SustainX
SMARTER ENERGY STORAGE

ICAES

Presentation to UNH ChemE's

April 5th 2013

Presented by:

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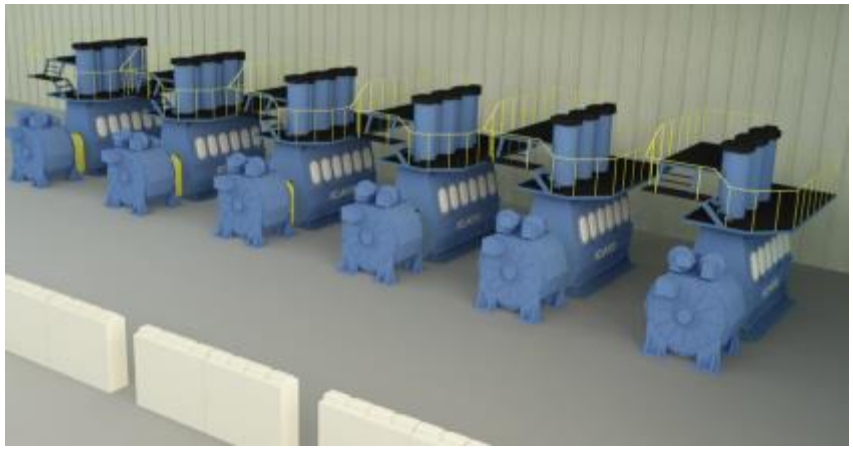
UNH BS, ChemE 2008

Dartmouth MEM 2010

Presentation Overview

- The Pitch
  - SustainX's history
  - The Need & Market
  - Existing Technology
  - The ICAES advantage
- The Technology
  - The Engine
  - Thermodynamics
  - Heat Transfer
  - Fluid Dynamics
  - Corrosion Control
- Internships at SustainX
- SustainX in the Media
- Q&A



Strong Technical & Financial Foundation

Technology

SustainX Founded (Dartmouth spin-out)

1kW – 5kWh Alpha System

40kW Pilot

1.5 MW Full-Scale Prototype

Product Development

2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013

Financing

Seed Round $500k

SBIR $150K

Series A-1 $4M

SBIR $1M

SGDP award $5.4M

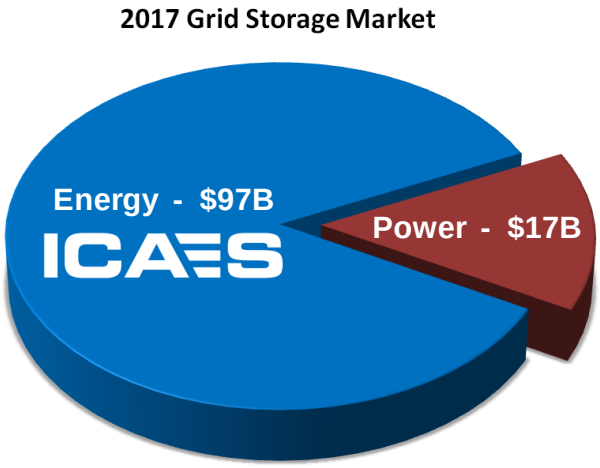
Series A-2 $20M

Isothermal Compressed Air Energy Storage (ICAES™)

Disruptive mechanical grid-scale energy storage solution

- Mechanical system using compressed air
- None of the cost, life, and safety issues of batteries
- Enables site-flexible and scalable bulk storage

