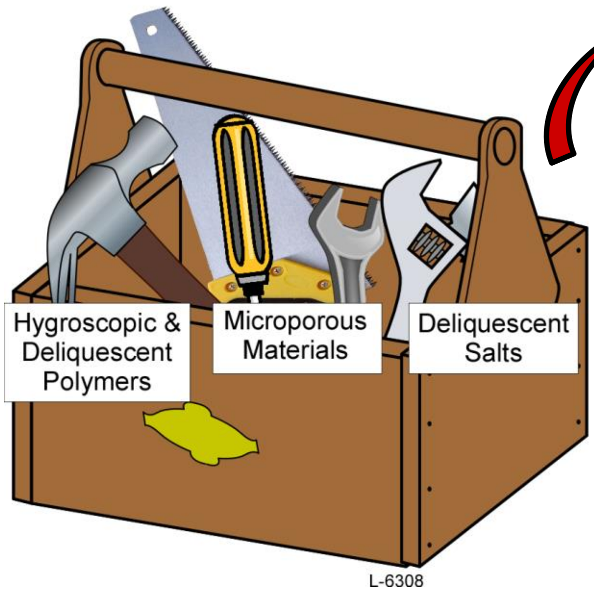
**Measurement:** Water Capture in Flow Configuration (g scale)

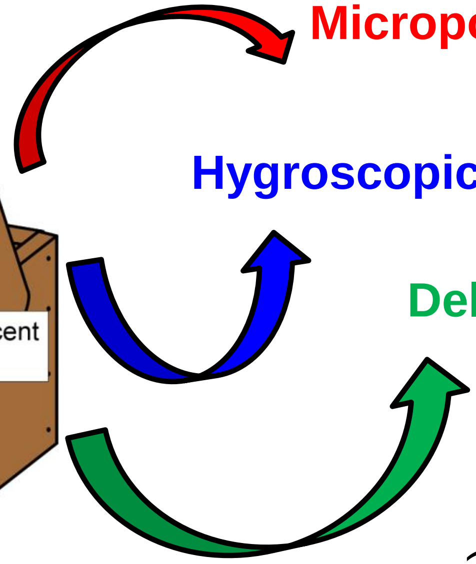
**Measurement:** Force Required for Water Release (g scale)

**We have assembled the equipment necessary to measure water capture and release under the relevant conditions**

# TA1 - Capture Materials Toolbox



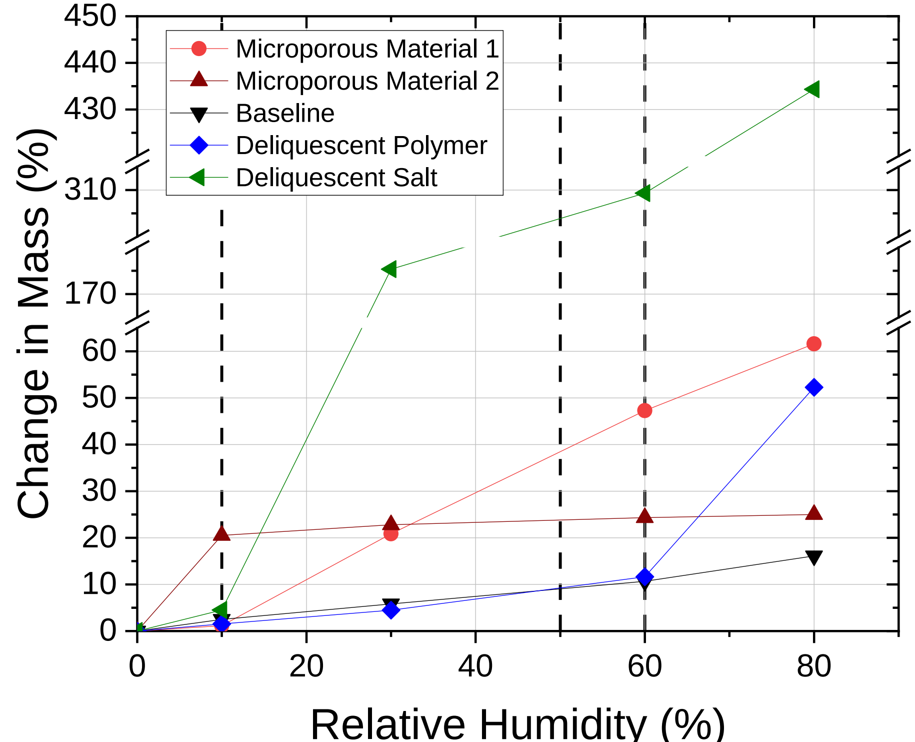


**Microporous Materials**

**Hygroscopic and deliquescent polymers**

**Deliquescent salts**




## Selection Criteria:

- Water capture capacity
- Rapid water uptake kinetics
- Material stability
- Scalable synthesis

