FAST Equipment Lease with Liberty University, Inc.

Cooperative Research and Development Final Report

CRADA Number: CRD-20-16802

NREL Technical Contact: Tessa Greco

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-83939
September 2022

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Suggested Citation
Greco, Tessa. 2022. *FAST Equipment Lease with Liberty University, Inc.: Cooperative Research and Development Final Report, CRADA Number CRD-20-16802.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-83939. https://www.nrel.gov/docs/fy22osti/83939.pdf.

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Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Office of Energy Efficiency and Renewable Energy (EERE), Water Power Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Cooperative Research and Development Final Report

Report Date: September 1, 2022

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Liberty University, Inc.

CRADA Number: CRD-20-16802

CRADA Title: FAST Equipment Lease with Liberty University, Inc.

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Name and Email Address of POC at Company:

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Sponsoring DOE Program Office(s): Office of Energy Efficiency and Renewable Energy (EERE), Water Power Technologies Office (WPTO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$23,000.00
TOTALS	$23,000.00

Executive Summary of CRADA Work:

Liberty University, Inc. (Participant) will receive government owned equipment from NREL to evaluate and perform fatigue testing of bladders in use for small scale pumped storage hydropower. NREL is providing technical support to advance Liberty University's pumped storage hydropower (PSH) concept towards commercialization. The concept creates modular upper and lower watertight enclosures (tanks or reservoirs) connected by a series of modular pipe lengths (penstock).

CRADA benefit to DOE, Participant, and US Taxpayer: Enhances the laboratory's core competencies

Summary of Research Results:

The Eldredge/Medina proposal focused on modular, closed-loop, scalable pump storage hydro (mcs-PSH) systems with an approximate power capacity range of 1 to 10 MW and operating in closed loop mode. In closed loop mode both reservoirs are isolated from a free-flowing water source. The problems addressed included reducing the costs for materials and construction, improving the ease of installation, and expediting the project development timeline. A secondary objective of this work was to facilitate standardization of components, to the extent possible, so that replication of similar mcs-PSH systems would not require a complete redesign.

Representing Liberty University School of Engineering (LUSOE), Eldredge and Medina were awarded a national lab voucher of $100,000 as fourth place winners of the competition. The funds were approximately distributed as follows, shown below:

Item	Amount	Lab providing support	Type of support
1	$62,500	ORNL	Computational simulations of fluid structure interactions resulting from fluid transients in the penstock.
2	$25,000	NREL	Equipment loan for setting up scaled physical test loop.
3	$12,500	ANL	Economic and market analysis of the proposed modular PSH system.

Task 1: Bladder Fatigue Testing.

Participant will receive leased equipment sent by NREL and, with technical support from NREL, set up bladder fatigue testing at the location chosen at Liberty University in Virginia.

A scaled physical test loop was setup at Liberty University's Center for Engineering Research and Education (CERE), using equipment from NREL support as well as an off-grid solar system and ancillary materials purchased via state grants obtained by the LUSOE team.