ICAES Adds Value Throughout the Generation and Transmission System



Source: Lux Research

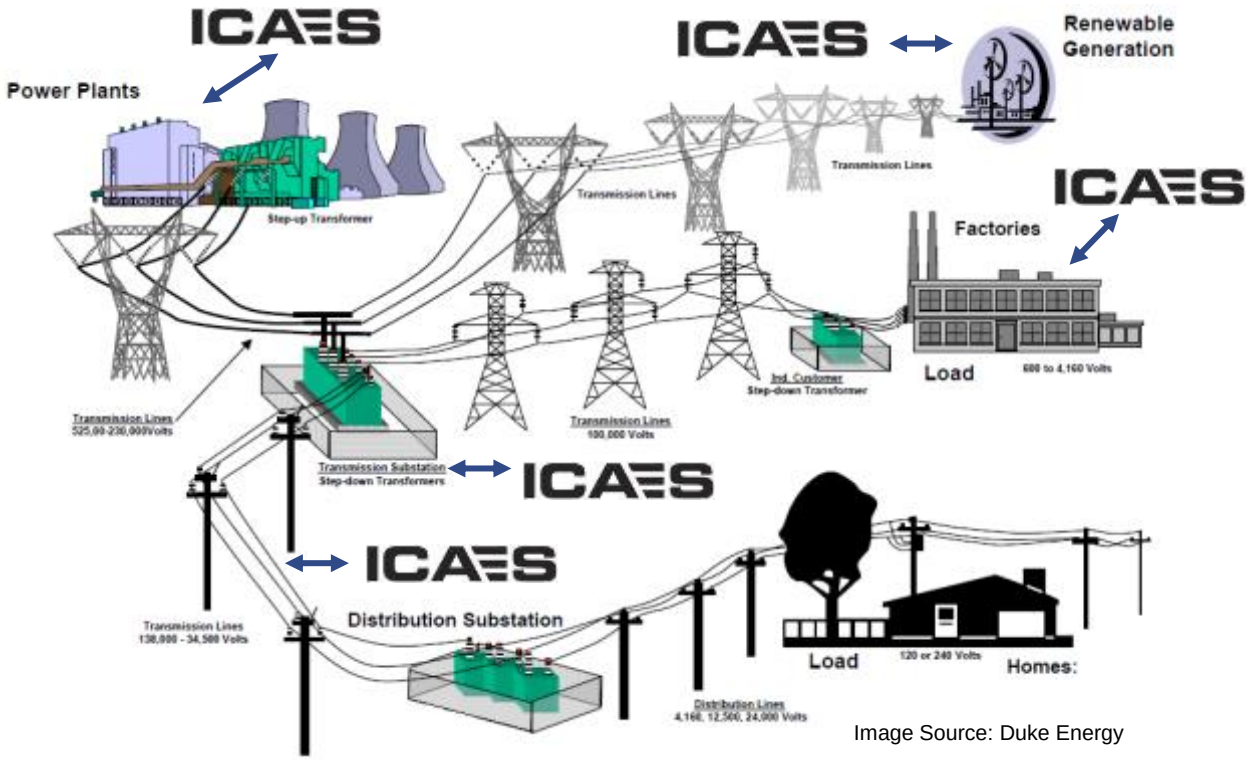


Image Source: Duke Energy

GENERATION	TRANSMISSION	END USER
Renewable Energy Integration Conventional Energy Load Leveling Waste Heat/Cogeneration	T&D Upgrade Substitution Transmission Congestion Relief High-Power Wind Ramping	Energy Management Electric Power Reliability & Quality Waste Heat/Cogeneration

Existing Technologies Are Limited

Pumped hydro, conventional CAES limited by siting, other issues

- Pumped hydro most widely used system, but geologically constrained
- CAES is excellent for bulk storage, but only two installations worldwide in 35 years
  - Two most recent US projects cancelled
  - Major drawbacks: siting & regulatory approval; fuel & emissions; water use

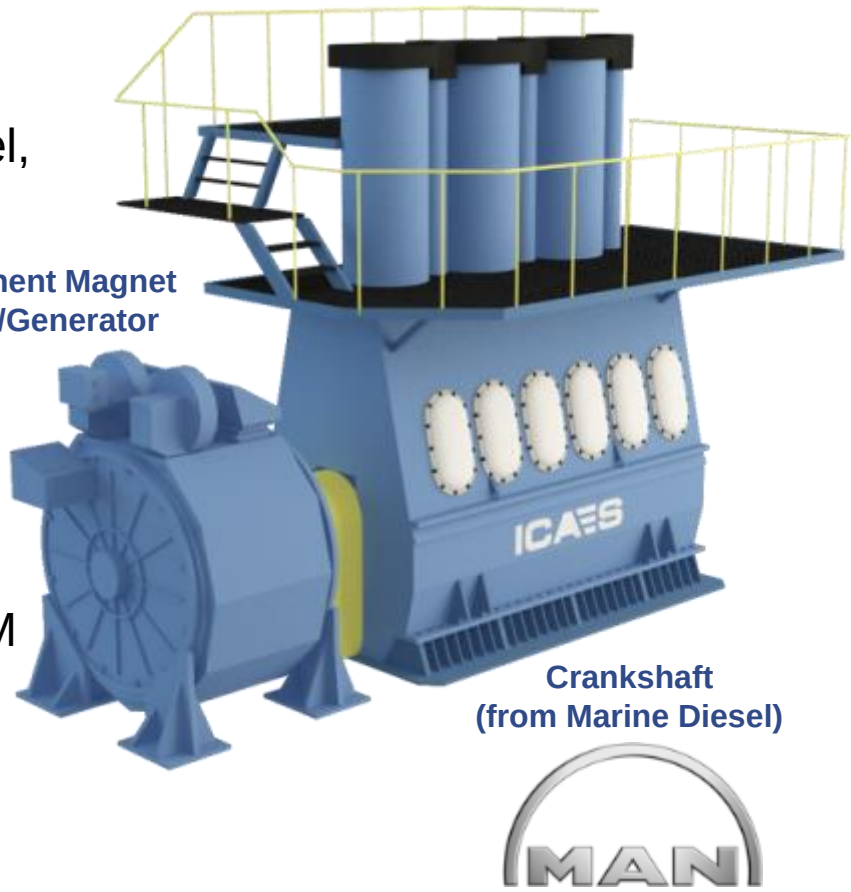
Batteries address limited, crowded market for power applications, not larger energy market

- Cycle life very limited = higher cost
- Hazardous materials = multiple fires
- Environmental impacts