**Combination of water capture functionalities provides desired water capture performance**

# TA1 - Water Storage Development

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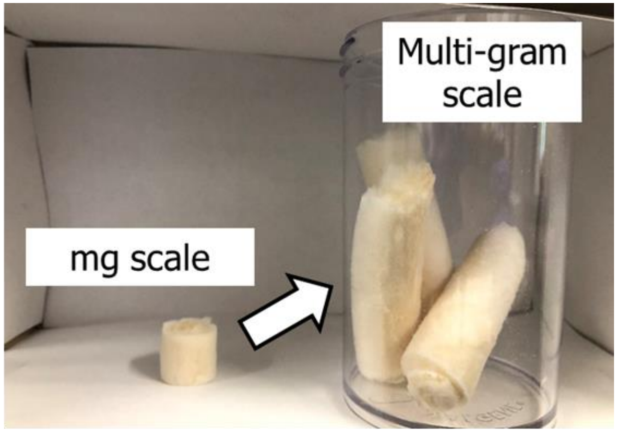
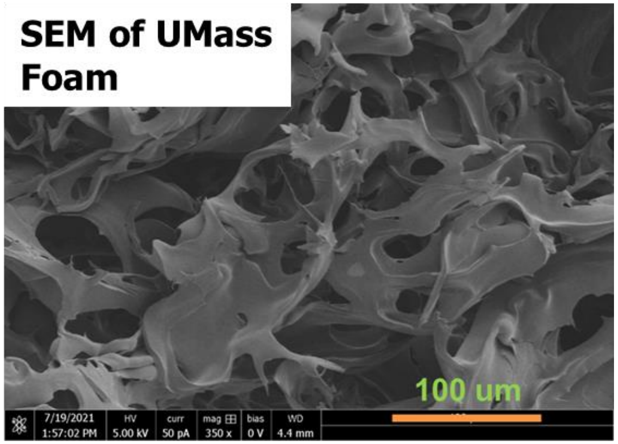
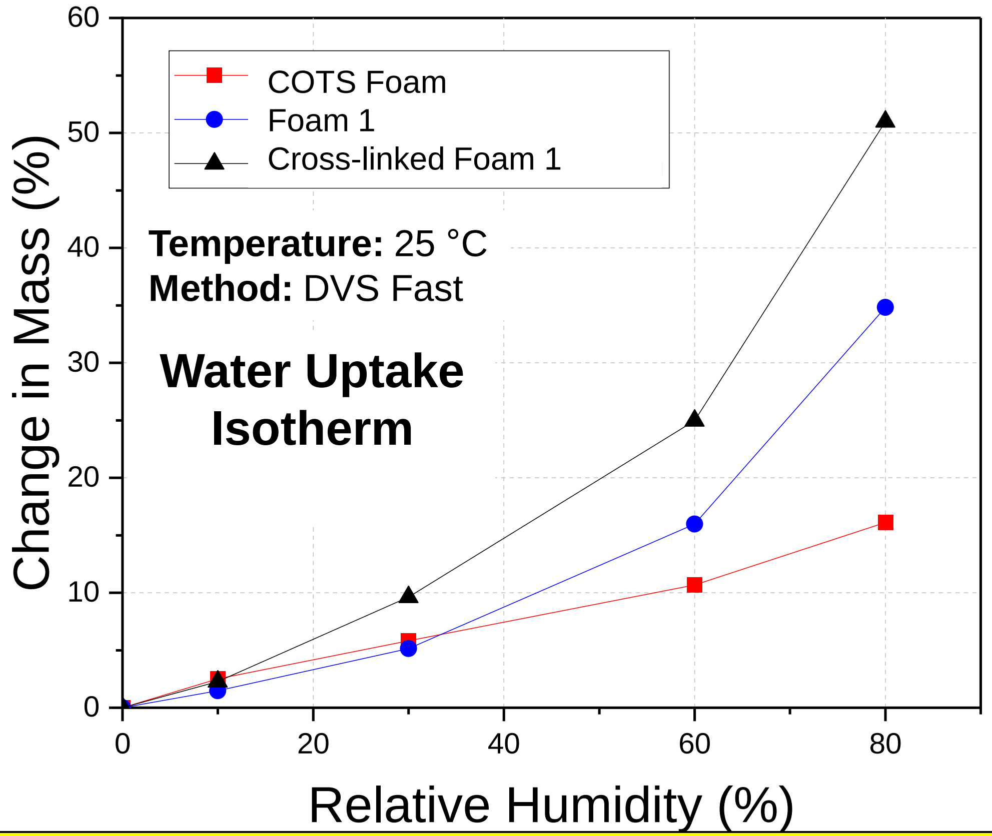
**Goal:** Exceed baseline water uptake of commercial off-the-shelf biopolymer foam