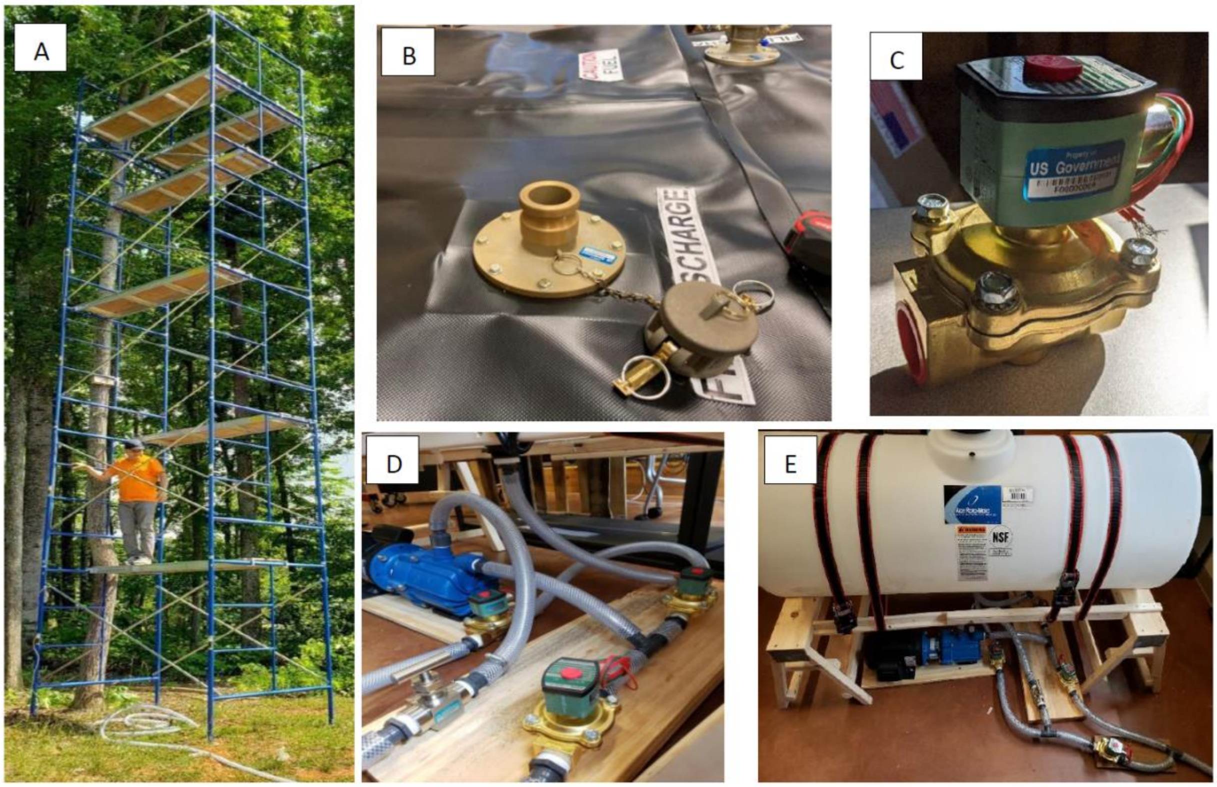


Fig. A.12: Various components of the test loop. (A) Scaffolding for mounting upper reservoir bladder tank; (B) bladder tank with charge/discharge opening; (C) solenoid valve; (D) pump and connections; (E) discharge PPE tank.

In addition to the physical test loop, analytical and experimental work was carried out in order to assess the fatigue of the bladder membrane under various conditions. Following previous work, the Liberty University team developed a python-based algorithm and GUI to determine the linear strength of the bladder membrane based on hydrostatic conditions for various capacities.