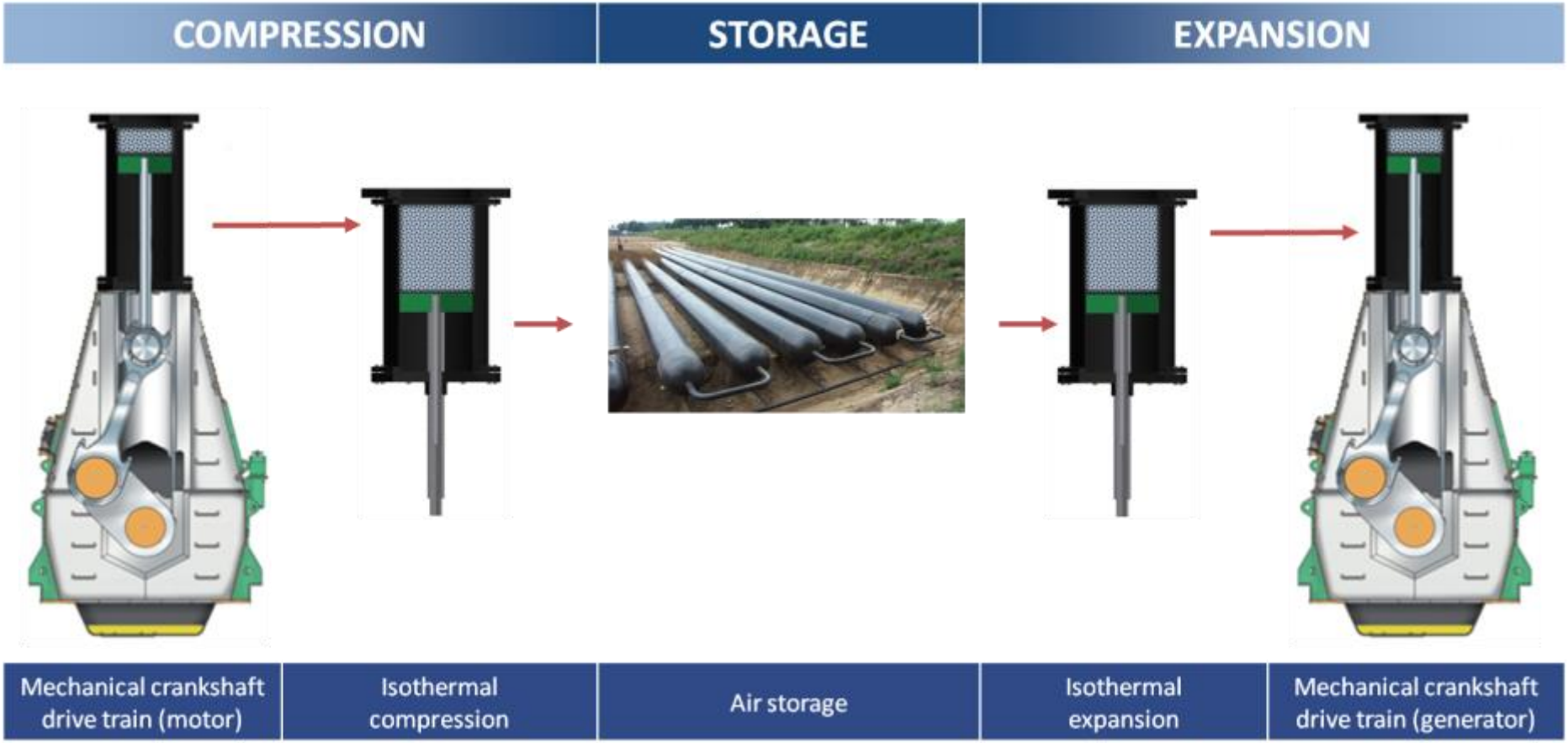
ICAES Overcomes Limitations of Existing Storage Technologies

Key advantages

- **Site-flexible:** can be sited where best utilized – not where geology mandates
- **Fuel free:** isothermal process consumes no fuel, produces no emissions
- **Proven components**
  - Crankshaft, generator, pipe-type storage
  - 20-year life at full power/capacity
  - Power industry understands mechanical O&M
- **Scalable:** power and energy scale independently as needed
- **Cost competitive:** low-cost grid storage solution



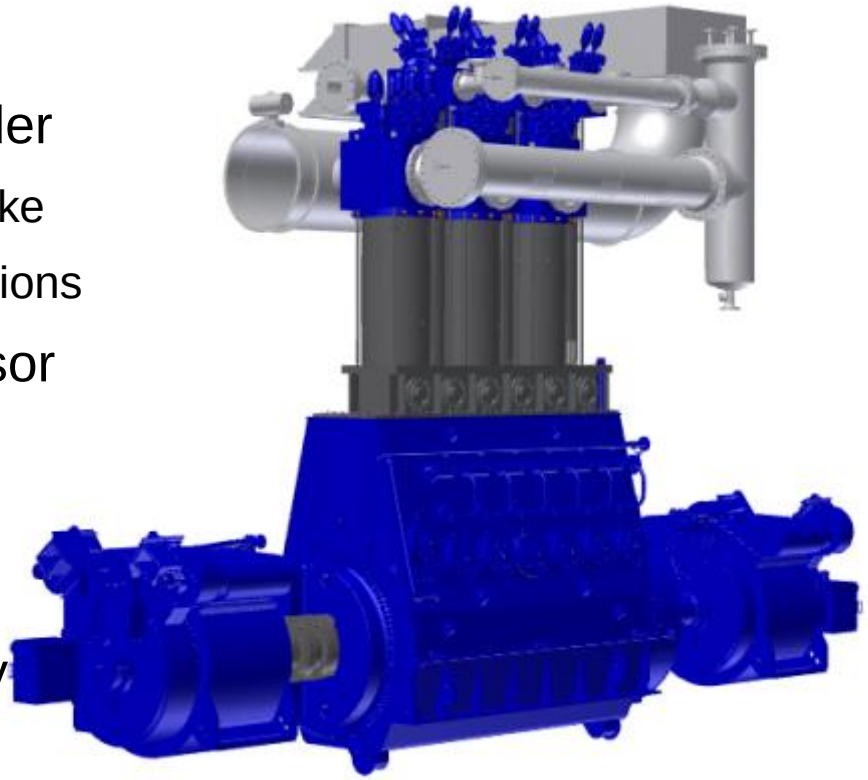
ICAES: Proven Mechanical Systems Using Air, Water, and Steel