**Methods:** Examine biopolymer foaming (by lyophilization) with and without crosslinking




**Engineered foams promote greater water uptake than baseline off-the-shelf foam**

# TA1 – Best Performing Materials To Date

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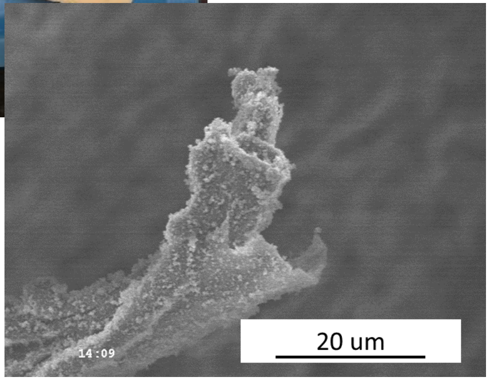
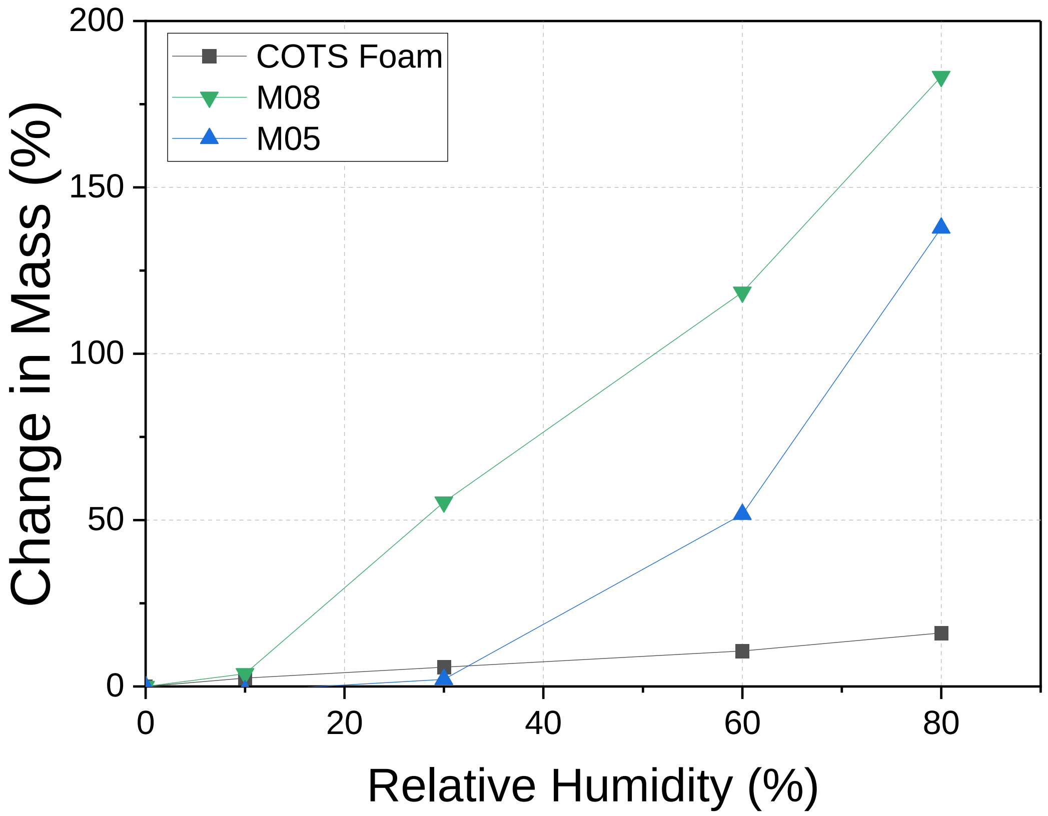


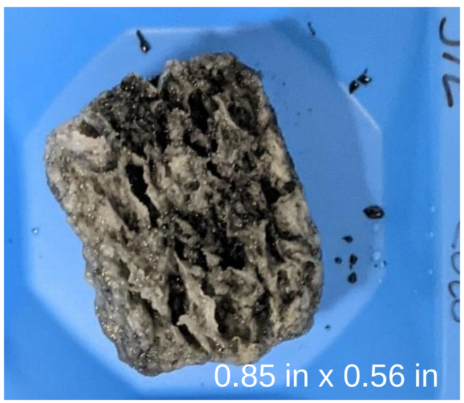

**M05 and M08 SMAFs have been the best performing materials with both capture and release functionality incorporated**

Physical Sciences Inc.

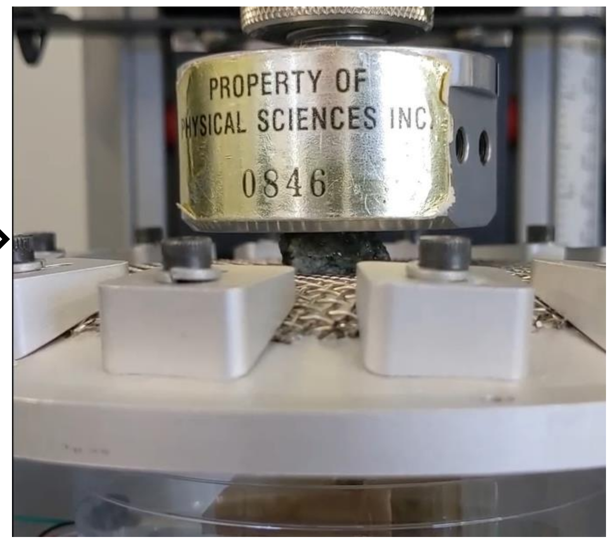
# TA1 - M05 SMAF Demonstration

VG-2021-197-12

- **Objective:** Demonstrate water release from SMAF material loaded at 70% RH
- **Methods:** Perform water uptake in humidity chamber, followed by release using compression set-up
  - [1]H NMR spectrum indicated contamination of water with polymers




SMAF coupon loaded at 70% RH




**Released water**

Filtration (0.45 µm)


