U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

FAST Forward: The FAST PSH Commissioning Prize Winning Concepts

A WPTO R&D Deep Dive Webinar

Welcome!

WPTO R&D Deep Dive Webinar Series
A look into the ongoing work of WPTO sponsored projects and program areas

November R&D Deep Dive Webinar:

Highlights of the Hydropower Licensing Report

Thursday, November 18, 1 – 2 p.m. ET

Logistics & Format

- Three FAST Prize winners will present
- Each presentation will be followed up with questions from the panelists
- This webinar will be recorded and made available to registrants
- Attendees’ microphones are muted and attendees are not visible on video
- If you have technical issues, contact Megan Lennox

Thank you for participating!

Pumped-Storage Hydropower FAST Prize

PSH provides:

- large-scale electrical system reserve capacity,
- contributes to grid reliability, and
- supports supply-demand balancing with quick response capabilities and

New PSH development has stalled due to:

- *Difficulty* associated with benefit quantification
- *Significant* upfront capital costs and long commissioning times

DOE WPTO initiated the **Pumped-Storage Hydropower FAST Commissioning** solutions for reducing the cost, risk, and timeline associated with PSH develo

The FAST Prize culminated in Fall 2019 with a shark-tank style pitch contest share of the $550k cash and in-kind pool.

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WATER POWER TECHNOLOGIES OFFICE

NREL
Transforming ENERGY

Hydropower Prize Request for Information

Help shape future hydropower prizes!

The National Renewable Energy Laboratory is seeking feedback from members of the hydropower industry, academia, research laboratories, and government agencies, as well as other stakeholders, to help identify opportunities for refining future hydropower prizes.

Please respond to the request for information at this link:

https://www.nrel.gov/water/market-acceleration.html

Jay Anders, Chief Operating Officer, EPC Projects at Rye Development

Carl Borgquist, CEO and President, Absaroka Energy

Erin Foraker, Hydropower and Renewable Energy Research Coordinator, Bureau of Reclamation

Michael Manwaring, Executive Vice President, McMillen Jacobs Associates

Debbie Mursch, Director Business Development,

GE Renewable Energy

Tom Elderedge and Hector Medina

Liberty University

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Hybrid Modular Closed-Loop Scalable Pumped Storage (hydroelectric & solar)

Progress on Analysis, Modeling and Experimentation

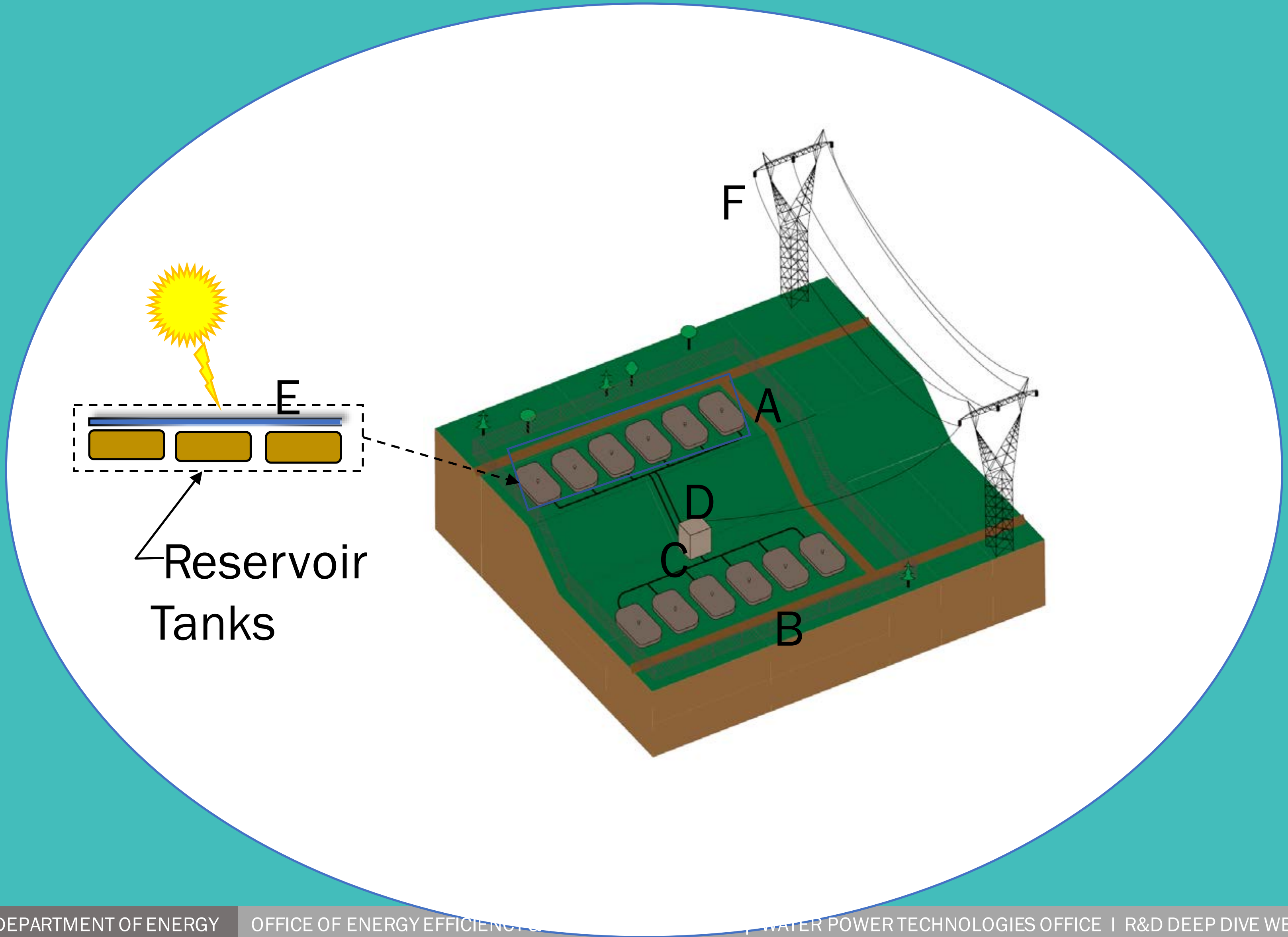
Dr. Hector Medina and Dr. Thomas Eldredge

Speakers and Introduction

Dr. Hector Medina is a Professor and Director of the Mechanical Engineering Program in the School of Engineering at Liberty University. He teaches Mechatronics and Dynamic System Modeling. His research interests include energy systems, controls of intelligent systems, bio-inspired multi-functional materials, and surface engineering. Prior to working at LU, he worked in LWD/MWD systems in the oil industry as well as RF radio systems and high school teaching.

Dr. Tom Eldredge has a Ph.D. degree in mechanical engineering from the University of Tennessee. He is a licensed professional engineer in Connecticut. He has over 25 years of experience in various aspects of the power generation industry. Presently he is an Associate Professor of mechanical engineering at Liberty University.

Overview of the technology

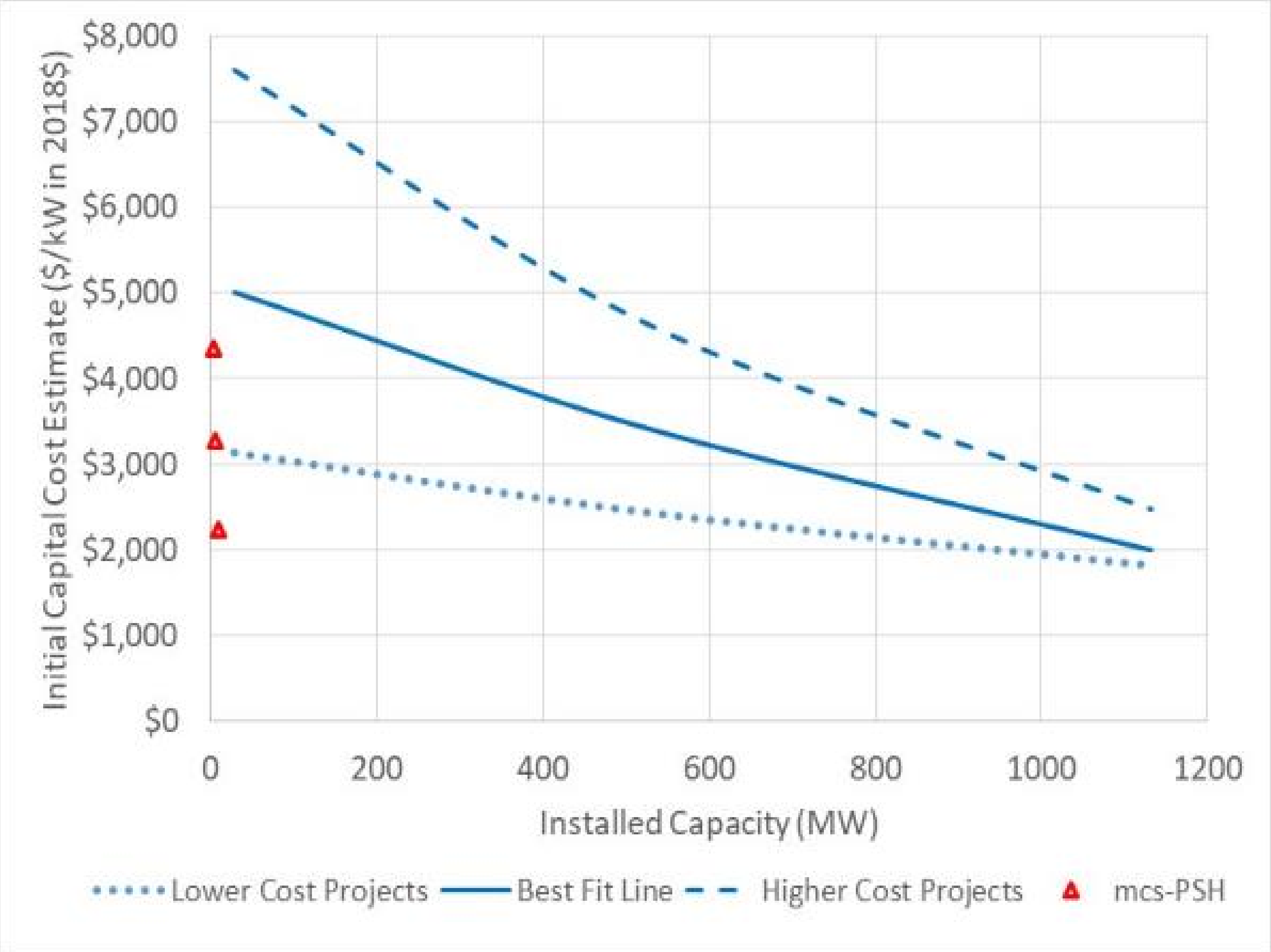


- *Hybrid PSH-Solar: combined renewable energy with innovative PSH system*
- *Modular components*
- *Closed Loop: does not rely on natural bodies of water*
- *Scalable (1- 10+ MW)*

A= Upper reservoir
B = Lower reservoir
C= Powerhouse (well pump)
D = Penstock
E = Solar panels
F = Transmission lines

Cost and Market Analyses

Comparison of initial capital cost estimate ($/kw) of current versus traditional PSH projects

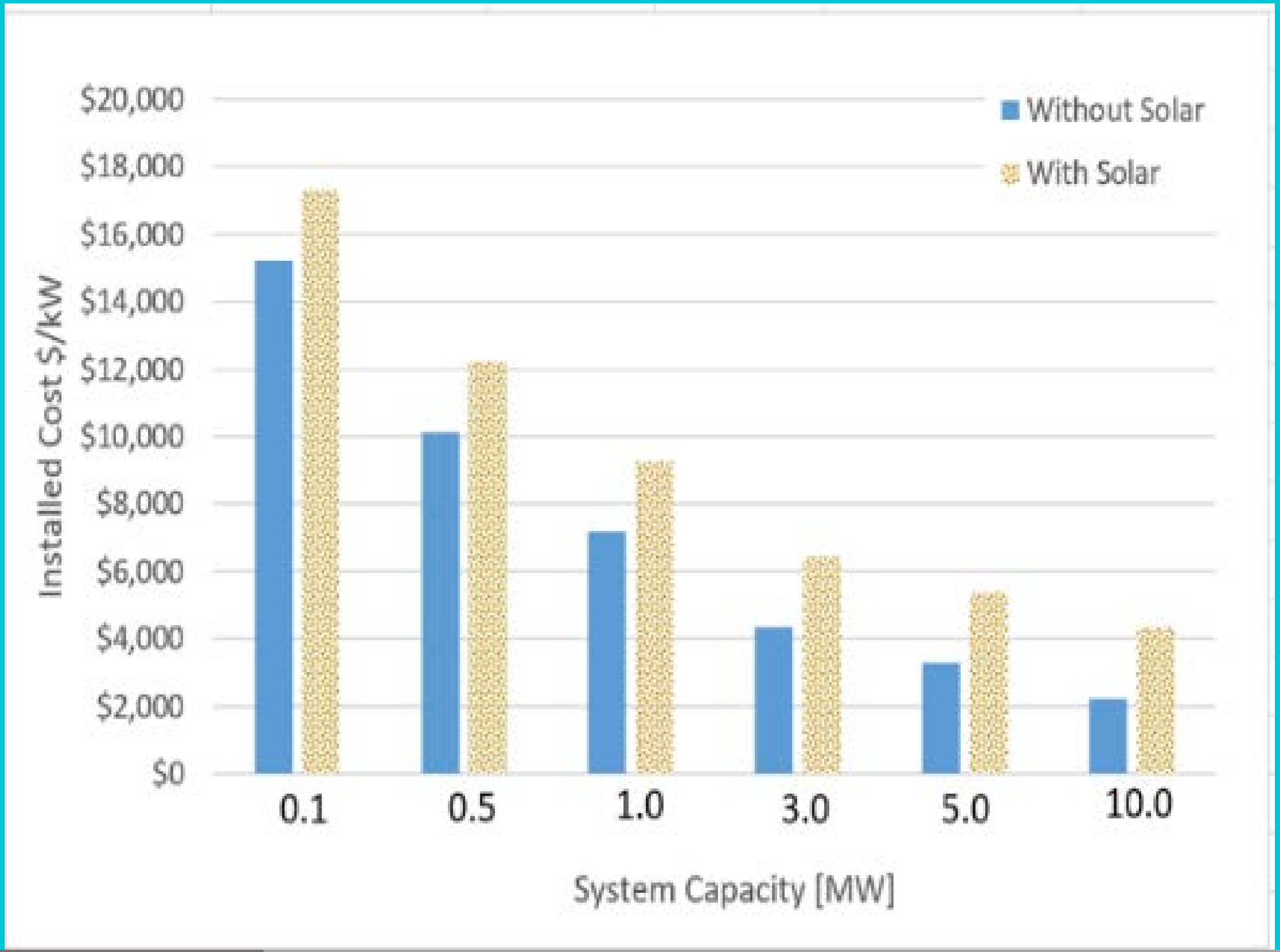


Dollar value is based on year 2018. Source: A. Witt, B. Hadjerioua, N. Bishop, and R. Uria, "Evaluation of the Feasibility and Viability of Modular Pumped Storage Hydro (m-PSH) in the United States" Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2015.