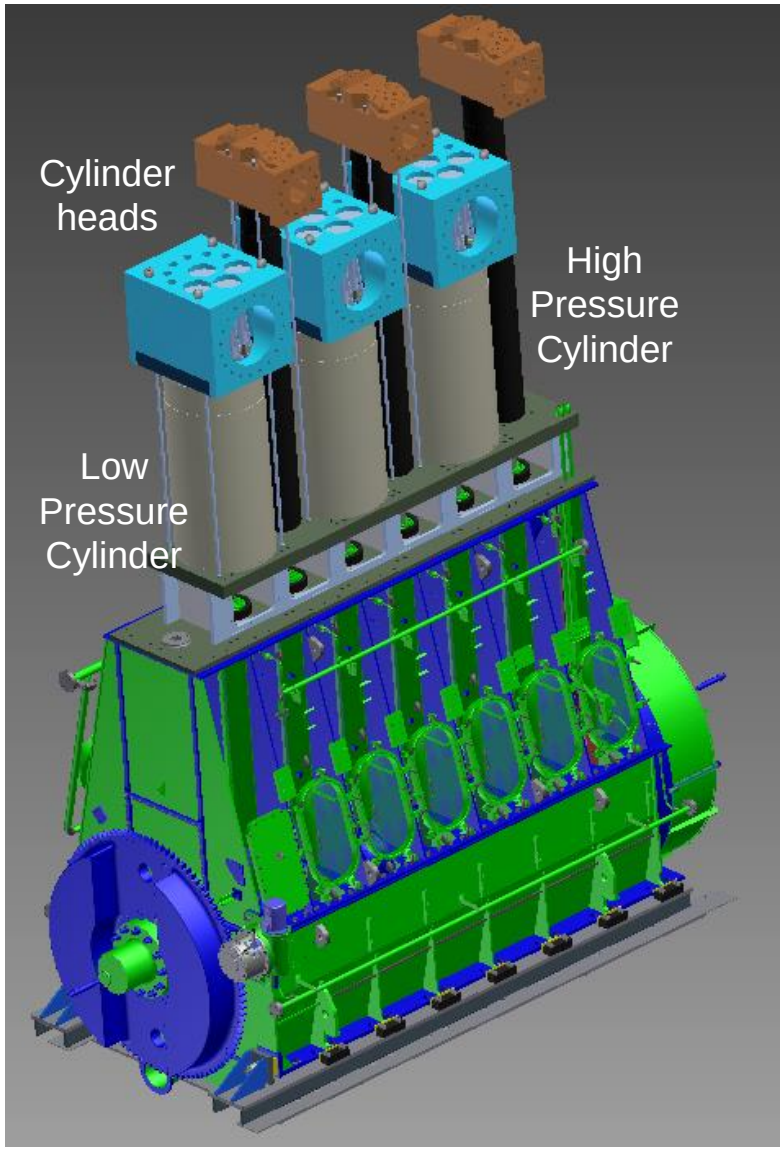
- Isothermal compressions and expansions are achieved with an air & water mixture
- Water is the heat transfer fluid & the heat sink or source

