Alexander Bell

Candidate for AEC's
Specialist - Composite Materials

September 2019

Overview

- Good morning!

- Introduction
  - About Me
  - Companies & Roles

- Presentation: Foam Rheology – What Makes Foam Flow

  At SustainX I started as an intern…

  … and became "The Foam Guy"

  (and the Corrosion Guy and the Water Chemistry Guy)

About Me

Education

Dartmouth – Master of Engineering Management (MEM)

- Half MEng / Half MBA - Thayer & Tuck collaboration

  Studies included: Technology Assessment; Entrepreneurship; Law, Technology & Entrepreneurship; Technical Project Management; Optimization; Climate Change & Engineering; Energy Utilization; Statistics; Operations Management; Corporate Finance; Marketing; Financial & Managerial Accounting

UNH – BS, Chemical Engineering

Elected focus on Biochemical Engineering, Air Pollution & Control, Natural & Synthetic Fossil Fuels, and Polymer Engineering

Grew up in Amesbury, MA, but have lived in FL, CA, WA, MD. Currently live in Madbury, NH

Companies & Roles

- Boston Metal (Woburn, MA) – Novel metal furnace technology
  - Process Engineer
    - Balance of Plant designer and project manager

- Building Envelope Materials (Amesbury, MA) – Retrofit Building Insulation (polyurethane foam)
  - Director of Engineering
    - Developer of polyurethane foam injection hardware

- Malta (Cambridge, MA) – Grid-scale Electro-thermal energy storage
  - Coolant Consultant
    - Researcher

- Vionx Energy (Woburn, MA) – Grid-scale Redox Flow Battery
  - Thermal Fluid System Consultant
    - Researcher, system modeler

- SustainX (Seabrook, NH) – Grid-scale Compressed Air Energy Storage
  - R&D Engineer
    - Air, Water, and Foam systems developer and designer

BEM

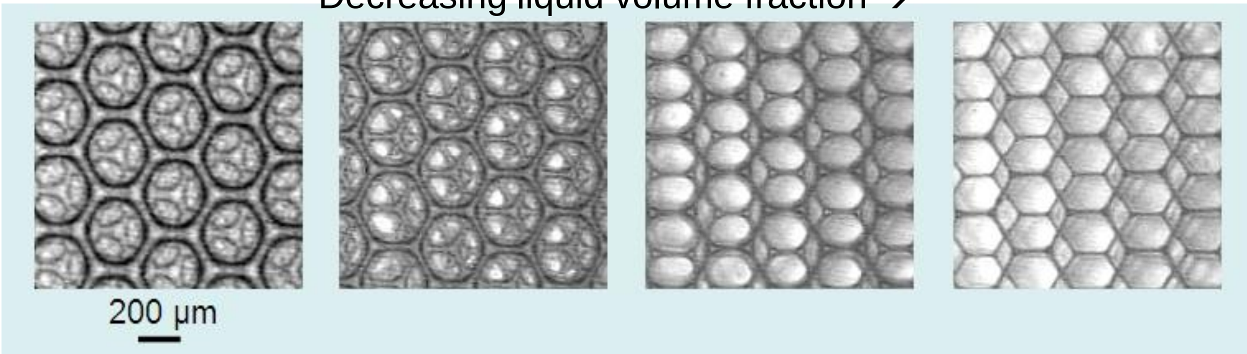
- Designed and Built Mobile Foam Injection System
  - With audio feedback for the operator
  - Patent pending

- I'm an off-the-shelf prototyping wiz
  - McMaster, Amazon Prime, eBay, Fastenal, Home Depot

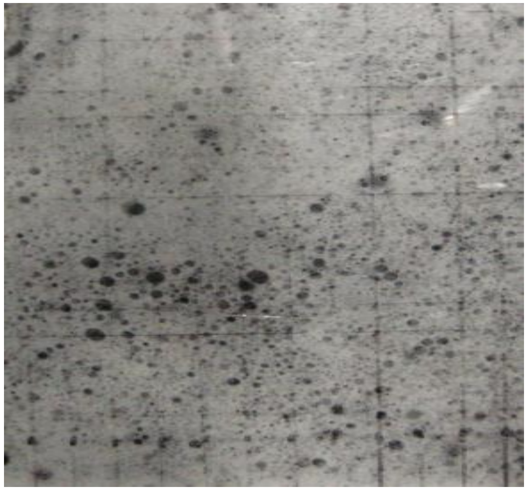
- Used Arduino as controls and DAQ
  - Taught myself Arduino for this project