COMPARE OVERALL SYSTEM COSTS (with & without solar)

Key Points

- Incremental solar costs increase for higher system capacities
- The solar compensates for RTE losses.



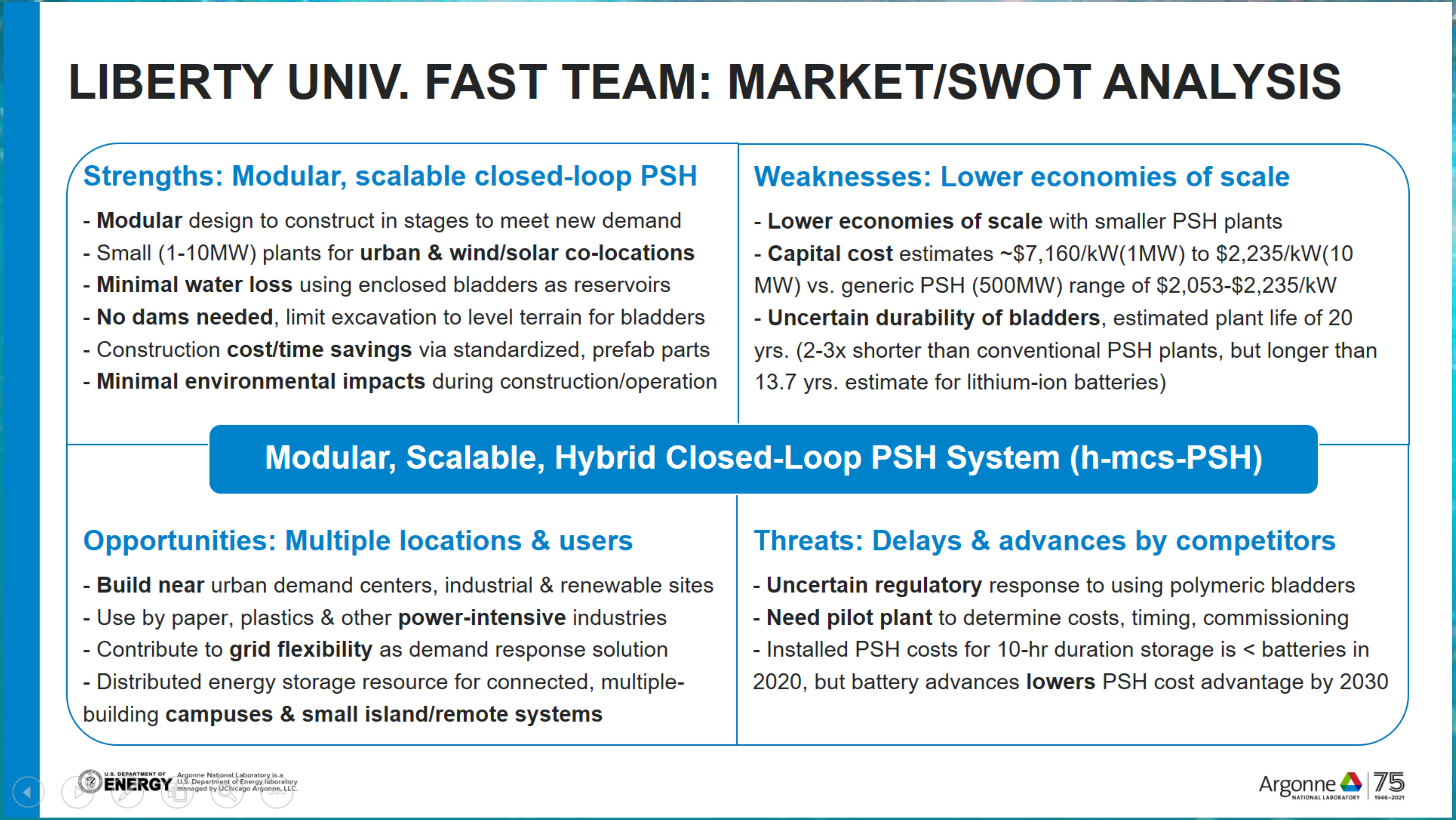
Tracking vs fixed tilt solar PV

- Single axis tracking improves efficiency ~30% over a fixed tilt system.

- For utility scale (> 2MW) installations single axis tracking and fixed tilt installation costs appear to be within about 4%.

- Conclude that single axis tracking is economically feasible and recommended.

Market Analysis: Modular, Scalable, Hybrid Closed-Loop PSH System (h-mcs-PSH)



LIBERTY UNIV. FAST TEAM: MARKET/SWOT ANALYSIS

Strengths: Modular, scalable closed-loop PSH

- **Modular** design to construct in stages to meet new demand
- Small (1-10MW) plants for **urban & wind/solar co-locations**
- **Minimal water loss** using enclosed bladders as reservoirs
- **No dams needed**, limit excavation to level terrain for bladders
- Construction **cost/time savings** via standardized, prefab parts
- **Minimal environmental impacts** during construction/operation

Weaknesses: Lower economies of scale

- **Lower economies of scale** with smaller PSH plants
- **Capital cost** estimates ~$7,160/kW(1MW) to $2,235/kW(10 MW) vs. generic PSH (500MW) range of $2,053-$2,235/kW
- **Uncertain durability of bladders**, estimated plant life of 20 yrs. (2-3x shorter than conventional PSH plants, but longer than 13.7 yrs. estimate for lithium-ion batteries)

Modular, Scalable, Hybrid Closed-Loop PSH System (h-mcs-PSH)

Opportunities: Multiple locations & users

- **Build near** urban demand centers, industrial & renewable sites
- Use by paper, plastics & other **power-intensive** industries
- Contribute to **grid flexibility** as demand response solution
- Distributed energy storage resource for connected, multiple-building **campuses & small island/remote systems**

Threats: Delays & advances by competitors

- **Uncertain regulatory** response to using polymeric bladders
- **Need pilot plant** to determine costs, timing, commissioning
- Installed PSH costs for 10-hr duration storage is < batteries in 2020, but battery advances **lowers** PSH cost advantage by 2030

U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY 75 1946–2021

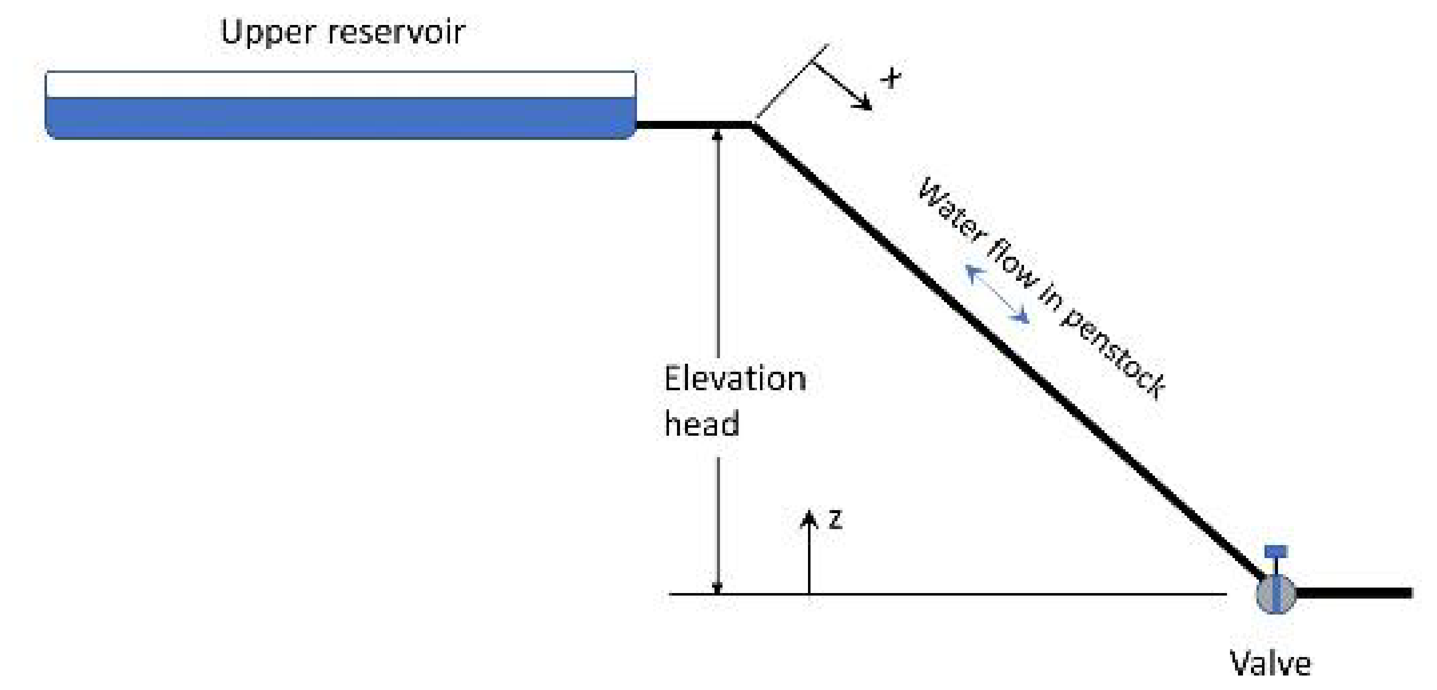
Penstock Analysis

Water Hammer Analysis

The 1D water hammer analysis was conducted by solving the Euler equation of motion and the continuity equation, as shown:

Continuity equation: $a^2 \frac{\partial v}{\partial x} + \frac{1}{\rho} \frac{\partial \rho}{\partial t} = 0$

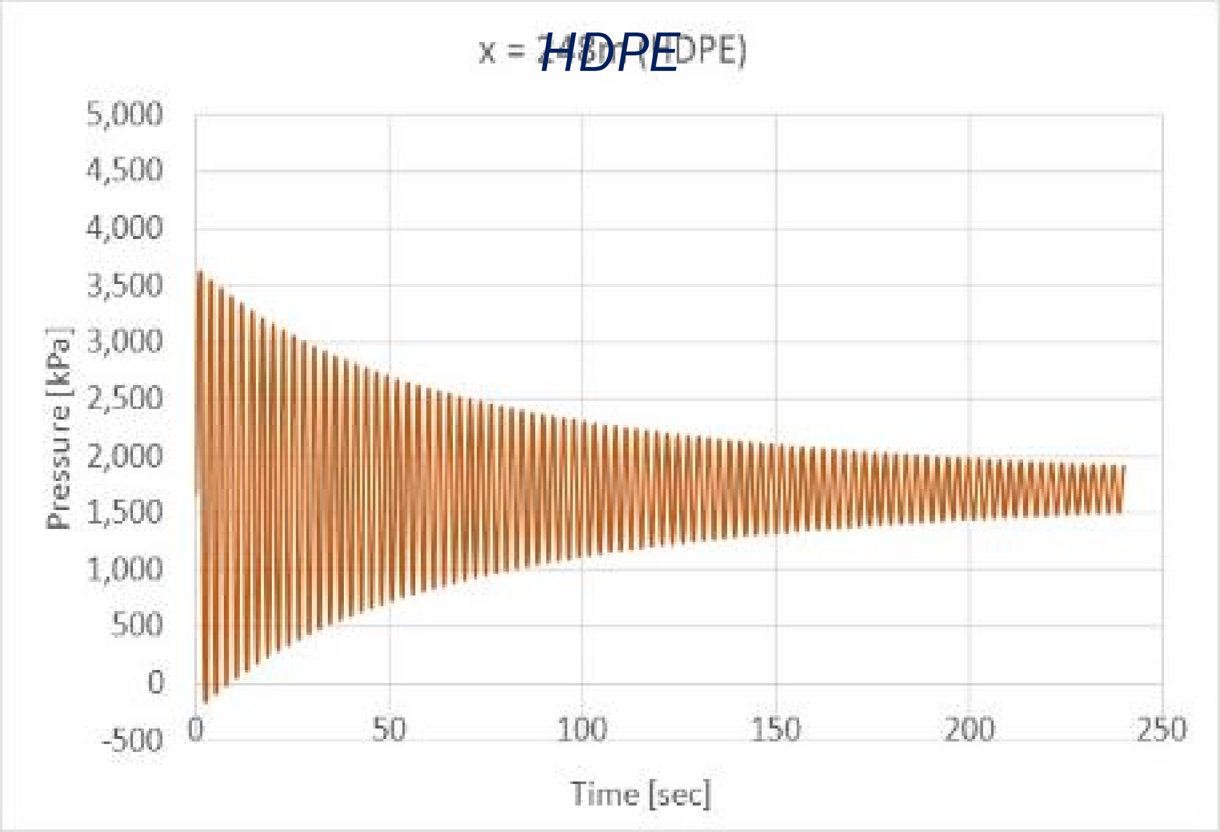
Euler's equation of motion: $\frac{\partial v}{\partial t} + \frac{1}{\rho} \frac{\partial p}{\partial x} + g \frac{dz}{dx} + \frac{f}{2D} v|v| = 0$