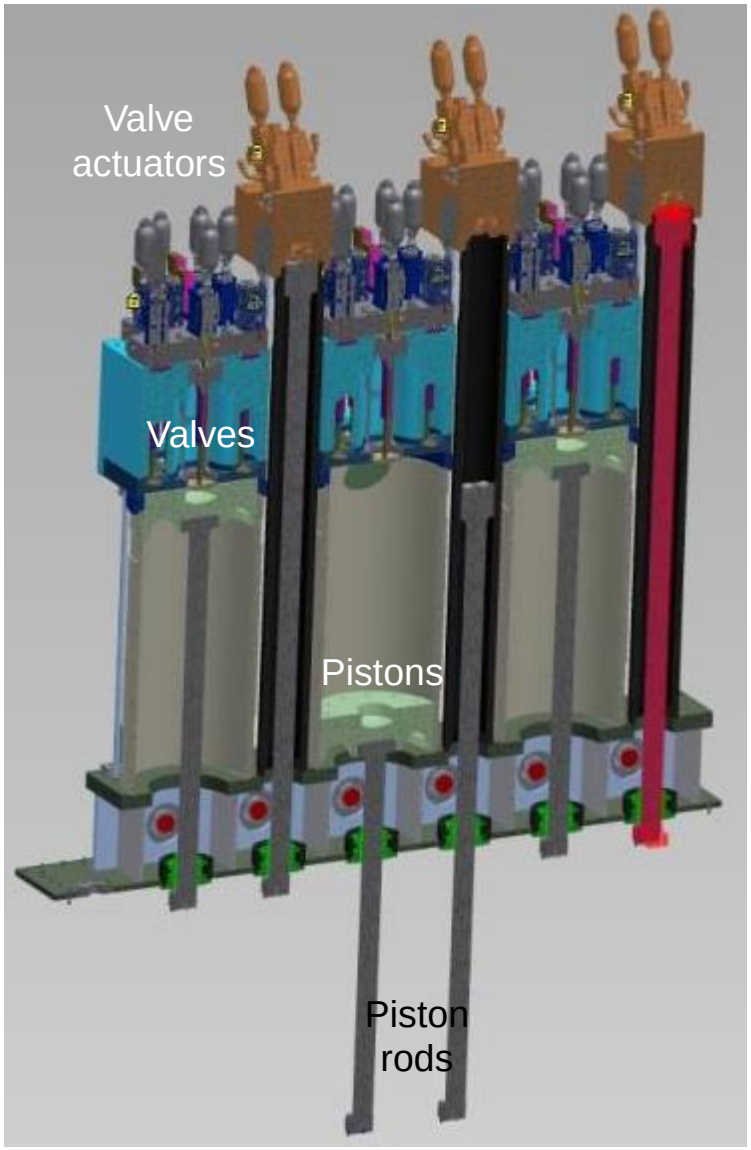
The Engine aka the Power Unit

- Permanent magnet motor/generators
  - Used in newer windmills (direct drive generators)
- Marine diesel engine drivetrain – 6 cylinder
  - Low speed, long stroke: 120 rpm, 1.5m stroke
  - Used in ships and stationary power applications
- Two stage reciprocating piston compressor /expander
  - 1st stage: large D cylinder, atm to 200 psi
  - 2nd stage: small D cylinder, 200 to 3000 psi
- Engine cylinders from hydraulics industry
- Custom engine valves – maximized flow area (high Cv), hydraulically actuated
- No intercoolers – heat is captured and stored in the water



The Engine aka the Power Unit





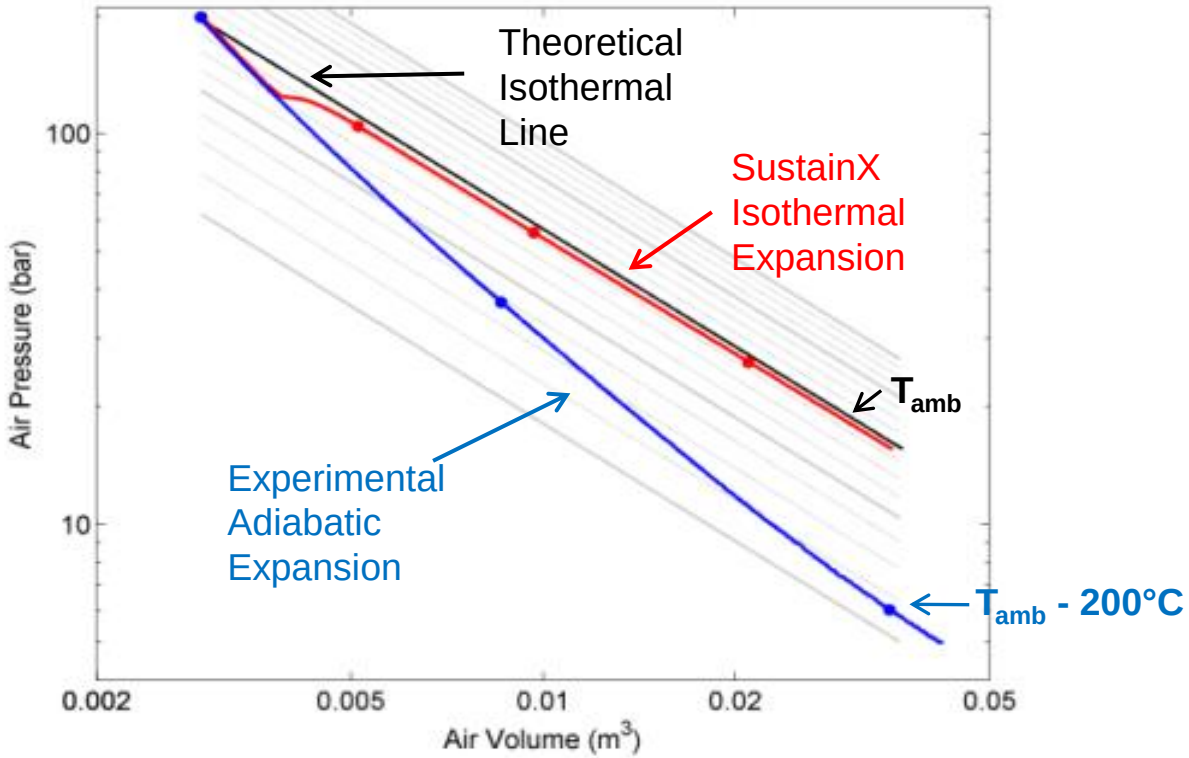
SustainX has demonstrated isothermal compressions and expansions at scale with water spray