**Filtered Water**

**Video demonstrates water release upon SMAF compression**

# TA1 - M08 SMAF Demonstration

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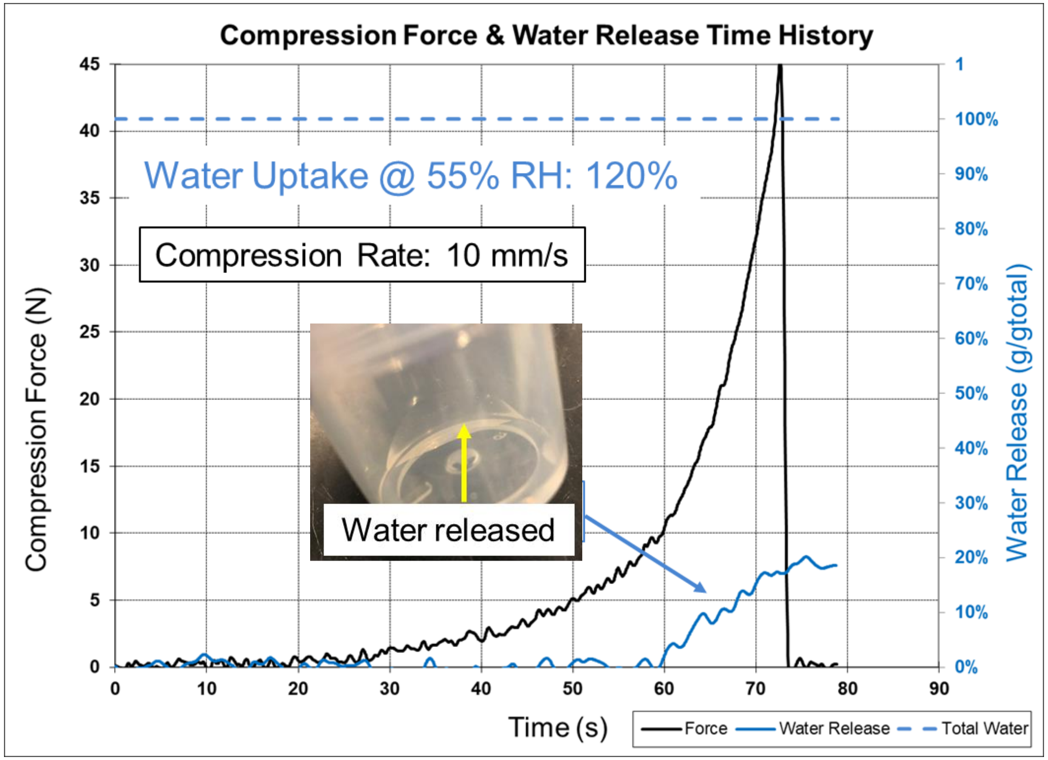
- **Objective:** Demonstrate water uptake and compressive release at 55% RH (M05 demonstrated at 70 % RH)
  - Fulfills one out of the three DARPA performance conditions (10%, 50%, 60%)


M08 SMAF coupon reached 120% water uptake after 16 hr at 55% RH




Achieved 20% water release with a 45 N force

**SMAF water capture and compressive release demonstrated at 55% RH**

# TA2 – SMAF Model Key Equations

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## Governing Equations

### Humid Air Flow Through SMAF

- Navier-Stokes (momentum equation)
- Assumptions: constant fluid and SMAF properties, laminar flow, no mass source/sink, gravity negligible
- Brinkman (B) Equations: continuity and momentum conservation for flow through porous media

$$\nabla \cdot \mathbf{U} = 0$$

$$\underbrace{\frac{\rho}{\varepsilon_p}\left(\frac{\partial \mathbf{U}}{\partial t} + \frac{1}{\varepsilon_p}(\mathbf{U} \cdot \nabla \mathbf{U})\right)}_{\text{Inertia}} = \underbrace{-\nabla p}_{\text{Pressure Source}} + \underbrace{\frac{\mu}{\varepsilon_p}\nabla^2 \mathbf{U}}_{\text{Viscous Diffusion}} - \underbrace{\frac{\mu}{\kappa}\mathbf{U}}_{\text{Foam Permeability}}$$

### Water Vapor ($c_v$) and Liquid Water ($c_l$) Mass Transport

- Assumptions: constant fluid and SMAF properties, liquid water advection negligible
- Advection-Diffusion (AD) equation with reaction rate defines mass transport:

$$\underbrace{\frac{\partial c_i}{\partial t}}_{\text{Transient}} = \underbrace{D_i \nabla^2 c_i}_{\text{Diffusion}} - \underbrace{\mathbf{U}_i \cdot \nabla c_i}_{\text{Advection}} + \underbrace{R_i}_{\text{Vapor to Liquid Source/Sink}}$$

## Key Parameters

### Water Capture

- Assumptions: sample size in DVS small enough for diffusion to be negligible, advection also negligible
- LDF model fit to DVS data at various RH:

$$R_l = -R_v = k\left(c_{l,eq} - c_l\right)$$

- $k$, and $c_{l,eq}$ both function of RH – calculated from local $c_v$

### Key Dimensionless Numbers

- Non-dimesionalization of Advection-Diffusion equations yields three key dimensionless numbers:

- Diffusivity ratio:

$$\lambda = \frac{H_2 0 \text{ in } SMAF}{H_2 0 \text{ in air}} = \frac{D_l}{D_v}$$

- Peclet number:

$$Pe_v = \frac{advection}{diffusion} = \frac{u_v L}{D_v}$$

- Damkohler number, 2nd kind:

$$Da_v = \frac{water\ capture\ rate}{diffusion} = \frac{kL^2}{D_v}$$

**Navier-Stokes and Advection/Diffusion Equations used to model water transport and capture by SMAF material**

# TA2 – SMAF Model Inputs and Outputs



VG-2021-197-15

## Inputs

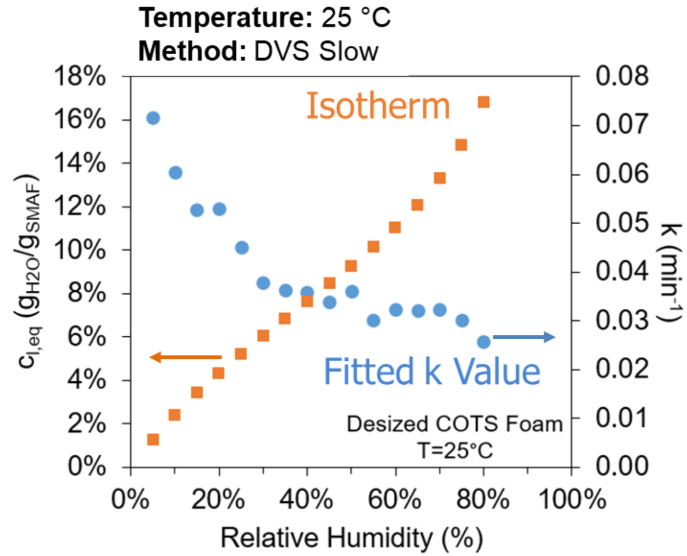
- SMAF Properties
  - Physical properties – form factor, density, porosity, permeability, stress-strain curve
  - Water capture/storage/release – isotherm define equilibrium capacity and rate constant, diffusivity, release vs. strain, unreleased capacity
- Environmental Conditions
  - Humid air temp, RH, and specific discharge
- System Properties
  - Common – turnovers per day, compression strain, battery power density, air handler efficiency
  - Specific – architecture specific parameters, e.g. material selection, air gap thickness, number of layers