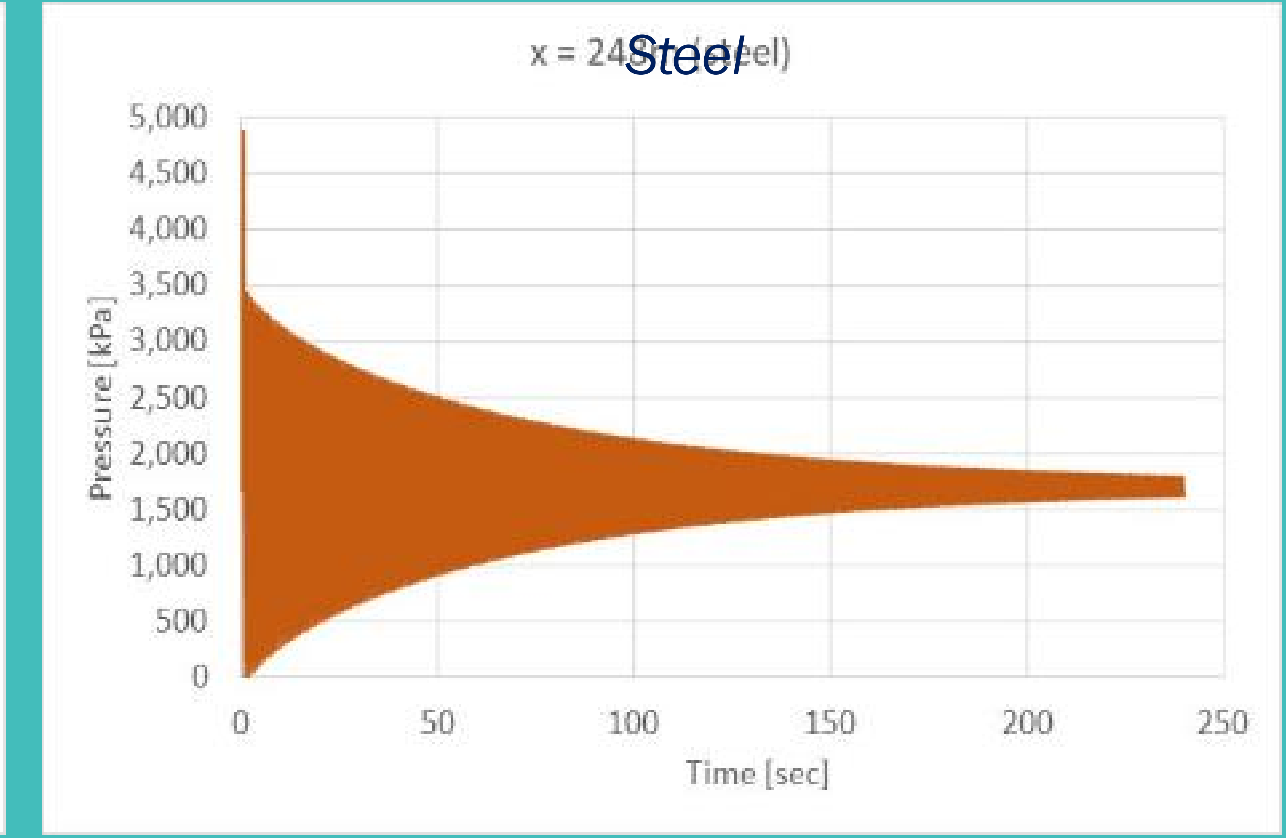
Water Hammer HDPE vs Steel

Key Points

- HDPE exhibits excellent fatigue characteristics.
- The HDPE pipe absorbs more energy than steel from cyclic loading.
- Pressure fluctuation frequency is ~3 times less than for steel.



HDPE



Steel

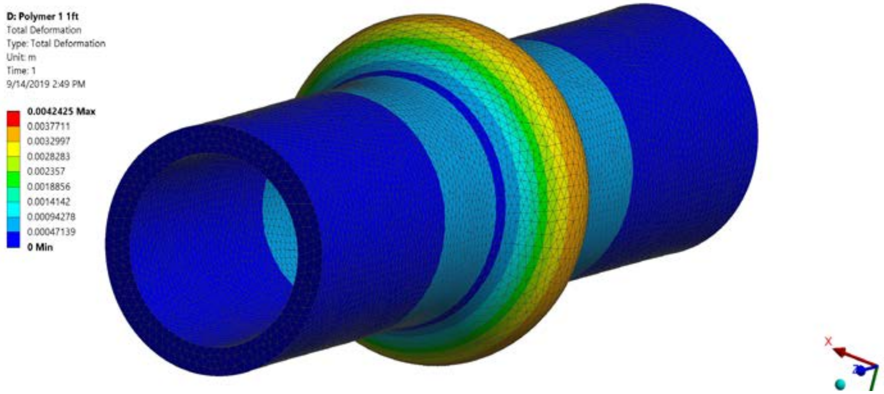
FEA and fatigue analysis on HDPE and steel near valve

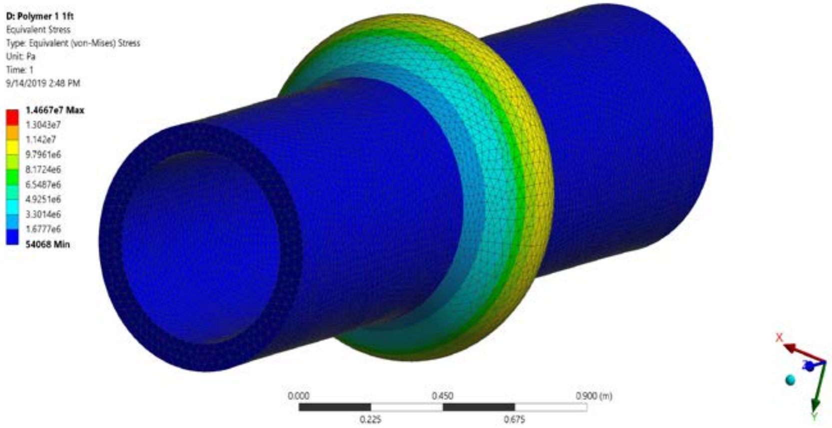
Key Point: HDPE it was found a theoretical infinite life for the cyclic loading assuming continuous opening/closing at 1 sec.

Deformation

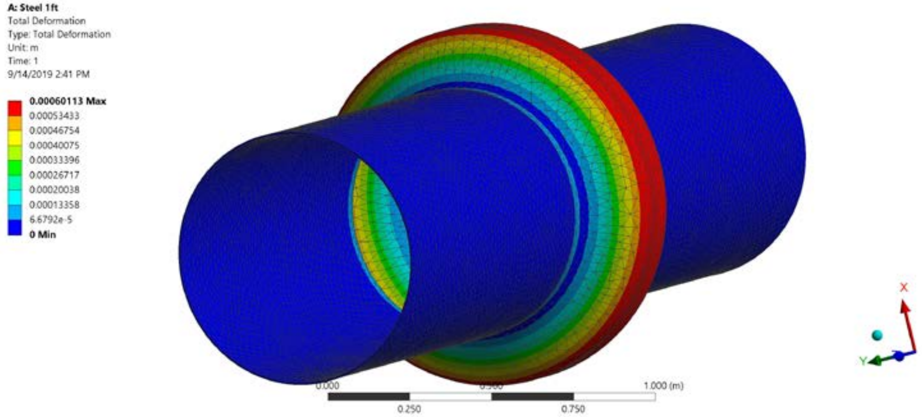
Stress

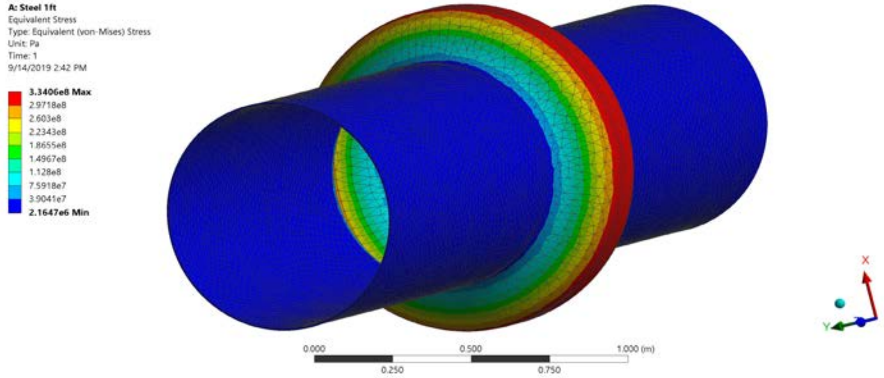
HDPE





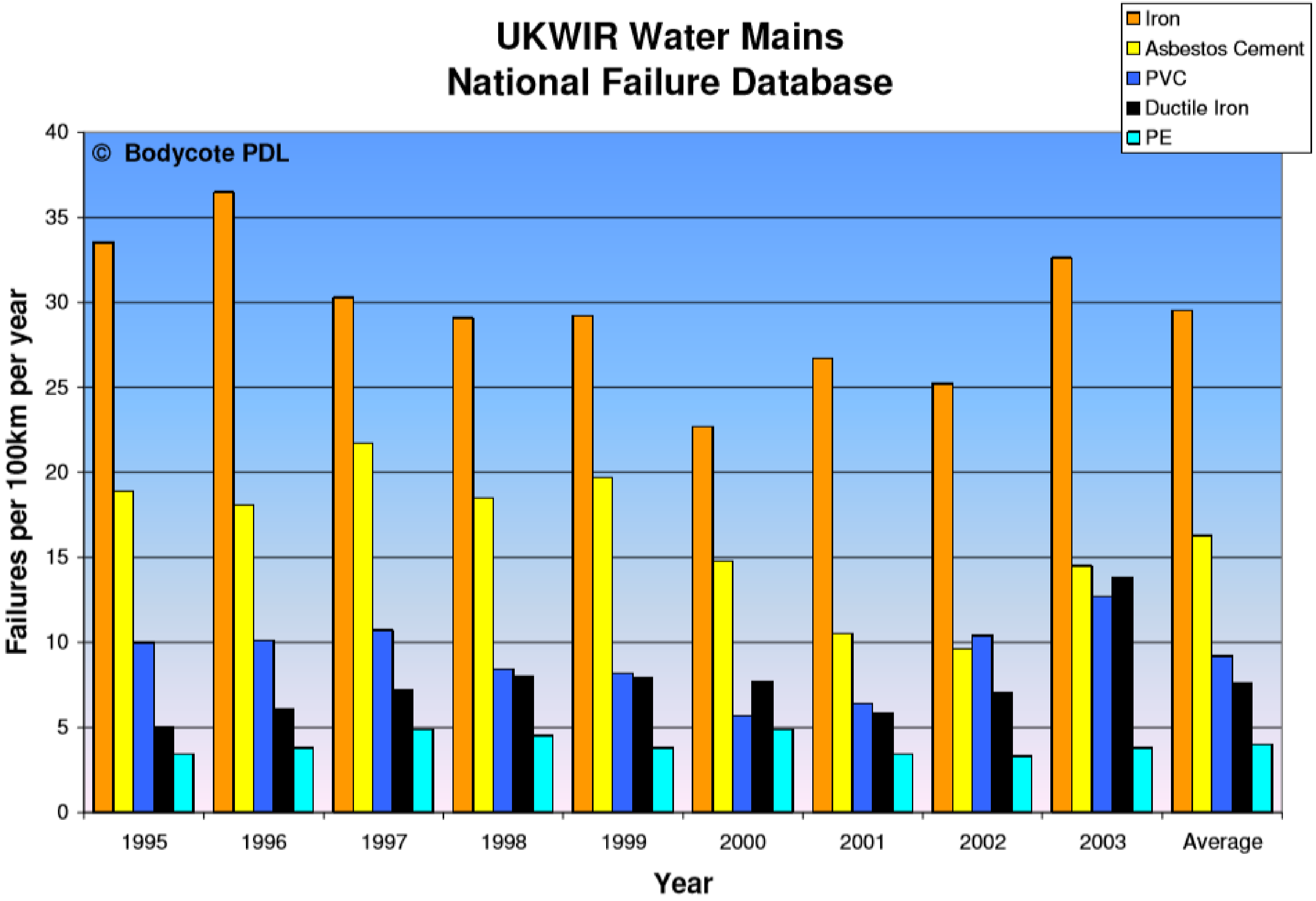
Steel





Benefits of HDPE Pipe

Figure from: MacKellar and Bodycote 2006



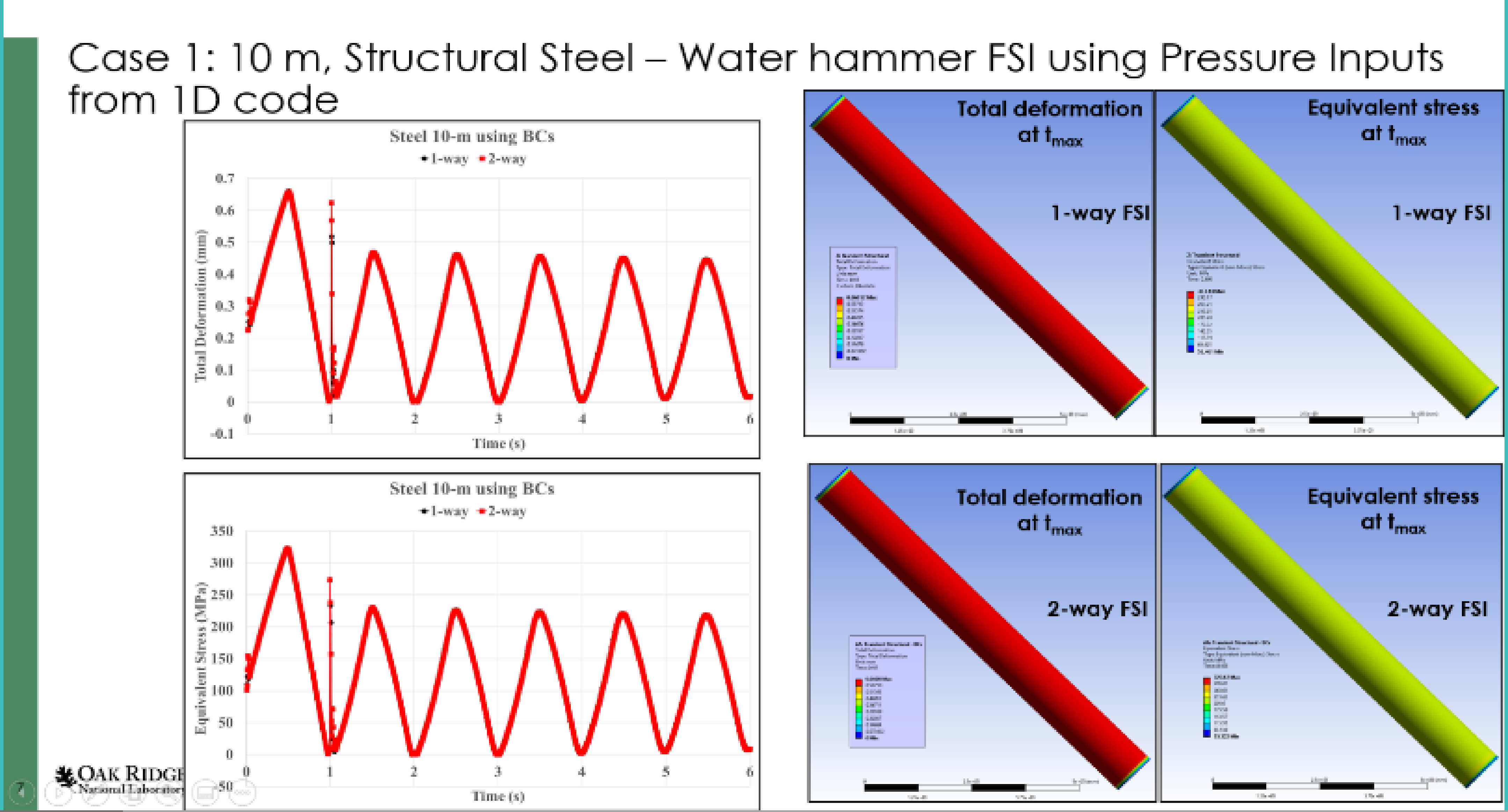
- *Lower pipe material cost than for steel and ductile iron.*
- *Installation costs lower than for steel and ductile iron.*
- *Data shows that installation is a safer process (fewer injuries)*
- *Connections less problematic*
  - ➢ *50 ft pipe lengths*
  - ➢ *Heat fusion joints (strong as pipe)*
- *HDPE has excellent fatigue characteristics*
- *Excellent hydraulic characteristics (low Manning coefficient)*
- *Not subject to corrosion or bio-fouling*