Full Scale Heat Transfer (December 2009)

Water spray - 3 second expansion

SustainX thermodynamic efficiency is 95%

- 95% of energy applied to or recovered from gas.
- Temperature does not deviate by >15˚C

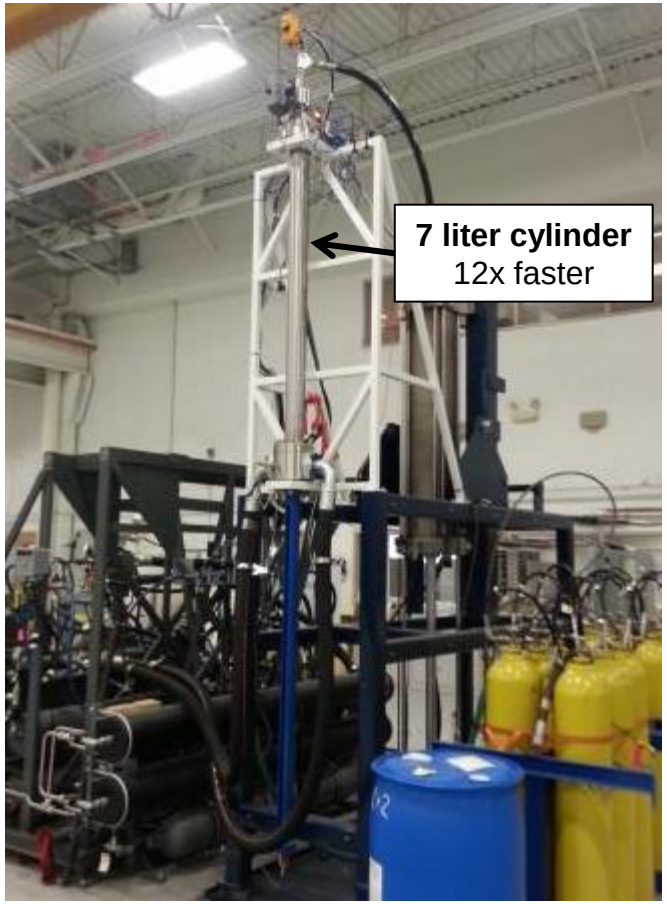


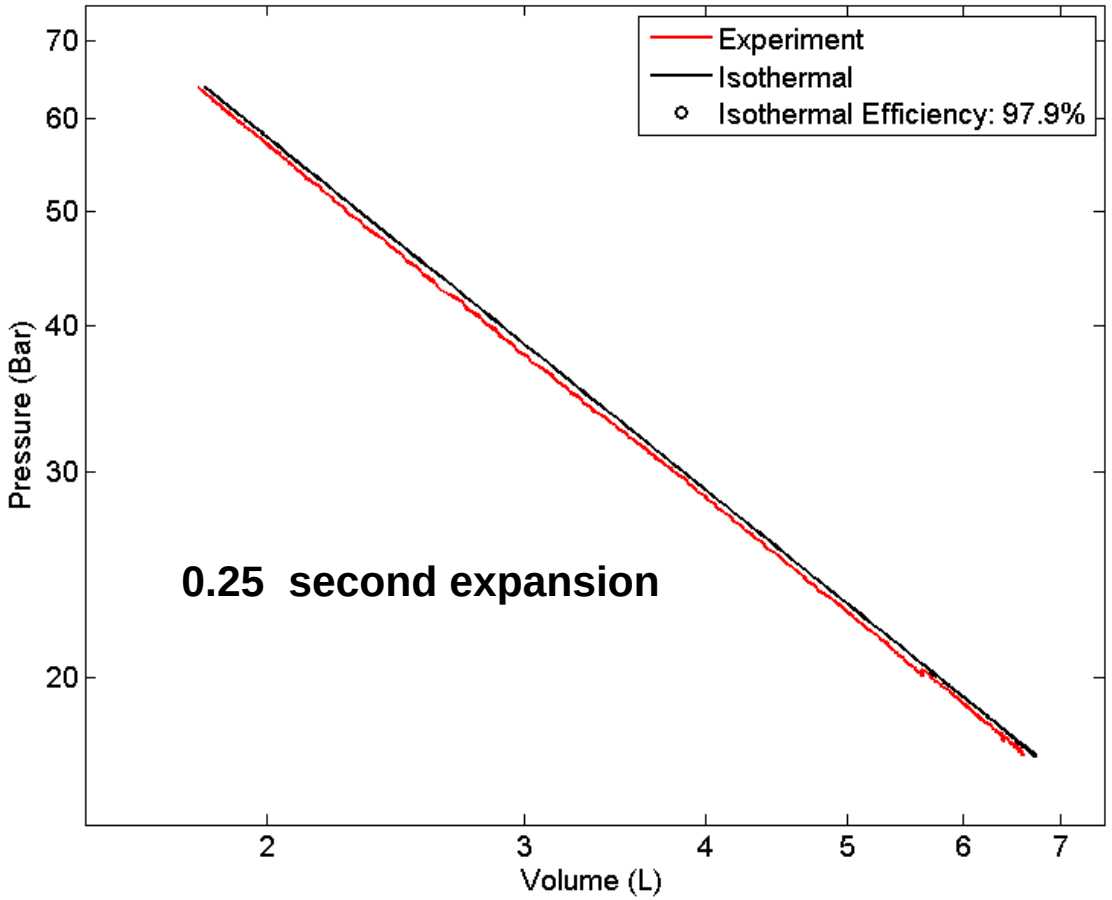
Non-isothermal cycle is 54% efficient.