## Outputs

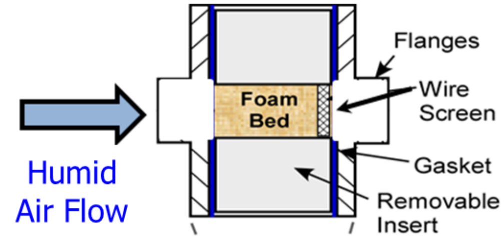
- Water Output
  - Water capture rate, total water capture per SMAF mass
  - Water released and required force from Instron testing
- System SWaP

DVS Data ($k$, $C_{l,eq}$)

$$R_l = k(c_{l,eq} - c_l)$$




Fixed-Bed Performance Prediction




**The goal of this modeling effort is to correlate intrinsic foam properties (DVS data) to performance in a flow geometry (prototype system)**

# TA2 – SMAF Model Construction

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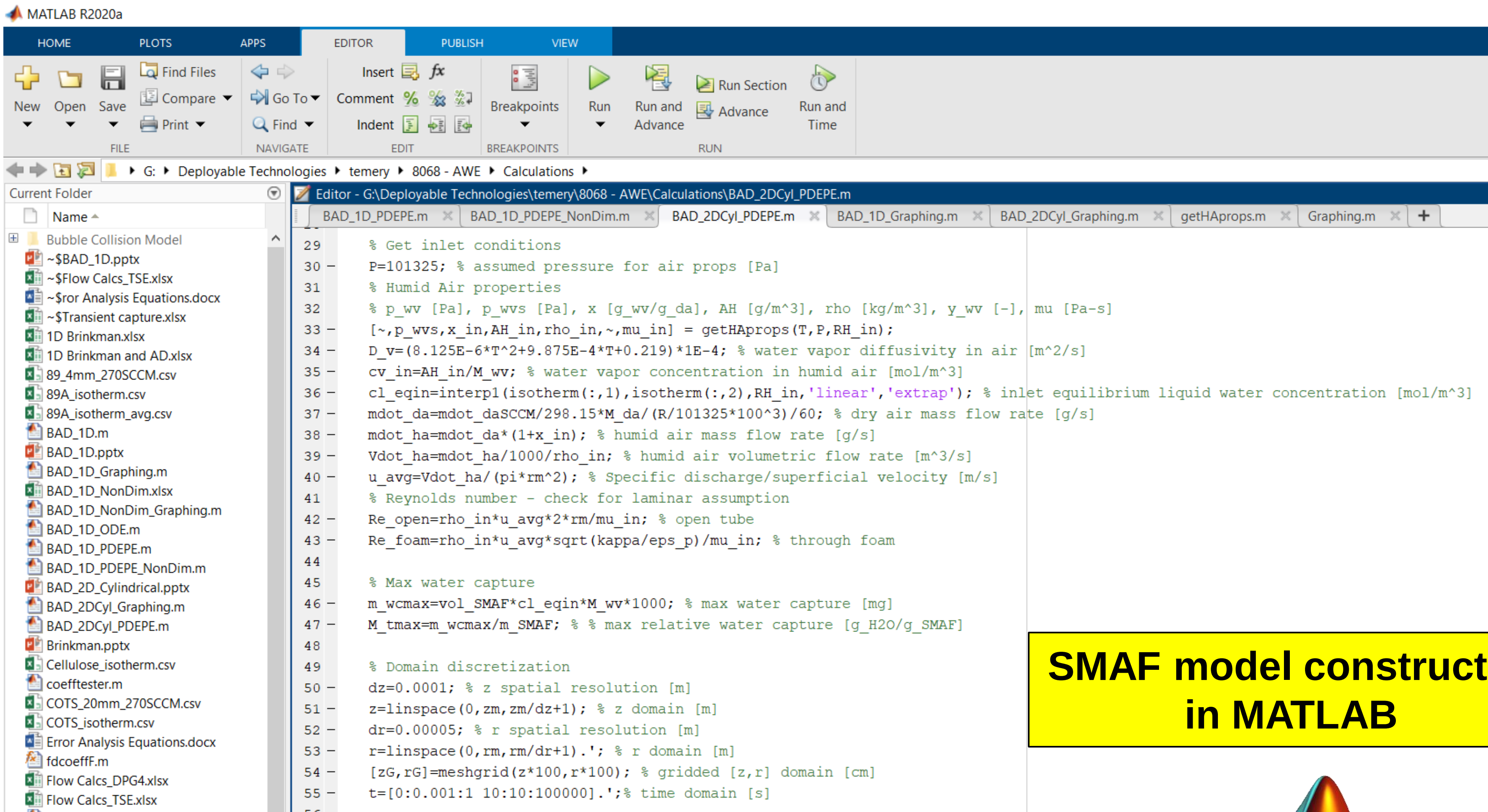