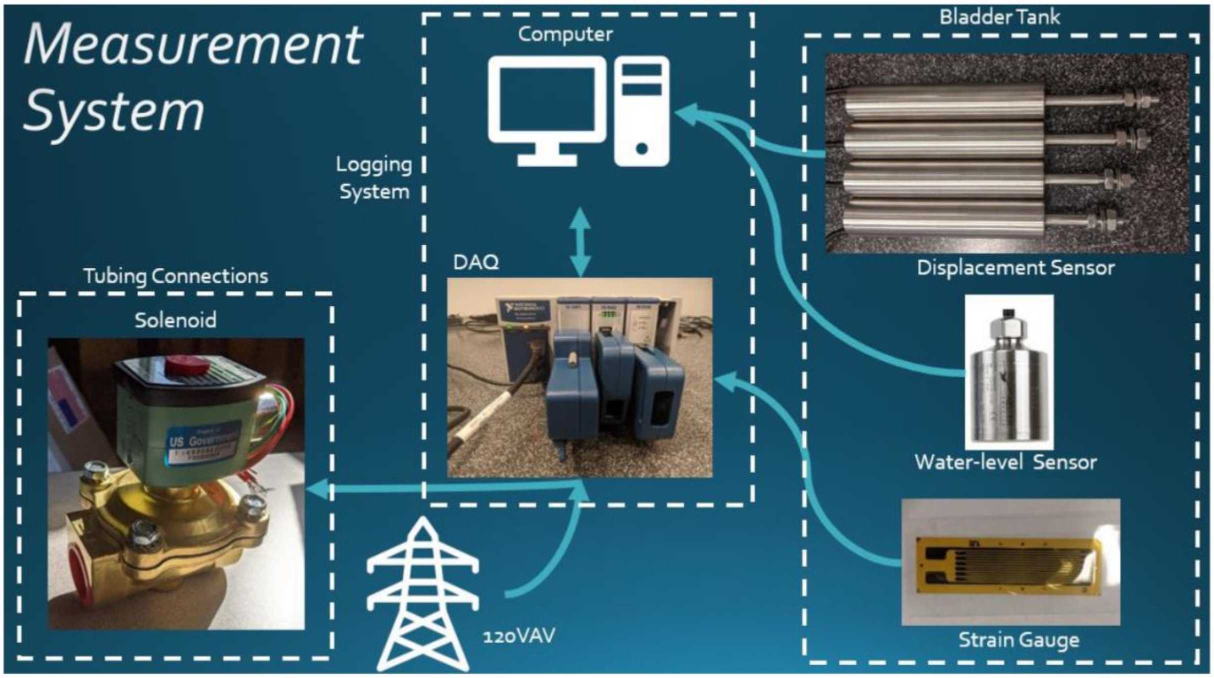


Fig. A.13: Various components of the data-acquisition and controls system. Solenoid valves will be actuated based on reservoir level conditions, which will be measured via water-level sensors. Strain gauges and displacement sensors will measure various levels of deformation on the bladder membrane.