- 54% of energy applied to or recovered from gas.
- Temperature deviates by >200˚C
- Substantial impact on lifetime, materials, and costs.

Foam = Faster Heat Transfer

- Foam demonstrated to be 12x better than spray
  - Spray: isothermal over 3 second expansion; foam: 0.25 second
  - Foam has much more surface area per unit water than spray

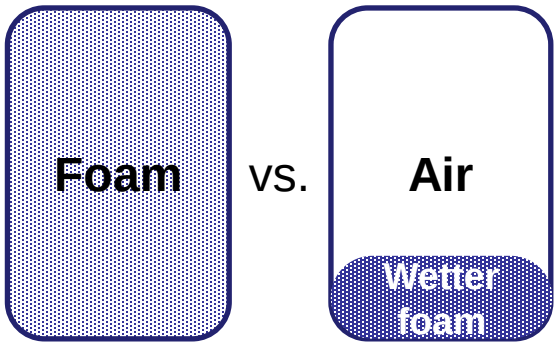




Foam Overview

- What is foam?
  - Air encapsulated by water; the bubbles are stabilized by surfactant
    - Air + Water with surfactant + Interface + Energy ➔ Foam
  - Water is the heat transfer fluid
  - For excellent heat transfer, all air needs to be inside the water as a continuous foam
  - Most of the process is closed: any breakdown in a foam results in air and a wetter foam

Example:
2:1 mass ratio,
water to air
97% gas volume
fraction (GVF)
34:1 ER
(Expansion Ratio)



0:1 mass ratio
100% GVF
0 ER

8:1 mass ratio
88% GVF
8:1 ER

Foam Rheology – how foam flows

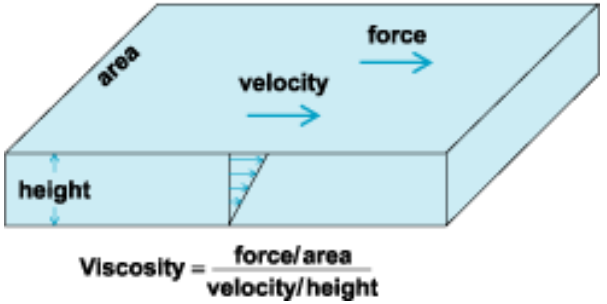
- Foam: complex, non-Newtonian fluid

$$\tau = \tau_0 + K\dot{\gamma}^n$$ Herschel-Bulkley fluid

  - Power law, shear thinning: $n < 1$
  - Bingham plastic, yield stress: τ_0
    - $\tau < \tau_0$: Elastic solid
    - $\tau \sim \tau_0$: Plastic deformation
    - $\tau > \tau_0$: Viscous flow
  - Wall slip: v_{slip}
  - Microstructure directly affects macroscale quantities
    - Gas to liquid volume ratio
    - Bubble size, distribution
    - Surfactant type

Newtonian fluids: shear stress is the product of viscosity & shear rate

$$\tau = \mu\dot{\gamma}$$



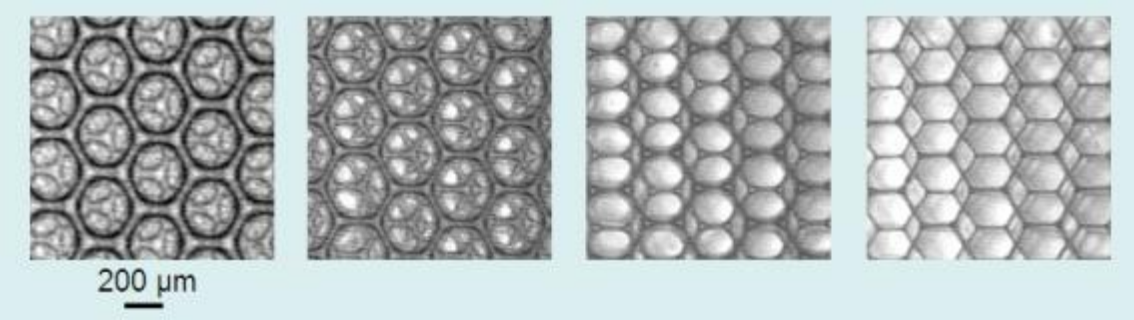
$$\dot{\gamma} = \frac{\delta v}{\delta l}$$

In a pipe:

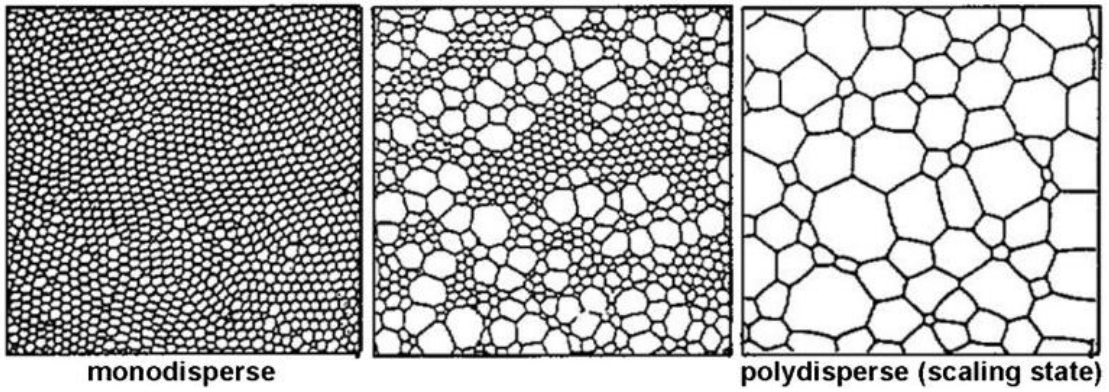
$$\tau = \frac{\Delta P}{L}\frac{D}{4} \qquad \dot{\gamma} = \frac{8\bar{v}}{D}$$

Foam Structure

- Foam Structure
  - Liquid content
    - High: more flexible walls
    - Low: stiff walls but more brittle
  - Bubble size
    - Small: packed, stable
    - Large: unstable
  - Polydispersity
    - Low: strong, reinforced structure
    - High: weak, point failures damage total foam
- More stable, stronger structured foam resists transitioning to slug flow better, but requires more energy to create and transport



Monodisperse foams of different liquid volume fractions ranging from wetter (left) to dryer (right). Note the shift from spherical bubbles to polyhedral with decreasing liquid volume fraction, these foams will resist shear and flow differently



Foams increase in polydispersity from a variety of actions including shear, coarsening, and drainage.

Corrosion Control Is Critical and Achievable

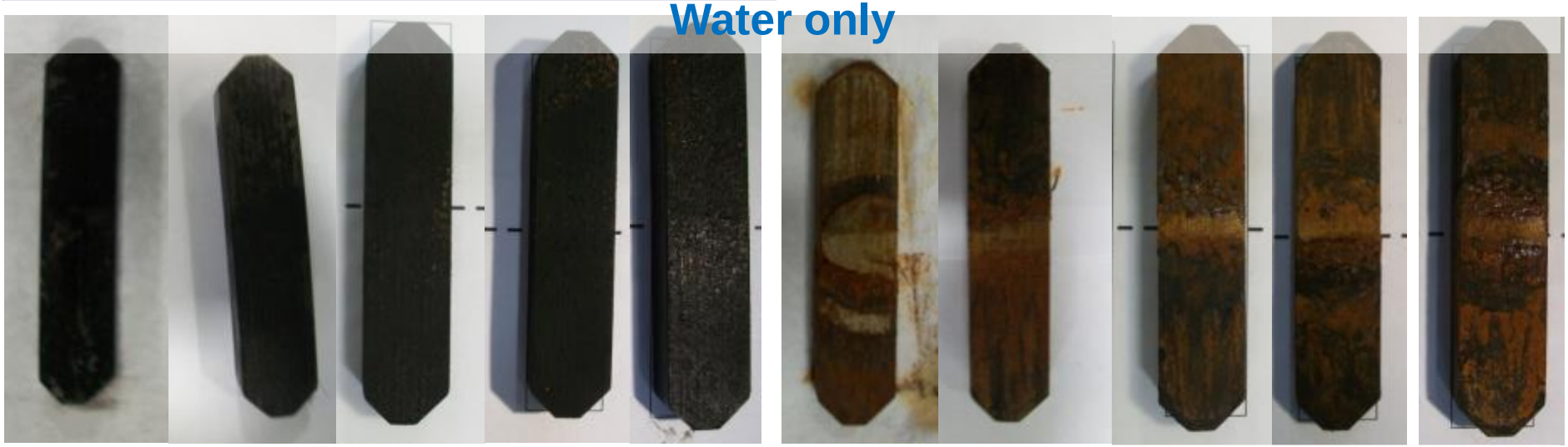
Daily Pressure Cycling: Atmospheric

Week 1	Week 2	Week 3	Week 4	Week 5

Daily Pressure Cycling: 2500 PSI

Week 1	Week 2	Week 3	Week 4	Week 5

Water only



Water w/ corrosion inhibitor

Internships at SustainX

- We're located in Seabrook, NH
- ~40 employees total, ~30 are engineers

- A number of interesting test stands
  - Help us concept, design, build, test, analyze, conclude
- Work on cutting-edge & novel projects: Heat transfer, Non-Newtonian rheology, multi-phase flows, valve testing
- Modeling and analysis in Matlab & Excel
- This summer: the full-scale engine assembly & testing

- careers@sustainx.com

Our latest test stand – full flow rate foam generator

SustainX in the Media

- TV spot – WLBZ –Bangor, Maine
  - http://www.wlbz2.com/news/article/233957/3/NH-company-looks-to-store-energy-with-compressed-air
- NPR
  - http://www.npr.org/2013/03/01/173136713/energy-start-up-banks-on-compressed-air-over-batteries
- NHPR
  - http://www.nhpr.org/post/flattening-curve-moving-two-way-grid

The End

Q & A