Extended FSI (fluid structure interaction) modeling of the penstock is being conducted with ORNL

1. **Modal analysis of the pipes** with different lengths, (L = 10 m, 15 m, and 25 m), and different materials (available in Ansys materials database)
    - Steel
    - Cast iron and Gray Cast iron
    - HDPE
    - PVC
2. **One-way FSI** for different lengths L = 10 m, 15 m, and 25 m and materials
    - Steel
    - Cast iron and Gray Cast iron
    - HDPE
    - PVC
3. **Two-way FSI** for different lengths L = 10 m, 15 m, and 25 m and materials
    - Steel
    - Cast iron and Gray Cast iron
    - HDPE
    - PVC
4. **Refined transient analysis.**
    - Transient fluid calculations and structure analysis using inputs of pressure/velocity from 1D simulations of LU to better simulation the water hammer effect to the pipe.

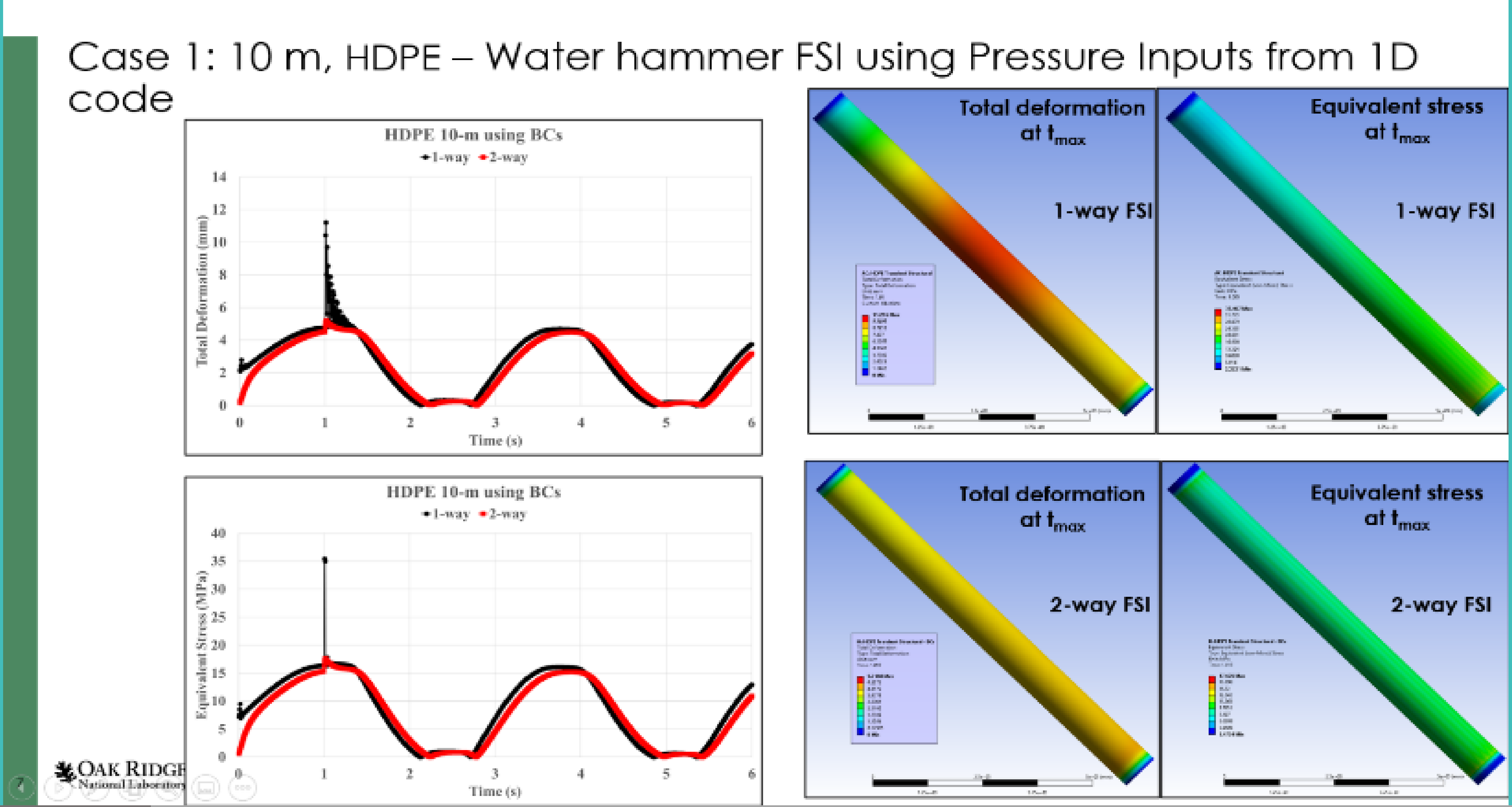
Work is on-going

FSI calculations for 10m steel pipe showing equivalent stress and total deformation using 1D inputs for boundary condition



Case 1: 10 m, Structural Steel – Water hammer FSI using Pressure Inputs from 1D code

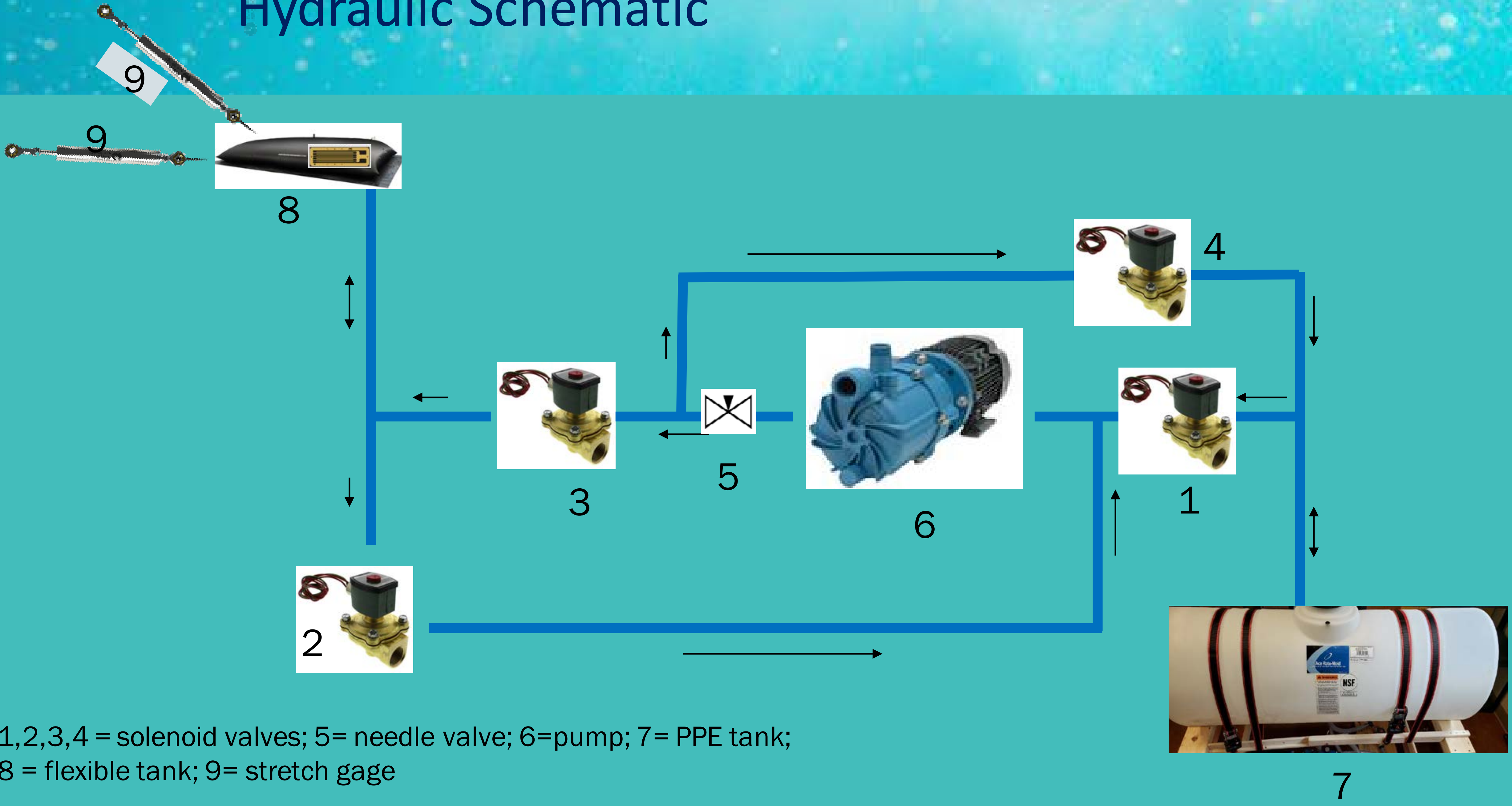
FSI calculations for 10m HDPE pipe showing equivalent stress and total deformation using 1D inputs for boundary condition



Case 1: 10 m, HDPE – Water hammer FSI using Pressure Inputs from 1D code

Small-scale testing setup

Hydraulic Schematic



1,2,3,4 = solenoid valves; 5= needle valve; 6=pump; 7= PPE tank;
8 = flexible tank; 9= stretch gage

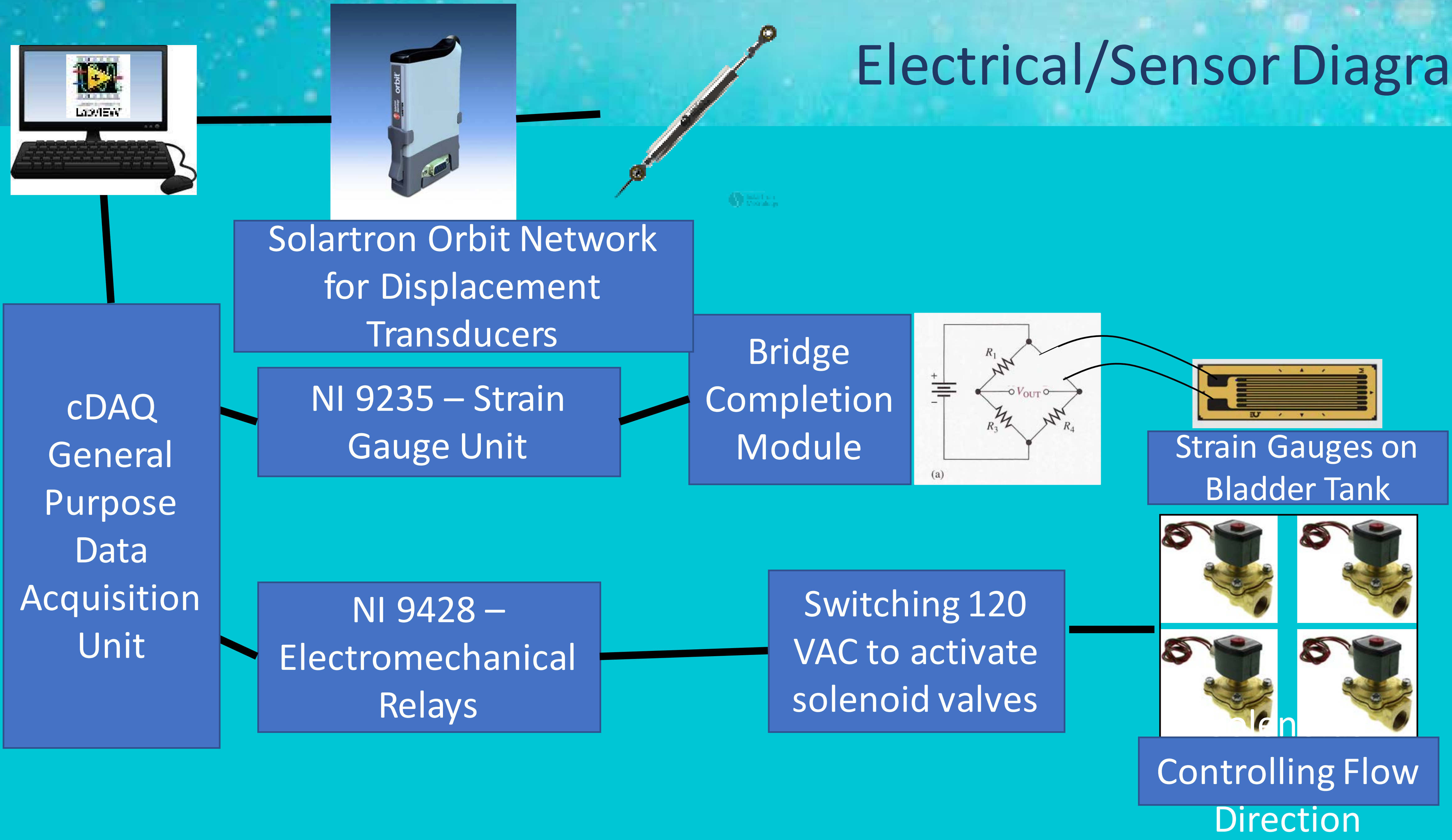
Experiment Overview

- Upper reservoir consists of two polyurethane-coated nylon-based bladder tanks
- Lower reservoir is a PPE tank with a SP10 Series Self-Priming pump to pump the water to the bladder tanks
- Cyclic testing will be performed to see durability and efficiency of the system