**SMAF model constructed in MATLAB**

# TA2 – Predicting SMAF Water Capture Performance

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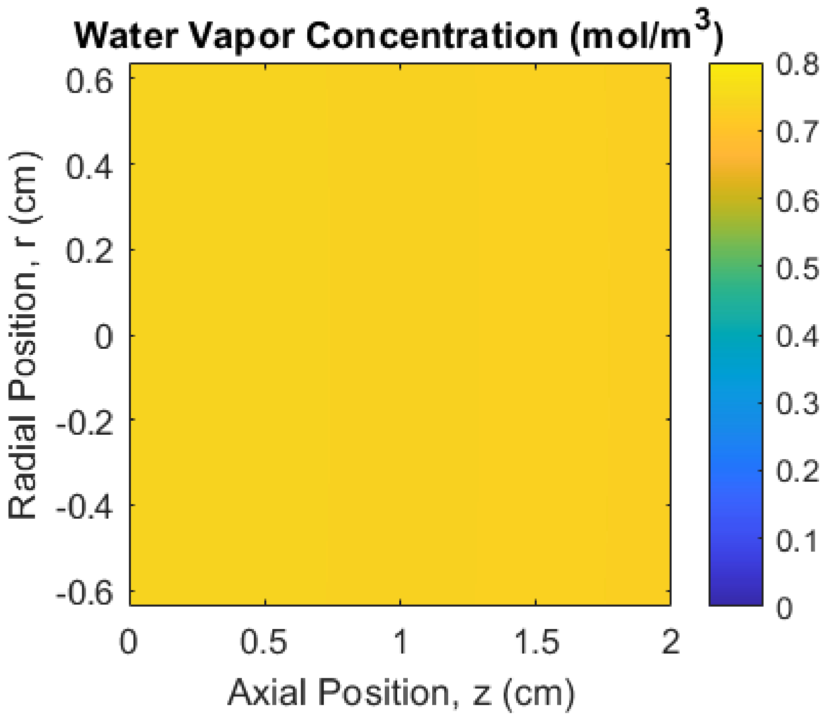
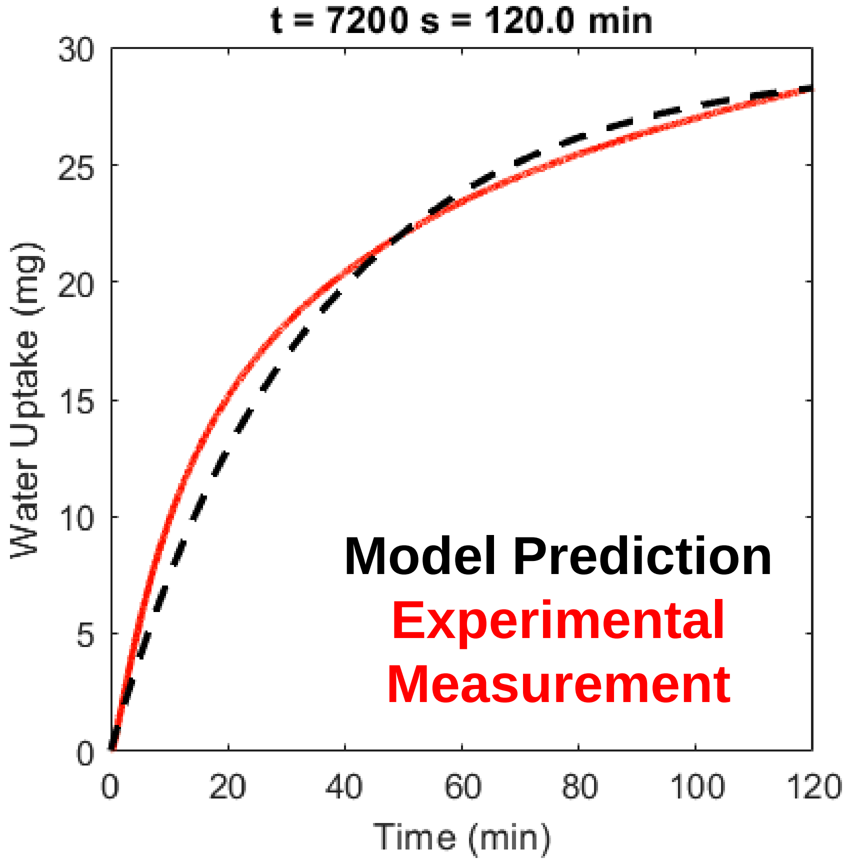
**PSI SMAF Model was used to predict the performance of a SMAF material**




**Animation shows that the PSI model prediction has good correlation with the experimental measurement**

# TA2 – Tracking Progress Towards Implementation

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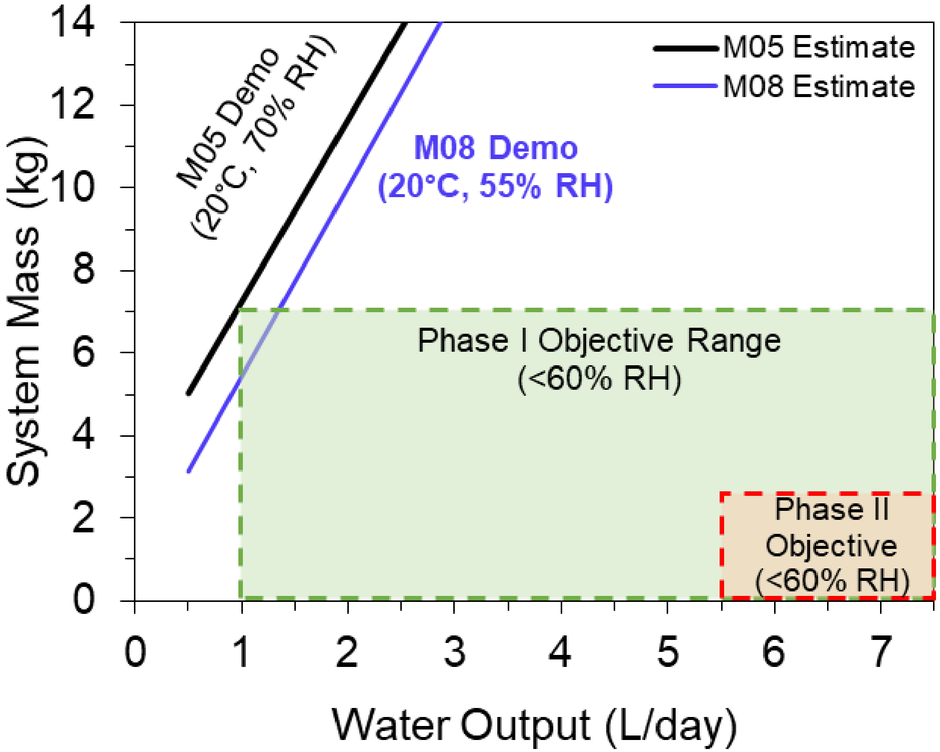
- **Goal: Provide a predictive modeling to assist in the overall design and ensure the required performance metrics are being met.**
  - **Black line** represents M05 demonstration
  - **Blue line** represents M08 demonstration
  - Computed using PSI rubber model using several key assumptions