SustainX: BenchTop Foam Test Stand

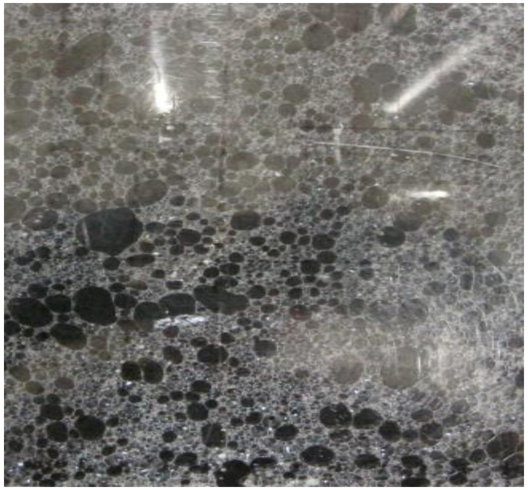
Decreasing liquid volume fraction →



Foam liquid volume fraction is independent of the texture & vice versa – both are critical for predicting foam behavior



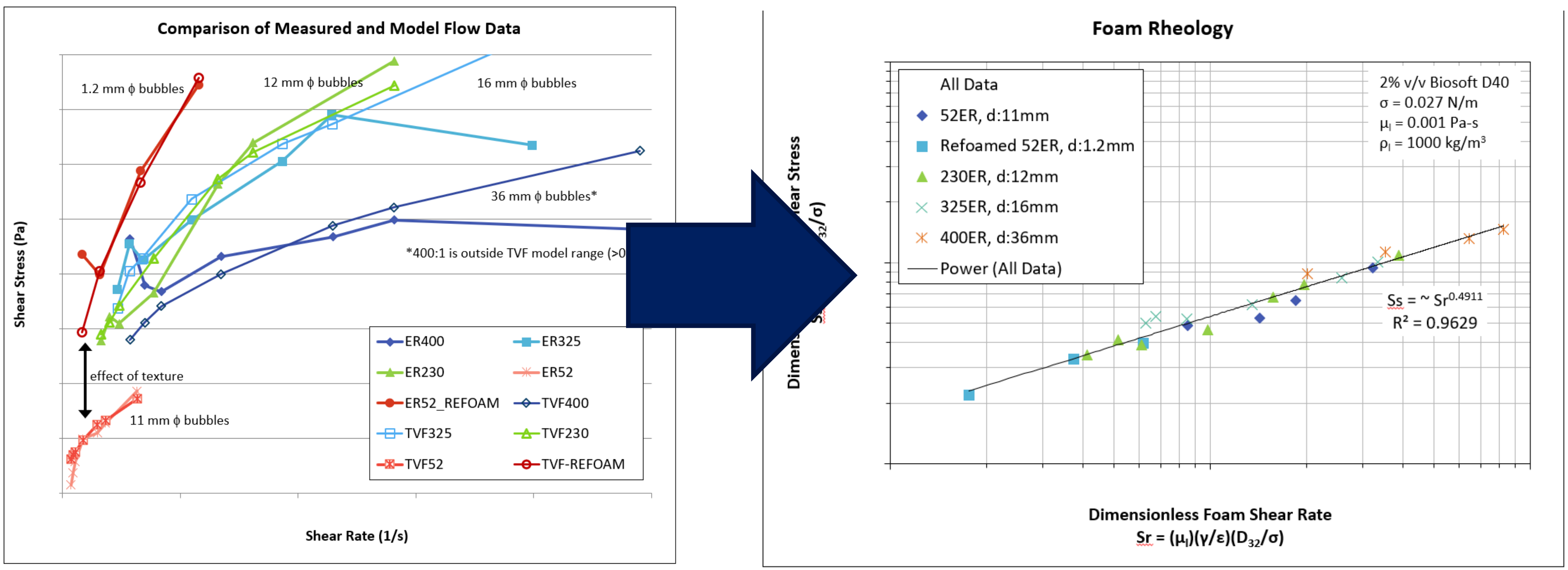
Fine textured foam:
Small bubbles, narrow distribution of sizes