Scaffolding used to create hydraulic head

- Load capacity to withstand at least 2 times the weight of full bladder tanks.
- Scaffolding assembled to a height of 30 ft.
- Six platforms utilized for safety and to hold the bladders
  - Bladder will be placed on the top level atop three platforms

Electrical/Sensor Diagram



cDAQ General Purpose Data Acquisition Unit

Solartron Orbit Network for Displacement Transducers

NI 9235 – Strain Gauge Unit

Bridge Completion Module

Strain Gauges on Bladder Tank

NI 9428 – Electromechanical Relays

Switching 120 VAC to activate solenoid valves

Controlling Flow Direction

Bladder Tank Membrane Material Analysis

Membrane Stress Modeling(I)

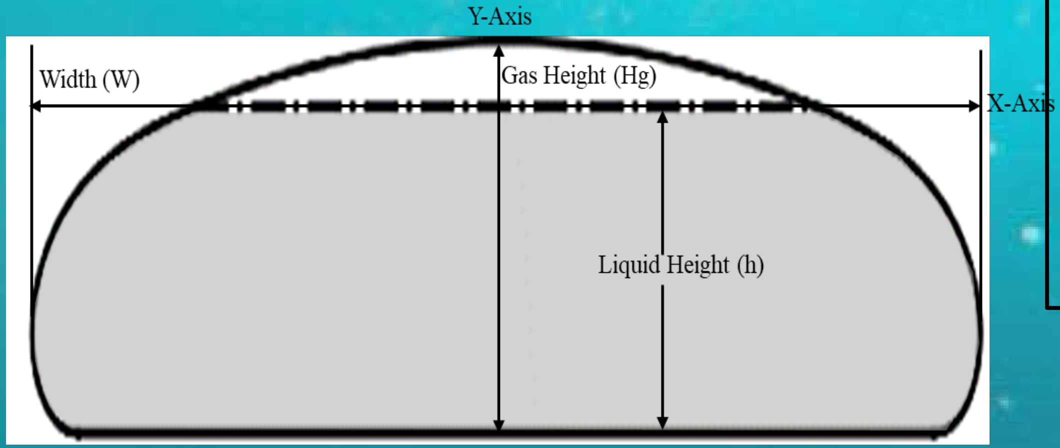
Constituent Equations

$$k = \frac{P_0 - y_- g\rho}{T}$$

$$y_- = \begin{cases} y, y \leq 0 \\ 0, y > 0 \end{cases}$$

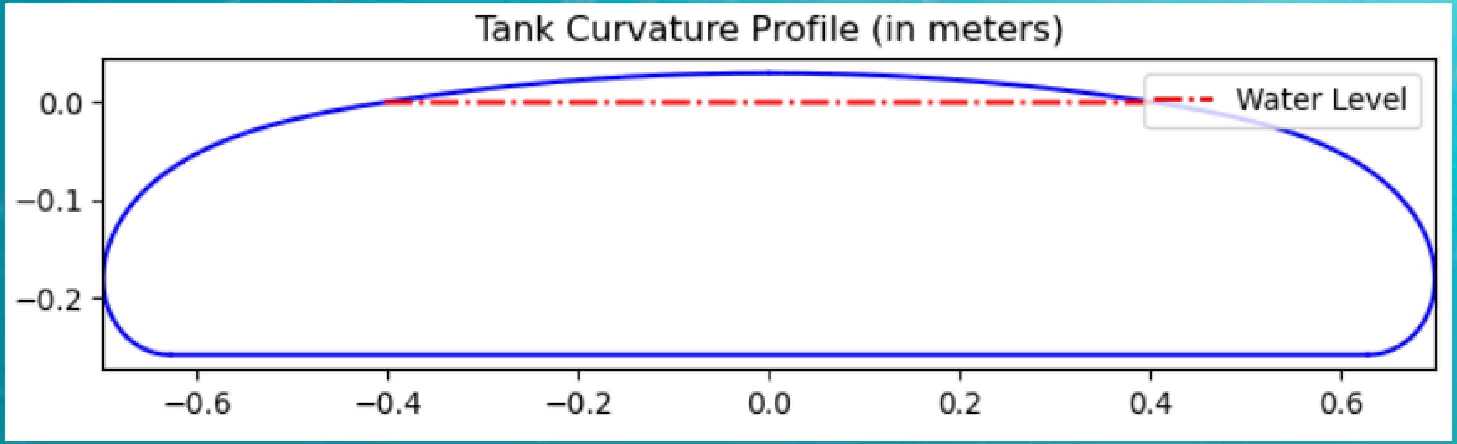
$$\begin{cases} \frac{d^2x}{ds^2} = k\frac{dy}{ds} \\ \frac{d^2y}{ds^2} = -k\frac{dx}{ds} \end{cases}$$

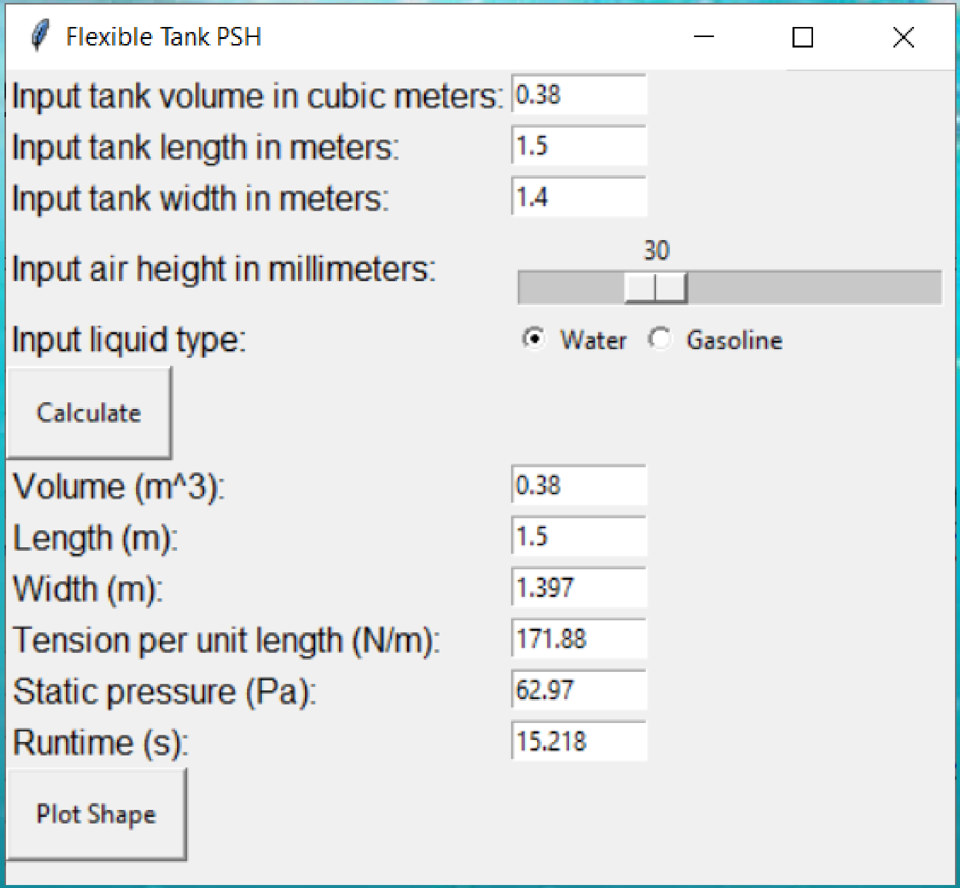
- The numerical model was implemented using MATLAB
  - MATLAB code was altered and converted to Python for use with our membrane bladder tanks
- Nomenclature
  - k- Curvature
  - s- Arc length
  - P_0- Static pressure above liquid
  - h- y_ liquid height
  - Hg- Gas height
  - T- Membrane stress force or tension per unit length
  - W- Width of collapsible tank
  - L- Length of collapsible tank



Collapsible tank schematic. The origin is the horizontal surface of the tank on the water surface. (Osadolor et al.)

Membrane Stress Modeling(II)



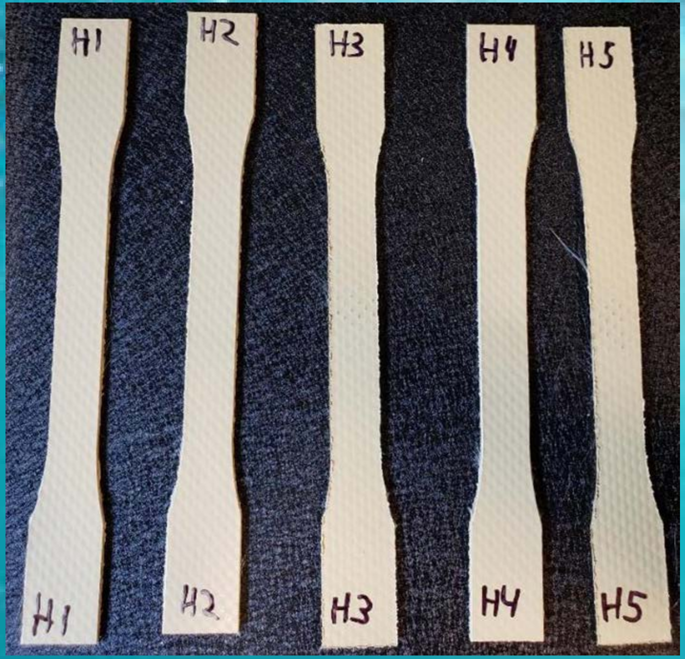


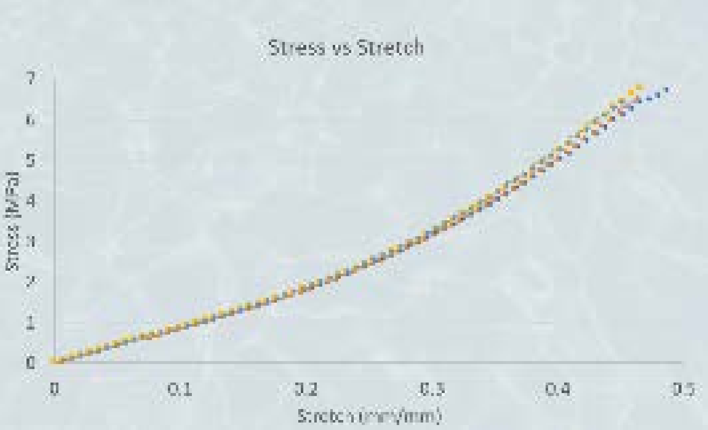
Input tank volume in cubic meters: 0.38
Input tank length in meters: 1.5
Input tank width in meters: 1.4
Input air height in millimeters: 30
Input liquid type: ● Water ○ Gasoline

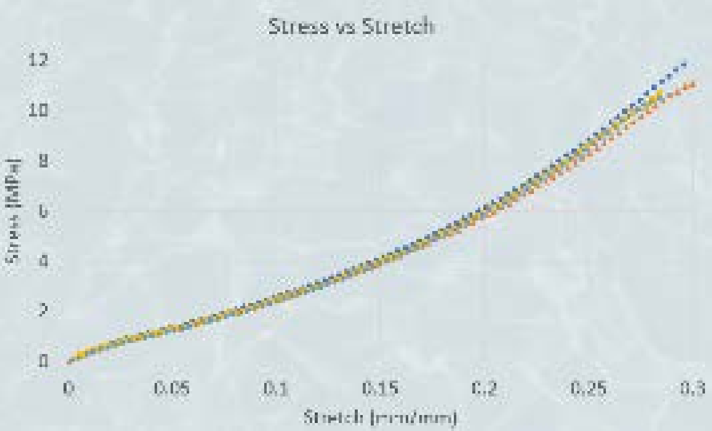
Volume (m^3): 0.38
Length (m): 1.5
Width (m): 1.397
Tension per unit length (N/m): 171.88
Static pressure (Pa): 62.97
Runtime (s): 15.218

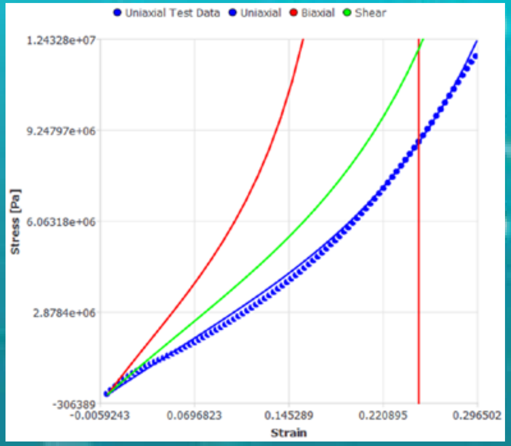
Membrane Mechanical Testing

- Monotonic
- Creep
- Fatigue
- Hydrolis
- UV-degradation









Panel Questions

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WATER POWER TECHNOLOGIES OFFICE

Doug Spaulding

Nelson Energy and Golder Associates

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WATER POWER TECHNOLOGIES OFFICE

UNDERGROUND PUMPED STORAGE HYDROPOWER (UPSH)