**Key Assumptions:**

- No SMAF material degradation over time
- Layered system model as initially proposed to estimate housing mass
- Minimal additional pressure drop as SMAF fills. Air flow requirements used to estimate fan and battery mass
- Two capture/release cycles per day
- Water is potable after filtration

**Improvements in performance at lower relative humidity and system performance have been achieved**

# Potential Technology Use Cases



- **Goal:** Identify potential use cases to which our SMAF approach can be tailored to both defense and commercial applications:

1. **Downed Pilot Scenario**

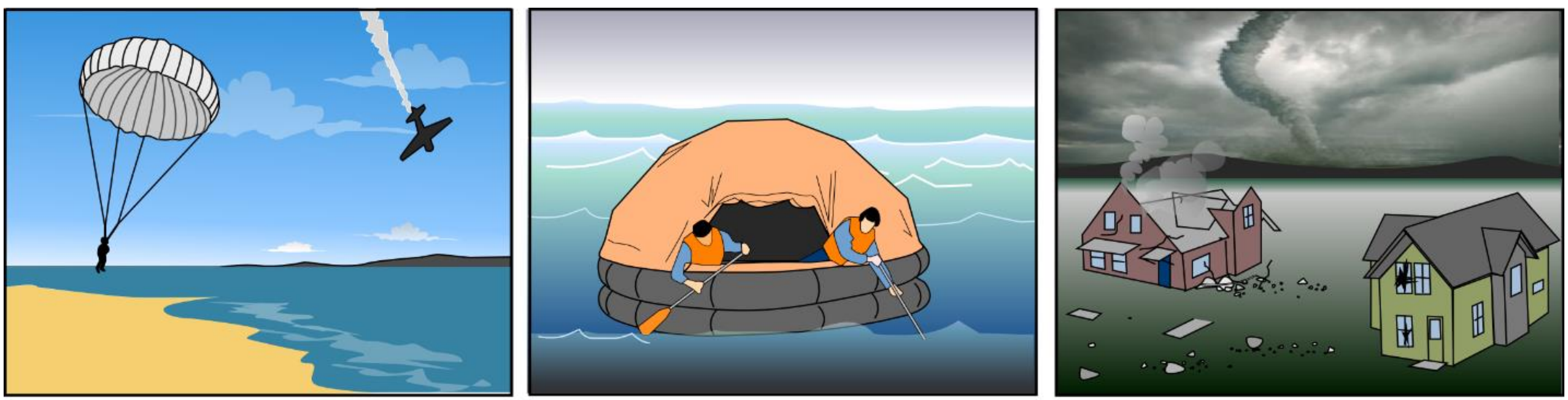
   Key Advantage: Low anticipated system noise generation

2. **Lifeboat Operation**

   Key Advantage: Surrounding conditions maintained at high RH

3. **Initial Household Water Generation after Disaster Event**

   Key Advantage: Ideal solution for use in tropical regions, where water production can be maximized.



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**The team is taking into consideration potential applications to guide prototype development**

# Conclusions and Next Steps

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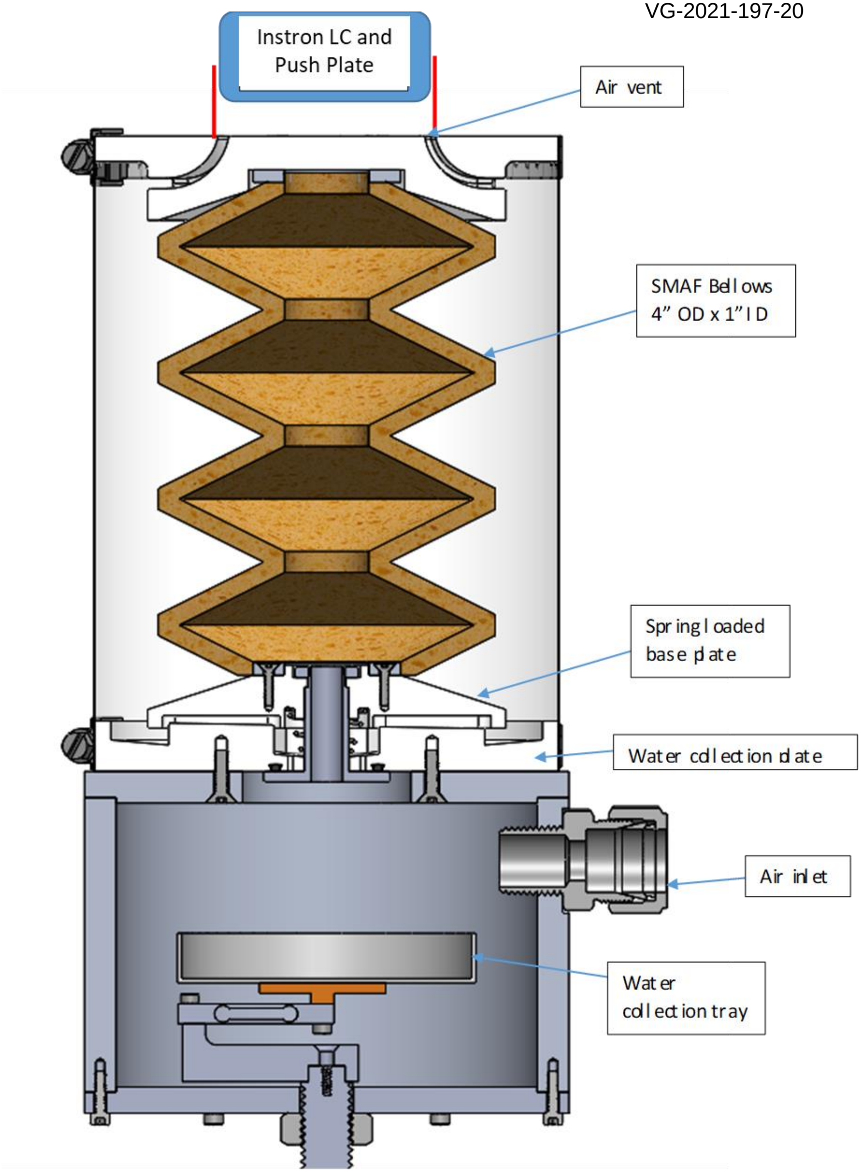
VG-2021-197-20