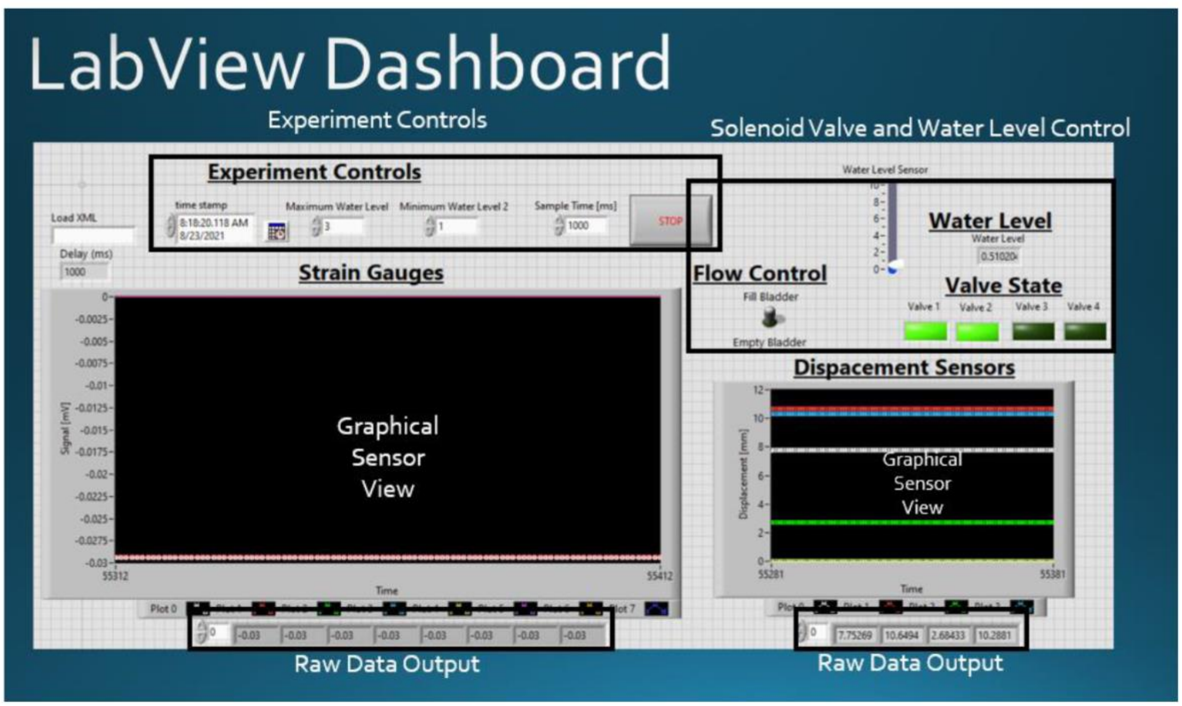


Fig. A.14: LabView dashboard showing the various environments to monitor and control information to and from the test loop. Notice the experiment controls, water level monitoring, flow control, valve state, and graphical sensor views for strain gauges and displacement sensors.

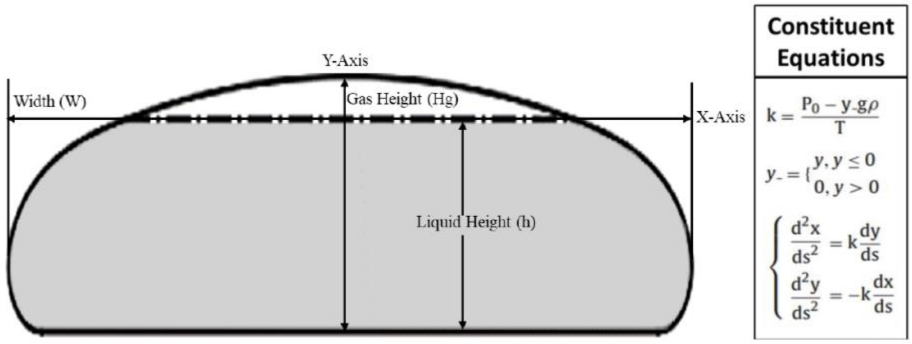
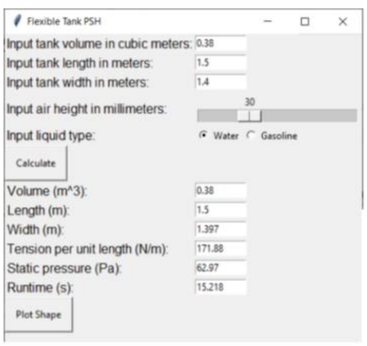


Fig. A.15: Visual statement of hydrostatic-based collapsible-membrane problem, based on Osadolor et al. 2016 (see reference footnote under item 2). The tank is considered to form the same shape in both the longitudinal and transverse directions. The heights of liquid and gas, as well as tank volume, can be varied. In the equations, k is curvature, g is gravitational acceleration, s is the arc distance, ρ is the density of the fluid, and T is linear strength of membrane, which is usually computed.



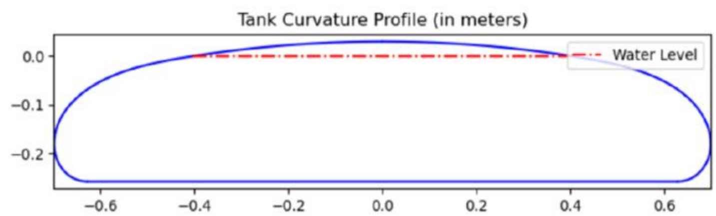


Fig. A.16: Some outputs from the analytical solution to the problem described in Fig. A.15. On the left, a python-based GUI shows numerical results; on the right, an example output of the collapsible tank curvature profile as produced by the program.