NELSON ENERGY LLC

AECOM

GOLDER

ACKNOWLEDGEMENTS -

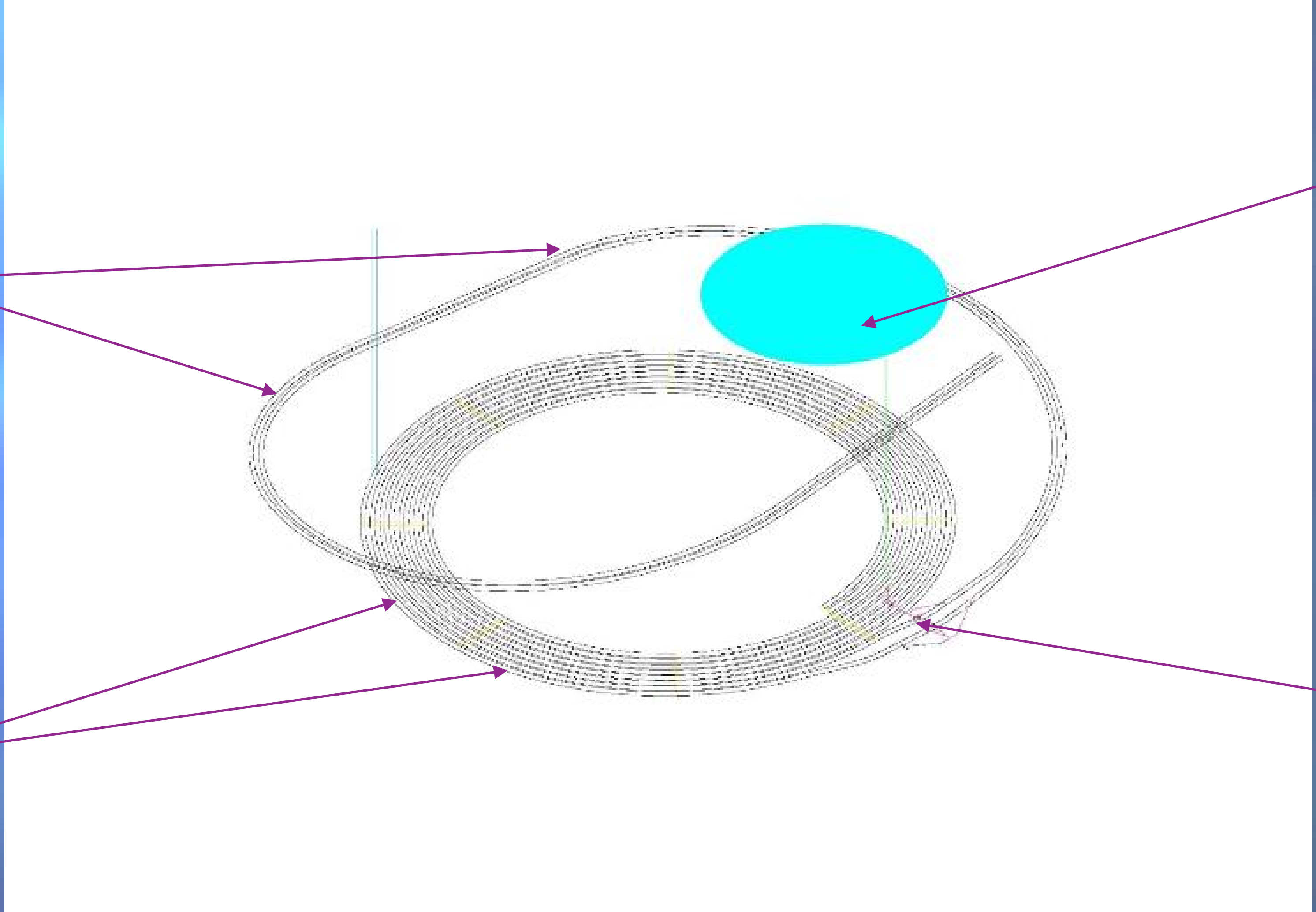
- FAST Sponsored Studies-

Argonne NATIONAL LABORATORY ---------- Market Analysis

Pacific Northwest NATIONAL LABORATORY --------- Groundwater Evaluation

CONCEPT OVERVIEW – UPSH USING TBMS

3-D Concept View-



Access Tunnel-
4 miles long-12 % grade

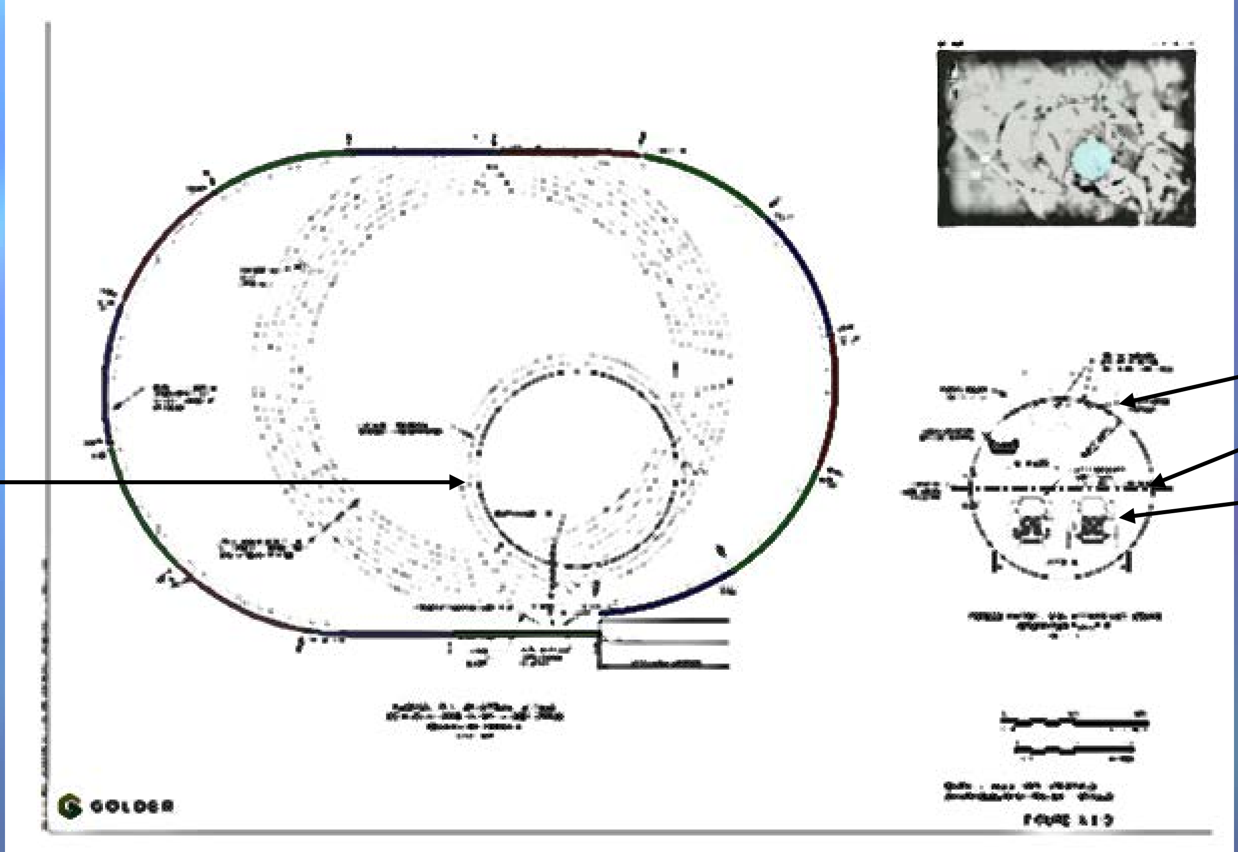
Upper Reservoir-
Constructed of excavated rock

Lower Reservoir-
2500 ft. deep

Underground Powerhouse

Siting Requirements-

- High quality, strong, impermeable bedrock
- Close to existing Transmission
- Water Source, if groundwater a FERC license may not be required
- High Head (2500 ft.+/-) reduces costs



Rock Fill Upper Reservoir

Access Tunnel Section

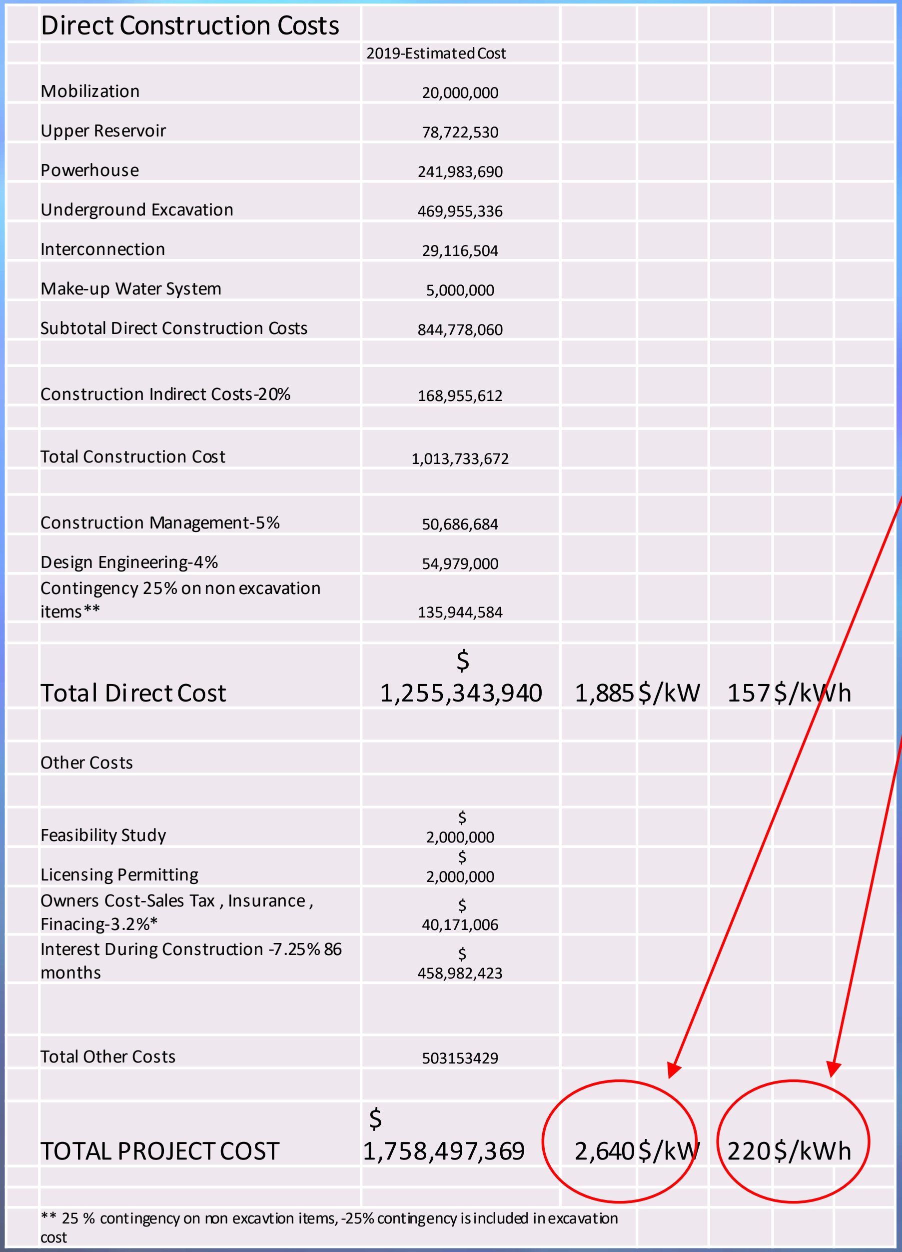
Haul Trucks

Note: Powerhouse can be accessed by vehicles –safety and constructibility advantage

ADVANCEMENT IN STATE OF THE ART-

- Use of TBMs drives down cost of UPSH
- UPSH Cost ($/kWh)is comparable with conventional PHS
- Economical Projects can be sited in topographically challenged areas (ie.-the Midwest)
- Projects can be sited close to existing transmission
- As a closed system, UPHS has minimal impacts

TOTAL PROJECT COST*



Direct Construction Costs			
	2019-Estimated Cost		
Mobilization	20,000,000		
Upper Reservoir	78,722,530		
Powerhouse	241,983,690		
Underground Excavation	469,955,336		
Interconnection	29,116,504		
Make-up Water System	5,000,000		
Subtotal Direct Construction Costs	844,778,060		
Construction Indirect Costs-20%	168,955,612		
Total Construction Cost	1,013,733,672		
Construction Management-5%	50,686,684		
Design Engineering-4%	54,979,000		
Contingency 25% on non excavation items**	135,944,584		
Total Direct Cost	$ 1,255,343,940	1,885 $/kW	157 $/kWh
Other Costs			
Feasibility Study	$ 2,000,000		
Licensing Permitting	$ 2,000,000		
Owners Cost-Sales Tax , Insurance , Financing-3.2%*	$ 40,171,006		
Interest During Construction -7.25% 86 months	$ 458,982,423		
Total Other Costs	503153429		
TOTAL PROJECT COST	$ 1,758,497,369	2,640 $/kW	220 $/kWh

** 25 % contingency on non excavtion items, -25% contingency is included in excavation cost

Costs ($2640/kW) and ($220/kWh) for 12 hours of storage are based on prefeasibility study for Granite Falls Site. Cost for other sites with similar strong impermeable rock formations should be similar..

*AECOM & Golder Associates -W/ 25 % Contingency-

Cost Comparison Versus Conventional PHS (Licensed-Under Development)-

Project	Size (MW)	Cost * ($/kW)	Energy Storage Hours	Storage Cost ($/kW-hr)
Swan Lake North	600	2406	8.8	273
Eagle Mountain	1300	1920	10	192
Tazewell	850	2350	10	235
Goldendale	1200	2363	12.3	192
Granite Falls	666	2640	12	220
Lithium Batteries (3 Batteries)	3576		10	356

*From publicly Available Cost info.