- **The PSI/UMass/CDI team is developing a new material called a Smart Moisture Adsorbing Foam (SMAF)**
- **SMAF material captures water from the atmosphere and releases water by compression**
- **Core concept has been demonstrated at 55% and 70% relative humidity**
- **SMAF model developed to described transport and adsorption in foam media**
- **Next steps include further optimization of SMAF formulation and construction of an operable prototype (due to IV&V team in July)**



# Backups

# DARPA BAA Requirements

Physical Sciences Inc.



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- **Broad Need –** Water transport to the warfighter is mission-critical but logistically challenging, requiring equipment, fuel, and personnel that limits tactical maneuver and decision space. Warfighter requires 3/7 L/day.
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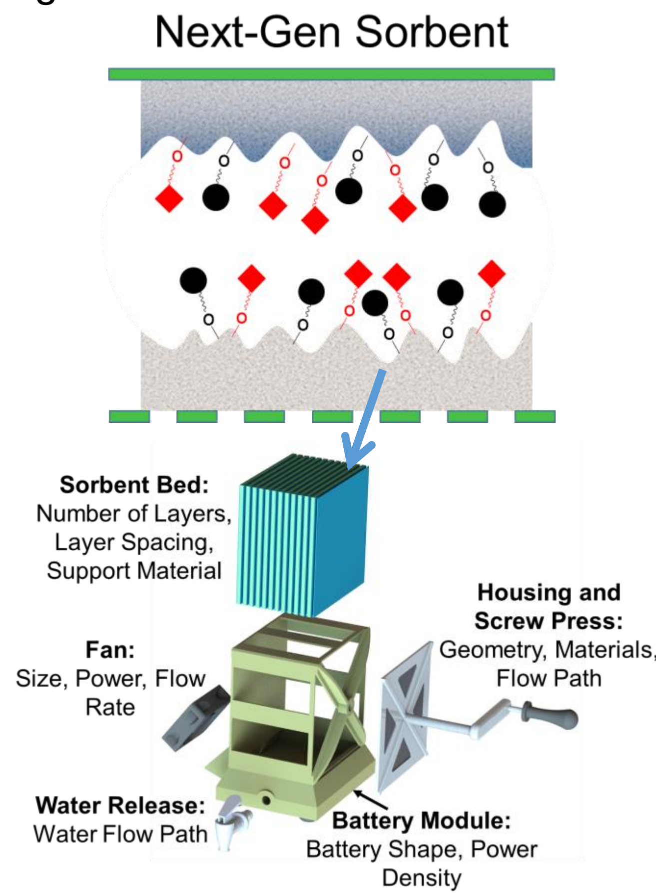
| Power | Must be contained onboard | Must be contained onboard |
| Volume | 6 L (0.21 $ft^3$) | 1.5 L (0.05 $ft^3$) |
| Unit Cost | - | - |
| Desired Properties | - | Water meets TB-Med-577 potability standards, Operational for >30 days at 24 hr runtime |

# PSI Team Program Objectives

Physical Sciences Inc.



- **Program Goal:** Develop a system capable of extracting potable drinking water from air, obviating the need for costly and dangerous transportation (Expeditionary Track).
  - Program broken into 2 technical areas (TAs)
    - TA1: Transformational Sorbent Materials Development
    - TA2: Extractor Modelling, Engineering and Sorbent Integration

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# TRL Analysis*

Physical Sciences Inc.

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- **Entering Phase I Program = TRL1/2**
  - Technology concept and/or application formulated.
  - Limited analytic studies
    - Process in place to produce and evaluate SMAF materials
    - System concept created

- **Exiting Base Program = TRL3/4**
  - Analytical and experimental critical function and/or characteristic proof of concept. Component and/or breadboard validation in laboratory environment
    - Material optimization performed
    - Breadboard system demonstration

- **Exiting Option Programs = TRL6**
  - Components and/or breadboard validation in relevant environment
    - Scalable sorbent production
    - Field demonstration in relevant environment (IV&V)

** Technology Readiness Levels in DoD, Defense Acquisition Guidebook 2010*