Coarse textured foam:
Large bubbles, wide distribution of sizes

SustainX: Foam R&D

- Goal: Wrangle a large number of variables into scale-independent design tools (chart, equation, rules)
- For instance, foam flow behavior depends on:
  - Pipe diameter, length, pressure drop, flow rate, liquid volume fraction, bubble size, surface tension, viscosity, gas & liquid densities
- We used testing and theory to find the underlying invariants in the data



BenchTop Test Stand

Objective: develop design rules, equations, and charts

- How to size pipes to carry foam → what pressure drop to expect, and how to keep foam from breaking

Tests Setup

- A variety of different LVF foams made: 400, 325, 230, 95, 52 ER
- Each foam type pushed through a pipe smaller than foam generation section (3” sch. 40)
  - Pipes: 3” sch. 80, 2” sch. 40 & 80, 1.5” sch. 40, 1” sch. 40 & 80
  - These achieve higher shear for same foam
- Pressure drop & foam breakdown measured
- Apparent viscosity: $\mu_{app} = \frac{\tau}{\dot{\gamma}}$

Shear Stress (Pa):

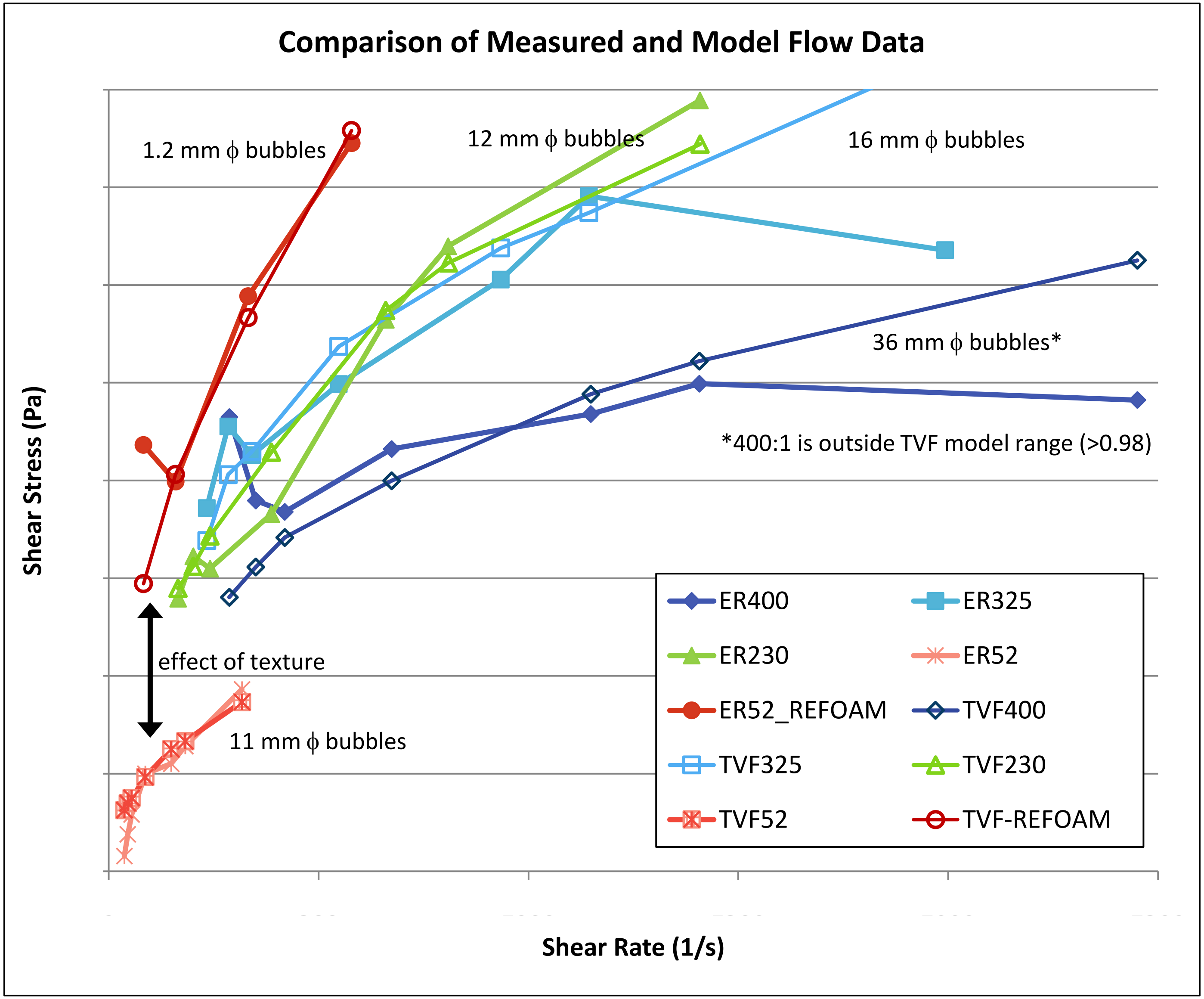
$$\tau = \frac{\Delta PD}{4L}$$

Shear rate (1/s):

$$\dot{\gamma} = \frac{8\bar{v}}{D}$$

ΔP – pressure drop (Pa)
D – pipe diameter (m)
L – pipe length (m)
v – average flow velocity (m/s)

Results



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D – pipe diameter (m)
L – pipe length (m)
v – average flow velocity (m/s)

TVF – tau, viscous friction model
Bubble sizes inferred from this model (more on that later)

Texture Inference

- Low Surface Modulus surfactants – "Dawn" like
  - Bubbles can slide past each other
    - Aka mobile bubble surfaces
  - Energy is dissipated via sliding → this is viscous friction (inside the foam films)
  - n ~ 0.5
- High Surface Modulus surfactants – "Gillette Foamy" like
  - Bubble interfaces are rigid – no bubbles sliding
    - Aka no surface mobility
  - Energy is dissipated via bubble distortion
  - This dissipation style requires more energy = higher pressure drop while flowing
  - n ~ 0.2-0.3

- Given a LSM surfactant – as Biosoft D-40 is – the Capillary number and shear stress are:

$$Ca = (\mu \dot{\gamma} R_{32})/\sigma,$$

Capillary number is a dimensionless shear rate that accounts for bubble size

μ – liquid viscosity (Pa-s)
R_{32} – Bubble radius (Sauter)
σ – surface tension (N/m)