Summary –UPSH -

- Has a much lower cost than batteries for long duration storage

- Cost competitive with conventional PHS

- Closed System (No fish, No water quality issues)

- **A UPSH site can be essentially environmentally benign**

- Using Groundwater- No FERC License may be required

- Can be sized for any amount of generation and storage

- Storage cost ($/kWh)decrease with increasing amounts of energy storage

NEXT STEPS-

-Identify Potential Sites-

Nelson Energy has obtained FERC preliminary permits for sites in Minnesota (2), Wisconsin, South Dakota and Texas

- Engage a Sponsor

Nelson Energy has discussed the concept in detail with five utility groups and one federal agency- interest , but no sponsors to date

- Conduct a Site Specific Pre-feasibility study

- Sponsor Conducts a full feasibility study-including subsurface exploration

For Further Information-

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Golden Valley, MN 55426
952-544-8133
doug@nelsonenergy.us

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Panel Questions

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
WATER POWER TECHNOLOGIES OFFICE

Gordon Wittmeyer and Biswajit Dasgupta

Southwest Research Institute

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WATER POWER TECHNOLOGIES OFFICE

STEEL DAMS FOR ACCELERATING THE DEVELOPMENT OF NEW PSH PROJECTS

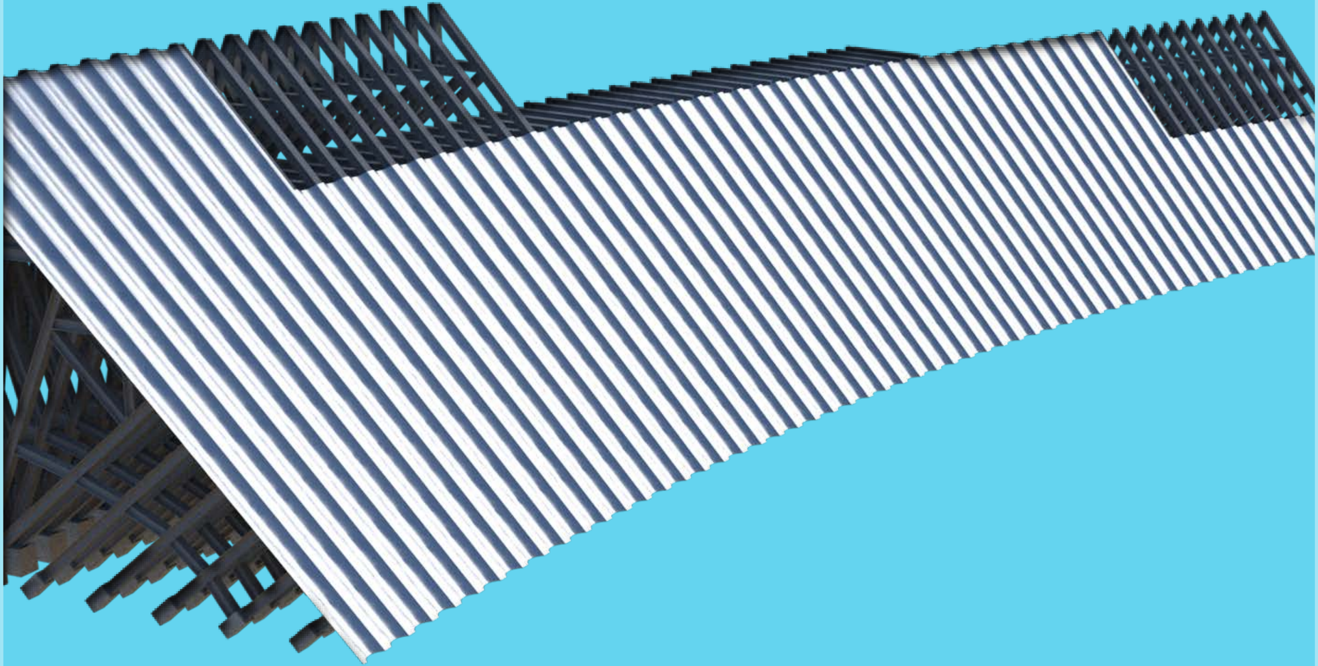
Gordon Wittmeyer and Biswajit Dasgupta
Southwest Research Institute

Michael Ingram and Vignesh Ramasamy
National Renewable Energy Laboratory

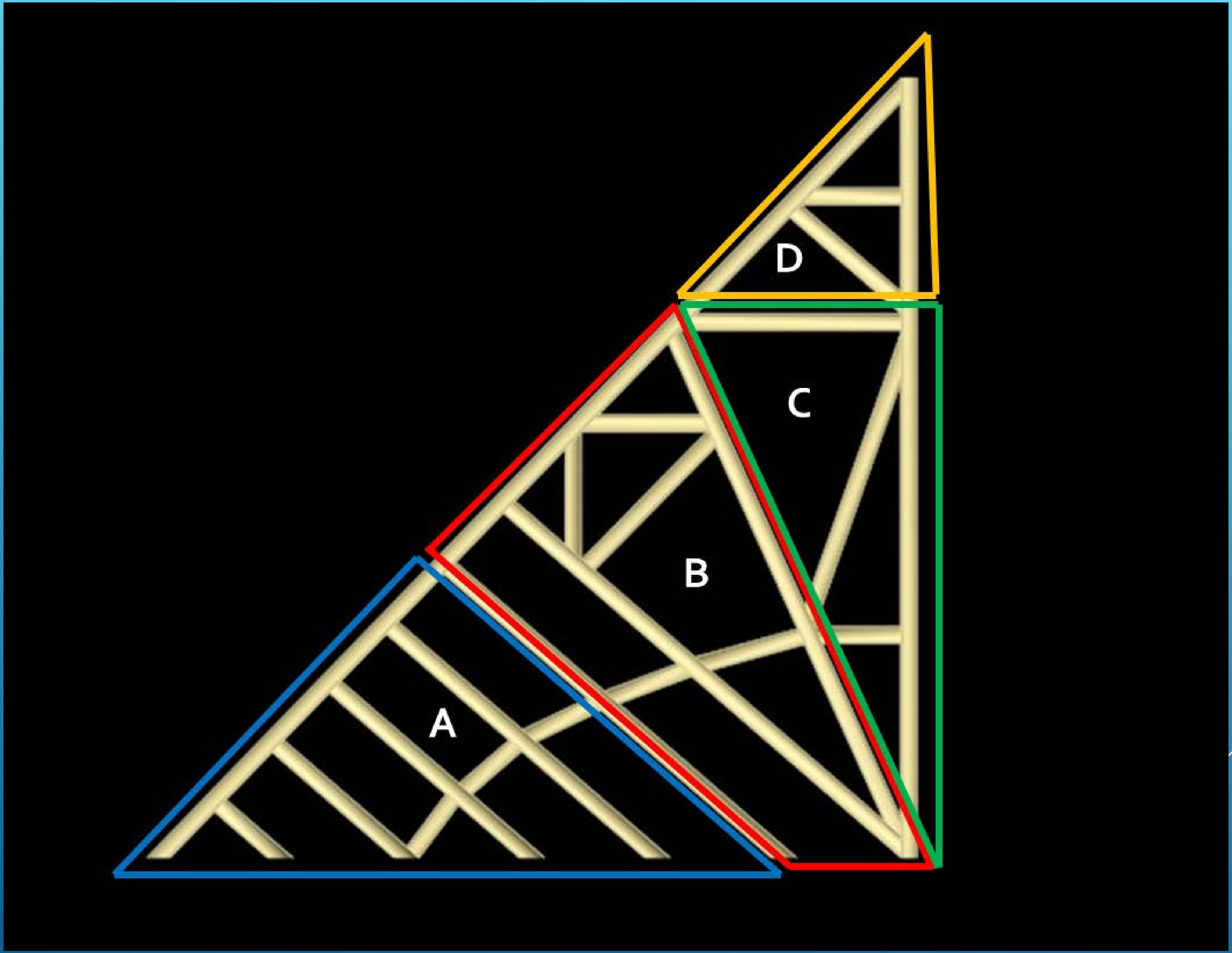
Vladimir Koritarov and Cathy Milostan
Argonne National Laboratory

October 27, 2021

MODULAR CONSTRUCTION OF RING-SHAPED MOUNTAIN TOP STEEL DAMS



- Right side advancing with placement of first steel frame modules
- Left side completed with all four frame modules and three water-tight plate modules



D
C
B
A

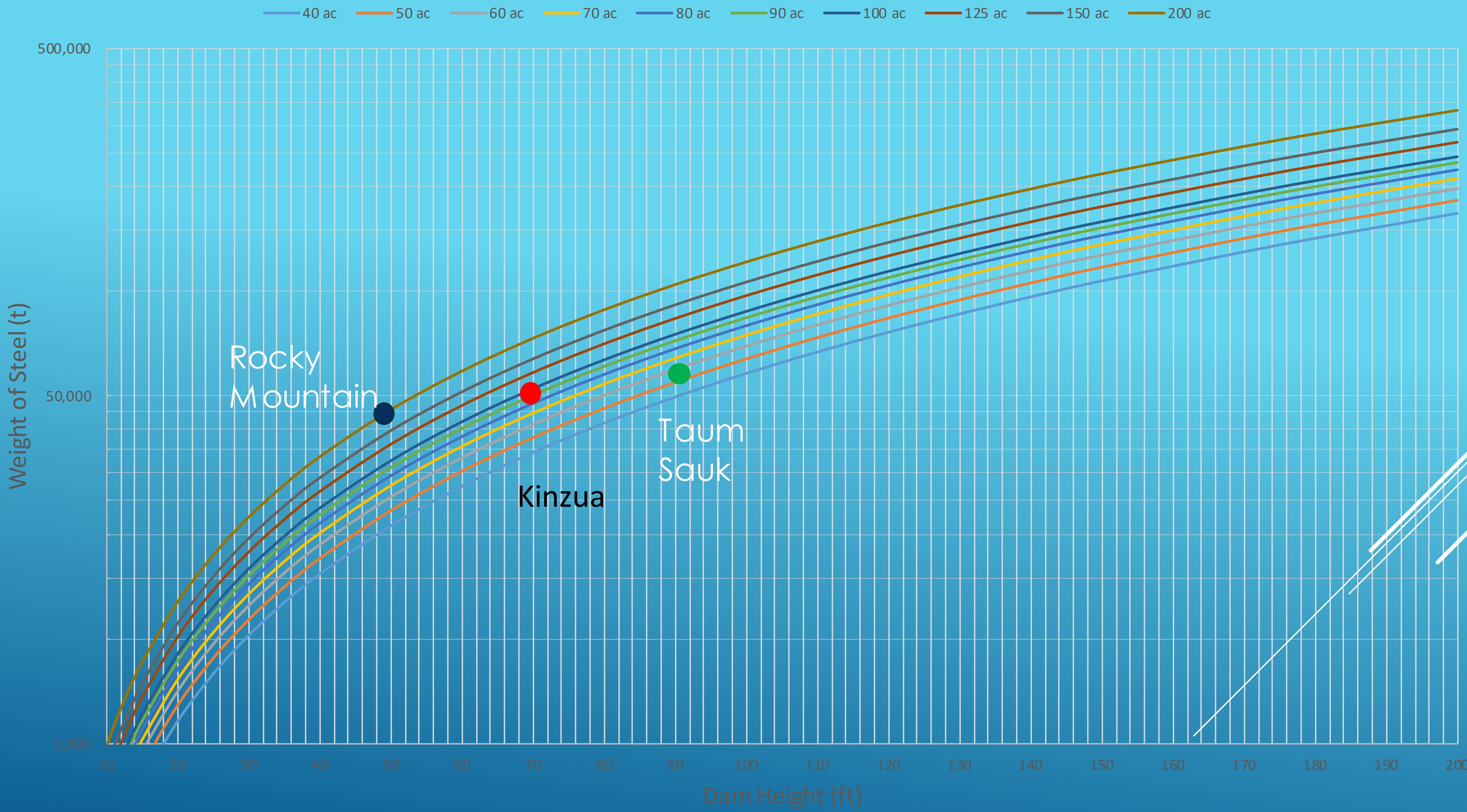
Kinzua, PA

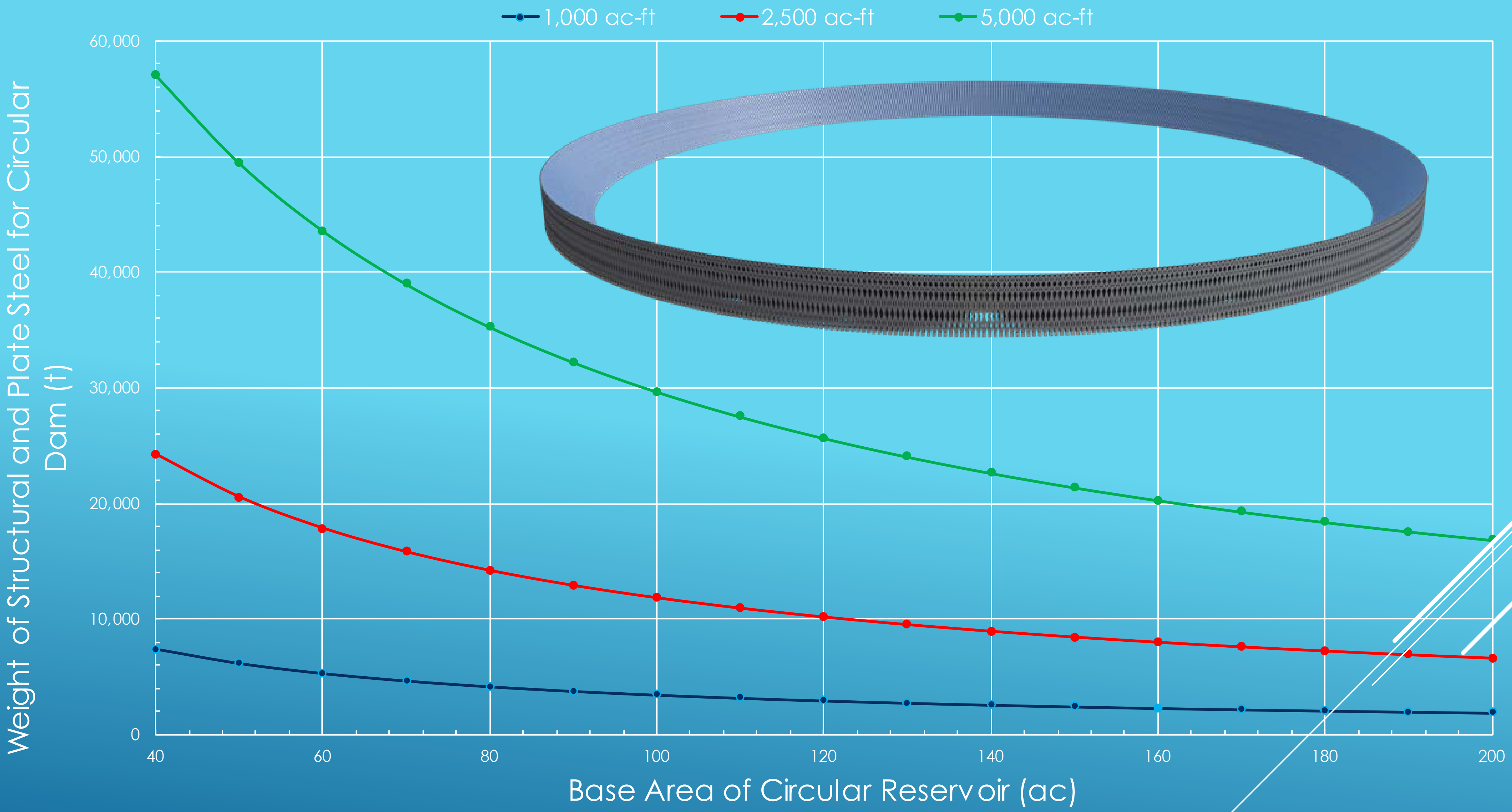
Taum Sauk, MO

Rocky Mountain, GA

Ludington, MI

Weight of Structural and Plate Steel vs Height for Circular Steel Dams with Base Areas Between 40 and 200 Acres