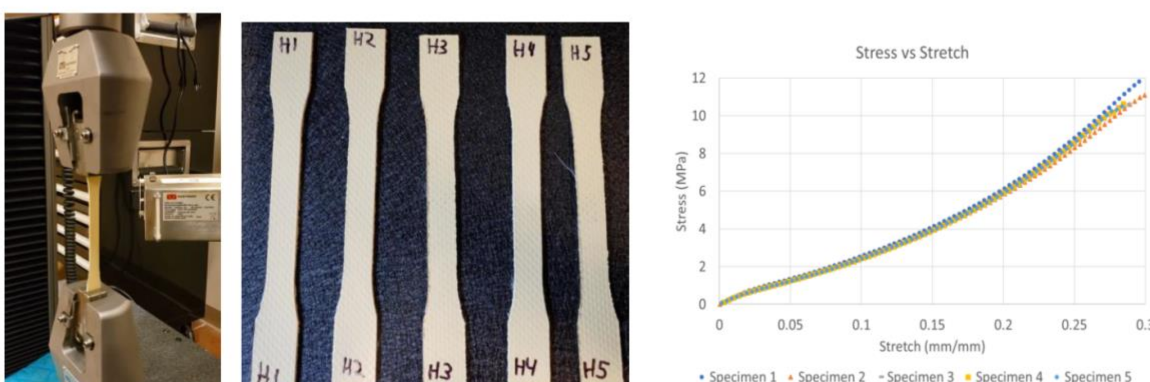


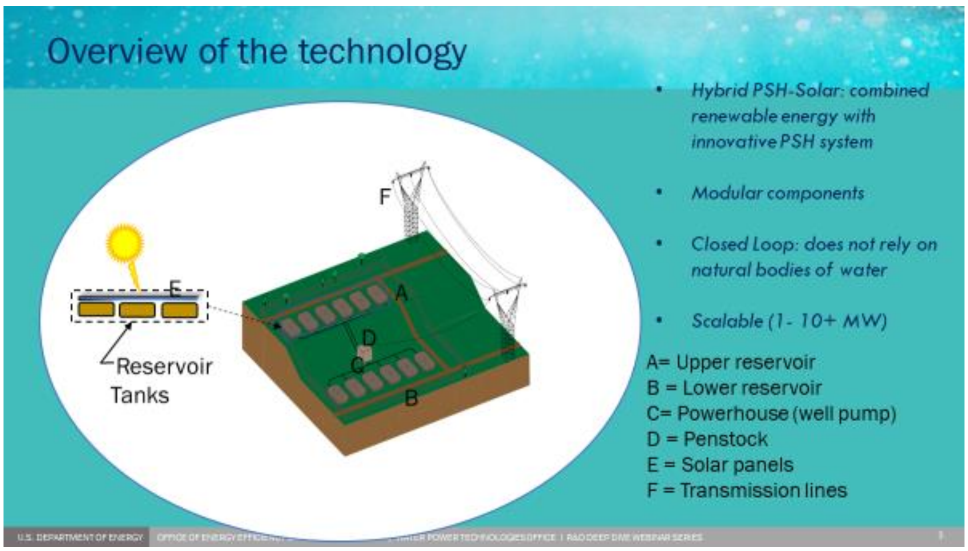
Fig. A.17: (Left) Mechanical testing of membrane specimens (middle). (Right) An example output of the results from the mechanical testing. Even though this schematic shows only monotonic, also creep and fatigue tests have been carried out. Conclusive results will be provided in the final report.

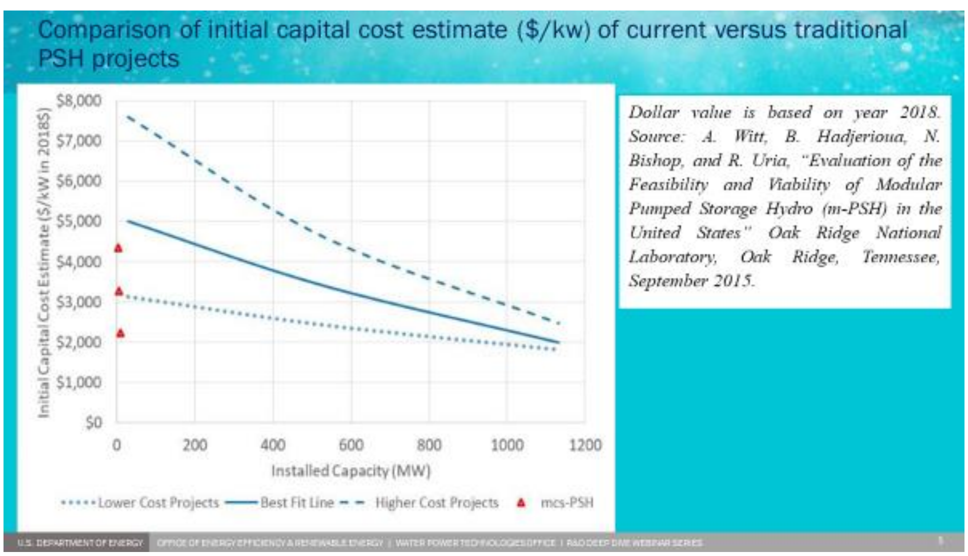
Task 2: CRADA Final Report.