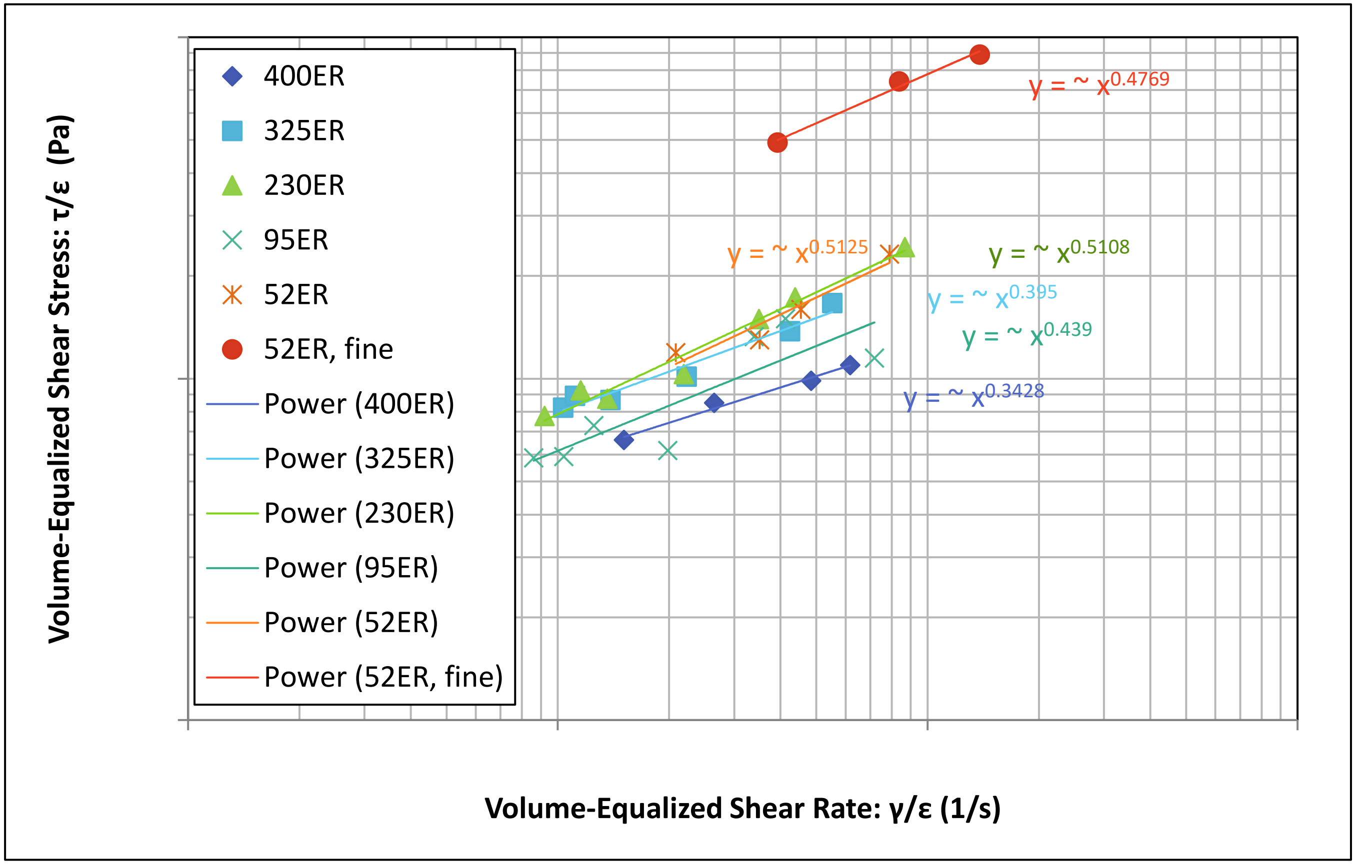
$$\tilde{\tau}_{VF} \approx 1.16\ Ca^{0.47}\ \Phi^{5/6}(\Phi - 0.74)^{0.1}/(1 - \Phi)^{0.5} \qquad (5)$$

where $\tilde{\tau}_{VF} = \tau_{VF} R_0/\sigma$ is the dimensionless stress related to the friction in the foam films and R_0 is bubble radius. The subscript "VF" denotes viscous friction inside the films.

Valid for: $0.80 < \Phi < 0.98$

- Given for a particular flowing foam's pressure drop data, bubble size can be calculated using equation 5.