1,000 ac-ft
2,500 ac-ft
5,000 ac-ft
Weight of Structural and Plate Steel for Circular Dam (t)
60,000
50,000
40,000
30,000
20,000
10,000
0
40
60
80
100
120
140
160
180
200
Base Area of Circular Reservoir (ac)

Current PSH Dams Compared to Equivalent Steel Dams

	Rocky Mountain	Taum Sauk	Kinzua (Seneca)
Height (ft)	80	92	115
Length (ft)	12,800	6,660	7,800
Surface Area (ac)	210	55	110
Reservoir Volume (ac-ft)	10,200	4,350	5,756
Dam Material	Earthfill	RCC	Rockfill
Dam Volume (yd^3)	10,738,000	3,750,000	268,000,000 (???)
Dam Cost (2020)	$215 million	$490 million	(???)
	Steel Dam	Steel Dam	Steel Dam
Height (ft)	50	92	70
Weight of Steel (t)	40,000	60,000	50,000
Dam Cost (2020)	$80 million	$120 million	$100 million

Proposed Demonstration Project

PSH alternative to 10 to 100MW BESS units being installed in the ERCOT market

PSH should provide 4 to 8 hours duration instead of typical 1 to 3 hours from BESS

Target CAPEX of $200 to $250 per kWh to compete with utility-scale Li-Ion BESS [Feldman et al. (2021): $341/kWh and $1,365/kW, $2019]

Target sites that can accommodate larger diameter, shorter-height circular steel dams to take advantage of minimum impoundment expense per unit energy stored

Design steel dam supports and plate systems to be built at the fabricator, transported by truck on the interstate highway system, and assembled with low-capacity lifts on site.

Use commercial off-the-shelf centrifugal pumps as turbines (PATs) to reduce CAPEX and order times

Big Harkey Canyon PSH Project Specifications

Upper Reservoir
Diameter = 666 ft
Depth = 10 ft
Max volume = 320 ac-ft
Max water level = 3,025 ft amsl
Min water level = 3,015 ft amsl

Lower Reservoir
Diameter = 1,800 ft
Depth = 10 ft
Max volume = 580 ac-ft
Max water level = 2,381 ft amsl
Min water level = 2,371 ft amsl
Pump inlets at 2,311 ft amsl

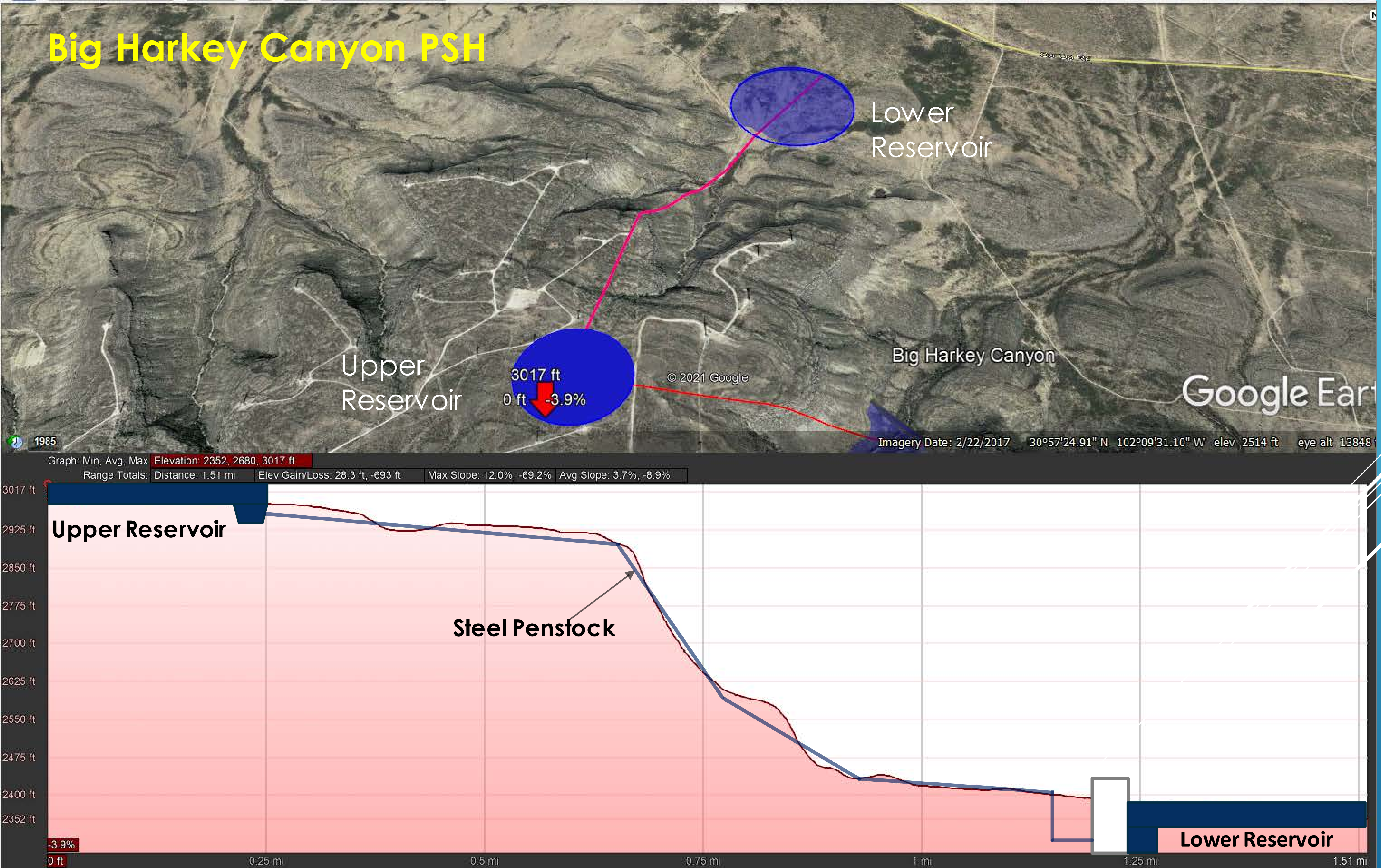
Rated Head = 613 ft
Head race and surface conduit 4,700 ft
Vertical shaft 90 ft

Discharge (8.6 hr) 550 cfs; 4 x 5 MW = 20 MW
Fill time 11.8 hrs; 4 x 5 MW

Energy required to fill = 235 MWh (η=85%)
Energy recovered = 177 MWh (η=85%)
Round trip efficiency 72%

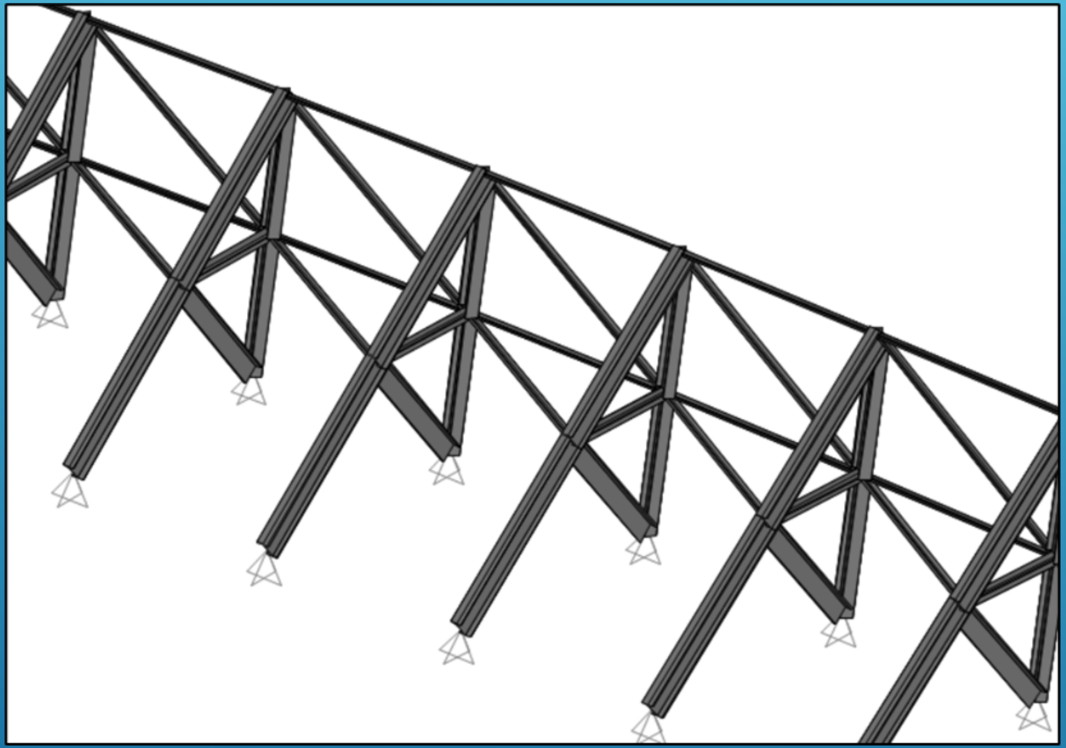
Conduit is 96 in diameter; Velocity of 11 fps

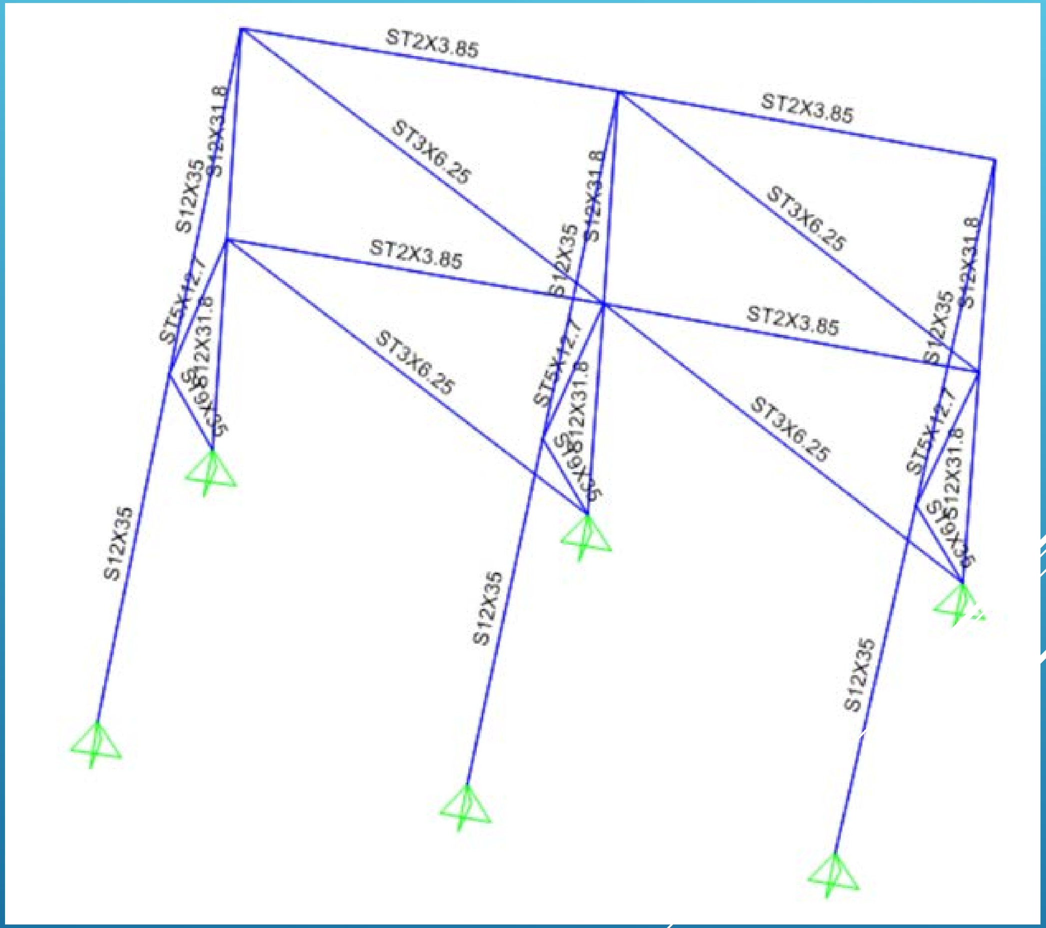
Big Harkey Canyon PSH



Graph: Min, Avg, Max Elevation: 2352, 2680, 3017 ft
Range Totals: Distance: 1.51 mi Elev Gain/Loss: 28.3 ft, -693 ft Max Slope: 12.0%, -69.2% Avg Slope: 3.7%, -8.9%

Design of Steel Structure and Concrete Foundations Optimized to Reduce Material Costs and Speed Assembly





General Bottom-Up Cost Model Developed to Estimate CAPEX for Big Harkey Canyon Demonstration PSH Project

Element	Cost ($)
Site Staging and Preparation	$2,287,015
Upper Reservoir	$5,041,564
Lower Reservoir	$5,464,176
Penstocks, Gates, Hoist, Trash Racks	$3,283,449
Pumps, Electromechanical Controls, Substation	$4,079,754
Transmission, Permitting and Interconnection	$4,388,202
Sales Tax	$1,006,715
Contingency (25%)	$6,387,719
Developer Overhead (6%)	$1,916,316
Profit (5%)	$1,692,745
Total	$35,547,655

Competitive PSH Facility with Relatively Low Capital Cost: Should be Competitive with Current BESS

PSH Plant Factors	Values
Rated Capacity	20MW
Energy Stored	177MWh
CAPEX/kWh/cycle	$200
CAPEX/kW	$1,726

PSH facility will still take longer to construct than a comparable BESS

Anticipate that the Levelized Cost of Energy Storage will be lower for this PSH project than an equivalent BESS

Panel Questions

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WATER POWER TECHNOLOGIES OFFICE

Thank you!

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