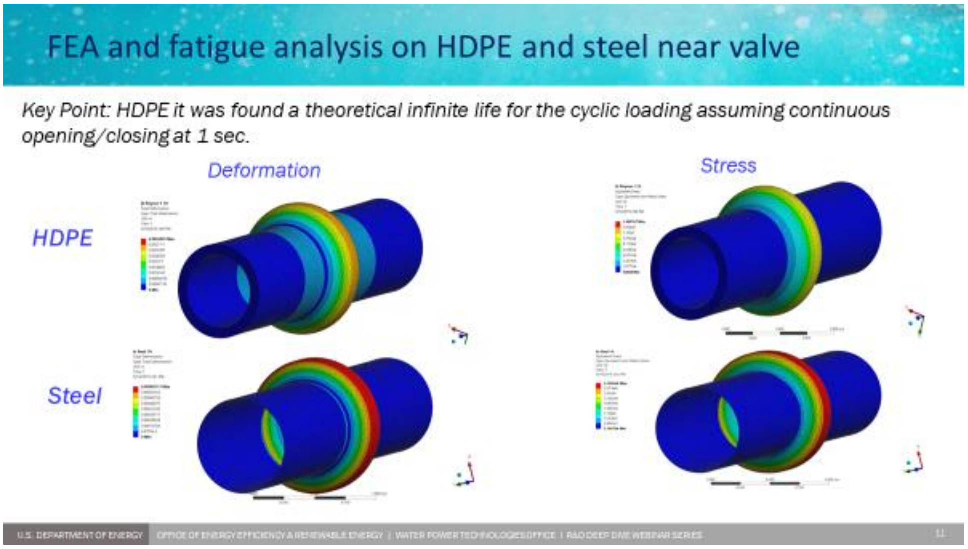
This report meets the requirement for the task CRADA Final Report. NREL will outline accomplishments of the CRADA based on the project final report, then prepare and submission in accordance with CRADA requirements, with participation from Participant.

Liberty University submitted a final report and final presentation in October 2021 which presented a summary of all work and resulting analysis that took place up until this point.

The final presentation was included as part of the FAST Forward final webinar, October 27, 2021, where winners presented on their progress and answered questions from a panel of reviewers. Representative slides are included below for reference.