Volume-Equalization



Specific Expansion Ratio: $\varepsilon = \frac{\rho_l}{\rho_f}$

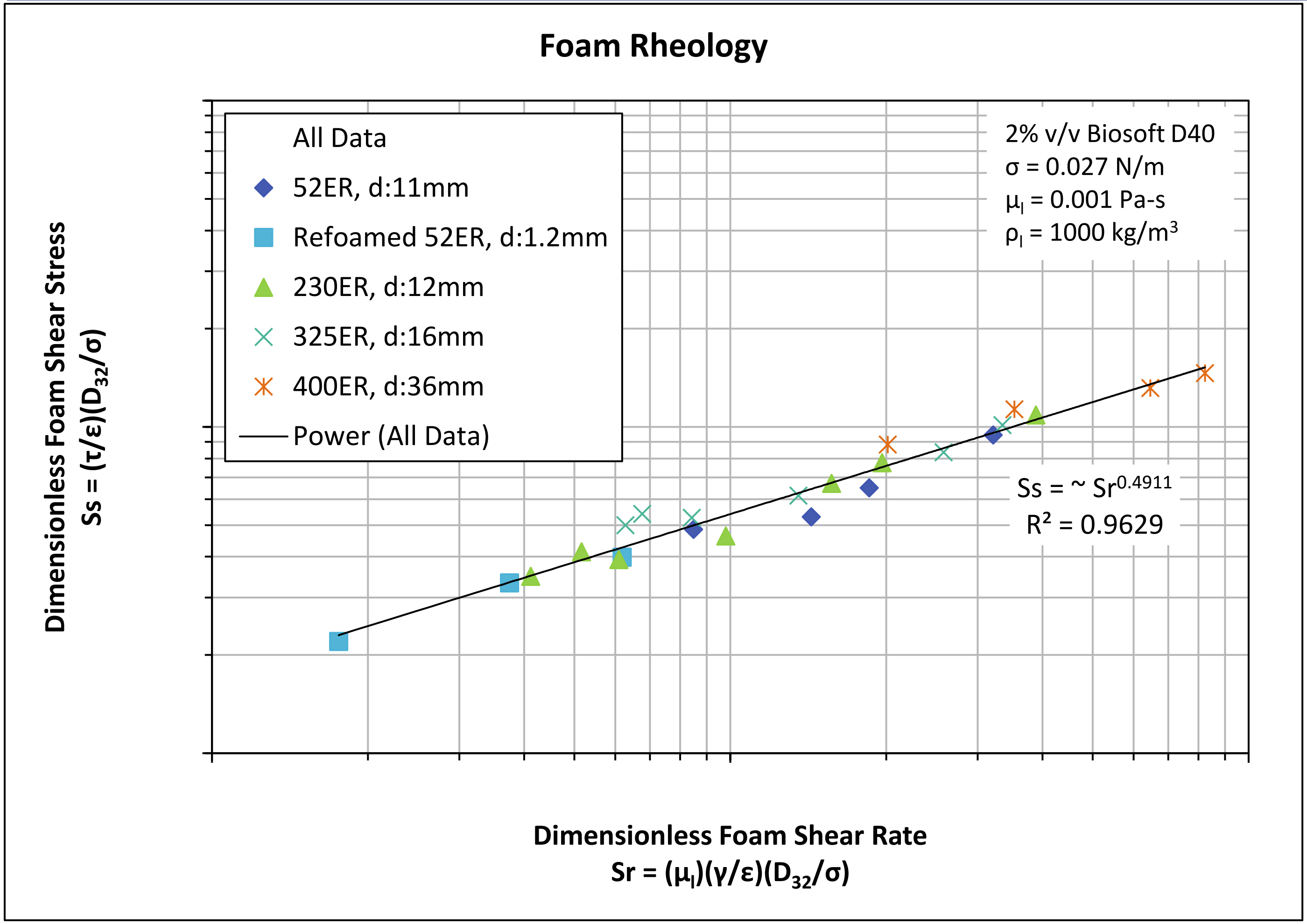
Foam density: $\rho_f = \Phi\rho_g + (1 - \Phi)\rho_l$

ρ_l – liquid density (kg/m^3)
ρ_g – gas density (kg/m^3)
Φ – gas volume fraction

At atmospheric pressure, ε ~ ER

- Volume-Equalization for foam takes into account the effect of different expansion ratios on rheology data
  - Both shear rate and shear stress are divided by the Specific Expansion Ratio, ε
- Power-law equations fit to the data show foam's shear-thinning property, n < 1:
  - $\tau/\varepsilon = k(\gamma/\varepsilon)^n$
- Texture is qualitatively apparent from the 52ER. Fine data are greater than the other foams – this verifies the observation that finer foams have higher pressure drops

Dimensionless Shear Rate & Stress



- Combine Capillary number with Volume-Equalization: All data sets are collapsed into one line!
  - Valid for 100 < γ < 1500 1/s
- Foam viscosity, μ_{app} can be predicted at any expansion ratio and texture
- Future viscosity & texture measurements will strengthen this model