FEA and fatigue analysis on HDPE and steel near valve
Key Point: HDPE it was found a theoretical infinite life for the cyclic loading assuming continuous opening/closing at 1 sec.
Deformation
Stress
HDPE
Steel
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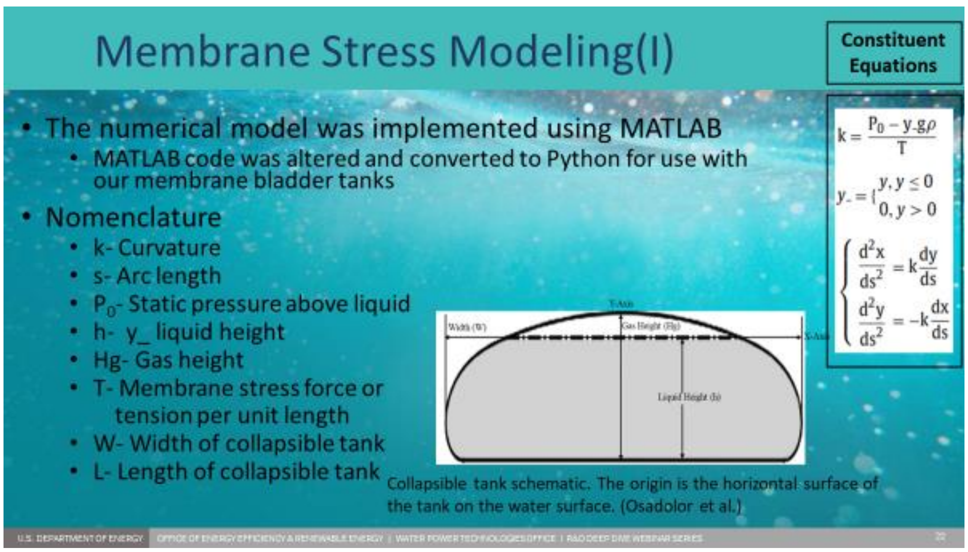
Membrane Stress Modeling(I)
Constituent Equations
$k = \frac{P_0 - y_{-} g \rho}{T}$
$y_{-} = \{ \begin{matrix} y, y \leq 0 \\ 0, y > 0 \end{matrix}$
$\begin{cases} \frac{d^2x}{ds^2} = k\frac{dy}{ds} \\ \frac{d^2y}{ds^2} = -k\frac{dx}{ds} \end{cases}$
• The numerical model was implemented using MATLAB
• MATLAB code was altered and converted to Python for use with our membrane bladder tanks
• Nomenclature
• k- Curvature
• s- Arc length
• P_0- Static pressure above liquid
• h- y_ liquid height
• Hg- Gas height
• T- Membrane stress force or tension per unit length
• W- Width of collapsible tank
• L- Length of collapsible tank
Width (W)
Gas Height (Hg)
Liquid Height (h)
Collapsible tank schematic. The origin is the horizontal surface of the tank on the water surface. (Osadolor et al.)
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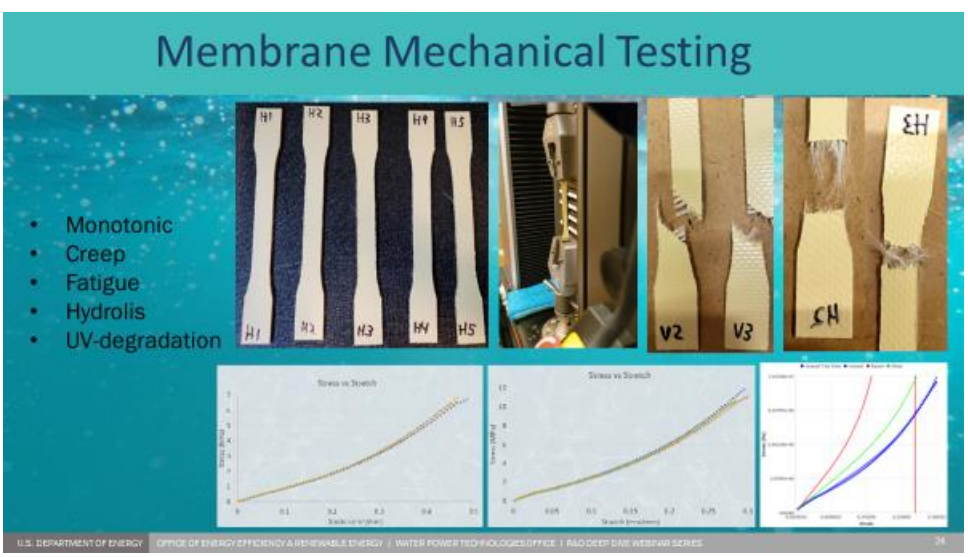
Membrane Mechanical Testing
• Monotonic
• Creep
• Fatigue
• Hydrolis
• UV-degradation
H1
H2
H3
H4
H5
V2
V3
Stress vs Stretch
Stress vs Stretch
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<u>Subject Inventions Listing</u>:

Liberty University Patent Application:

Hybrid Renewable Pumped Storage Hydropower Energy Storage System. Application Serial No. 17/671,146, Medina, Hector & Eldredge, Thomas.

<u>ROI #</u>:

None