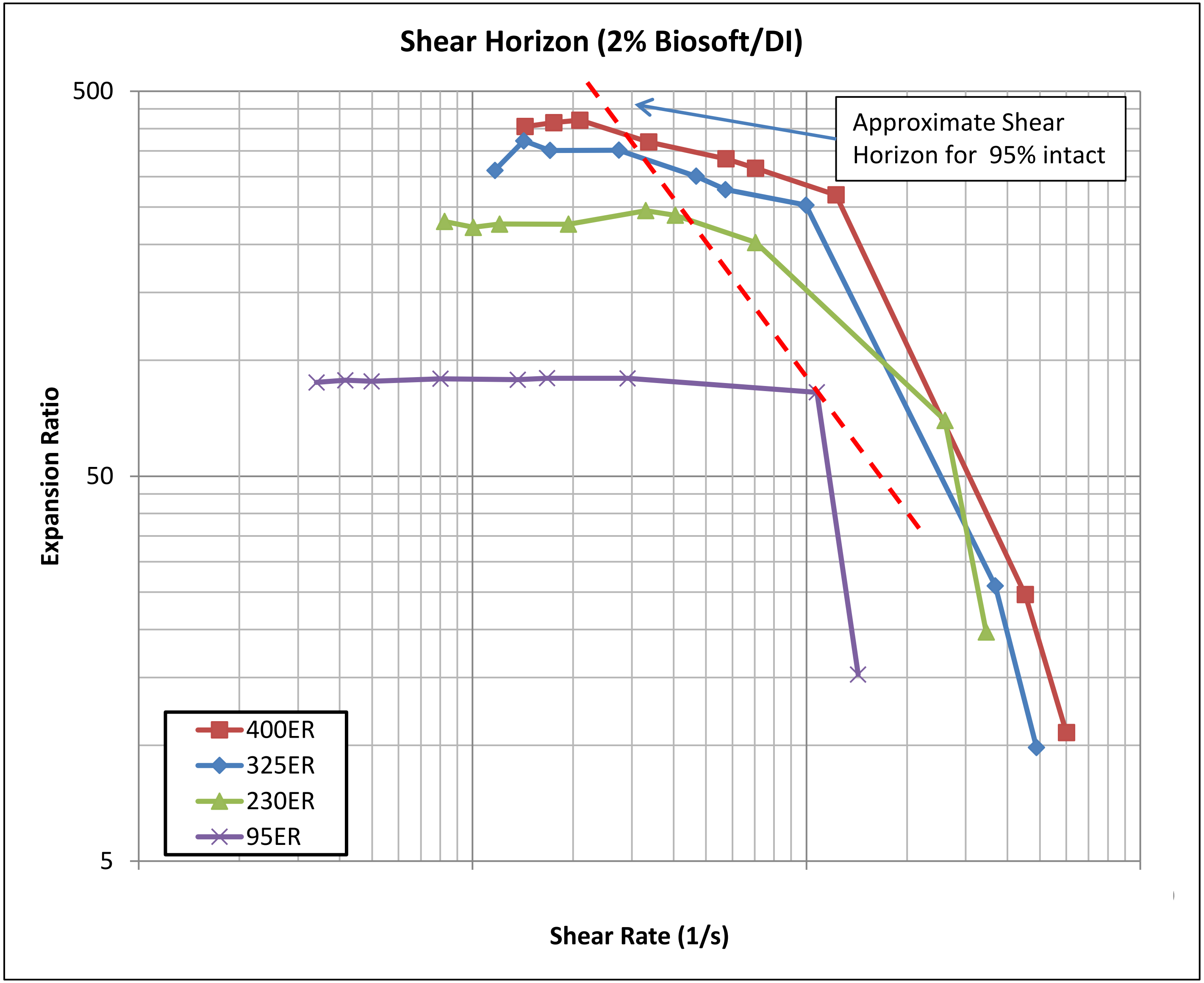
$$\mu_{app} = \frac{\tau}{\dot{\gamma}}$$

Shear Horizon

- Foam is sensitive to shear
  - Too little, it doesn't flow – it acts like a solid
  - Too much, it breaks down
  - Just right – plug flow

- The Shear Horizon is the cliff to avoid, or embrace
  - For intact Foam Transport, operate shear far way from the horizon e.g. size valves to be low shear
  - To achieve intentional Foam Separation, create shear far exceeding the horizon

Shear Horizon vs. Expansion Ratio

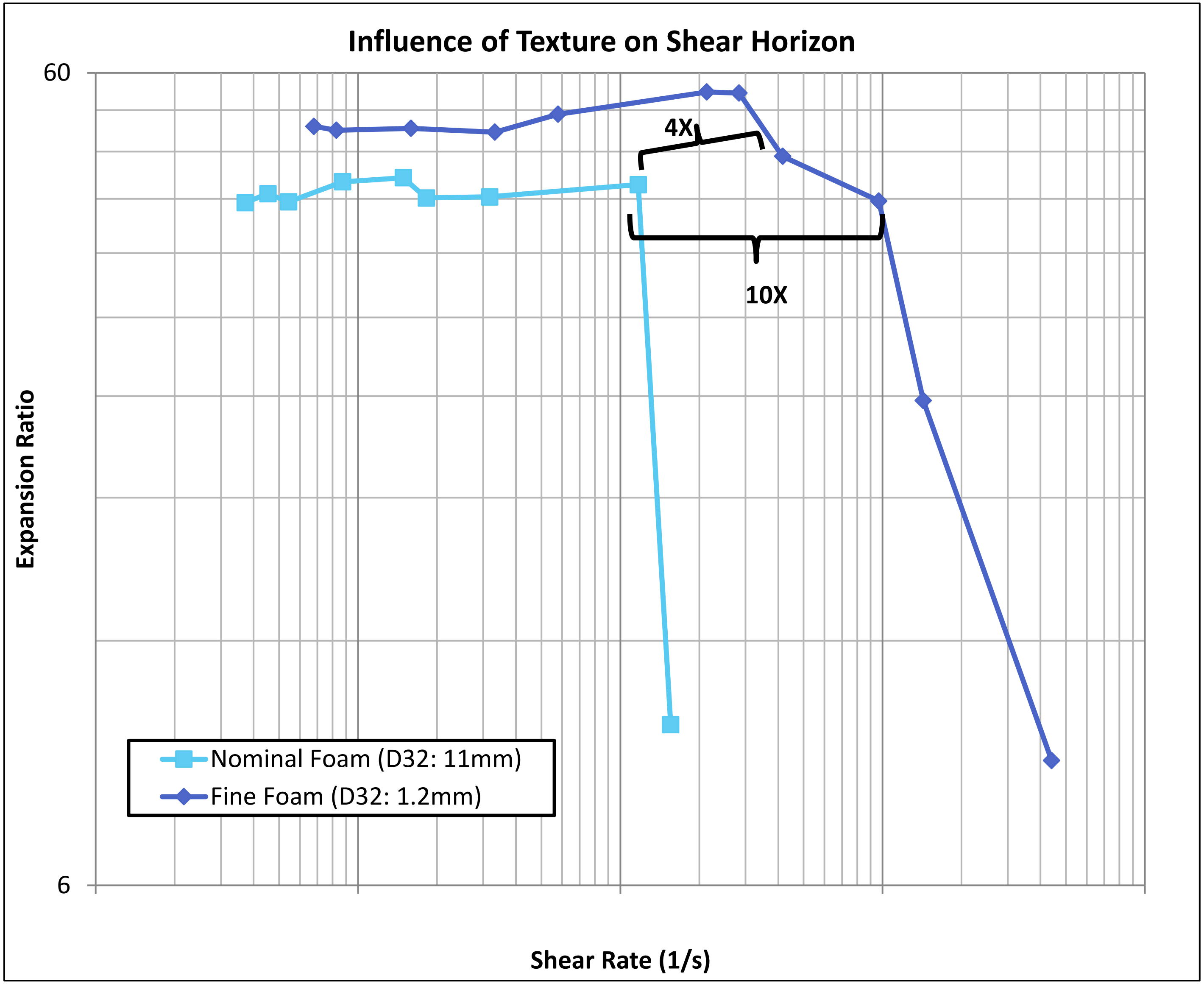


The Shear Horizon

When sheared, drier foams break down at lower shear rates, i.e. drier foams are more brittle or fragile

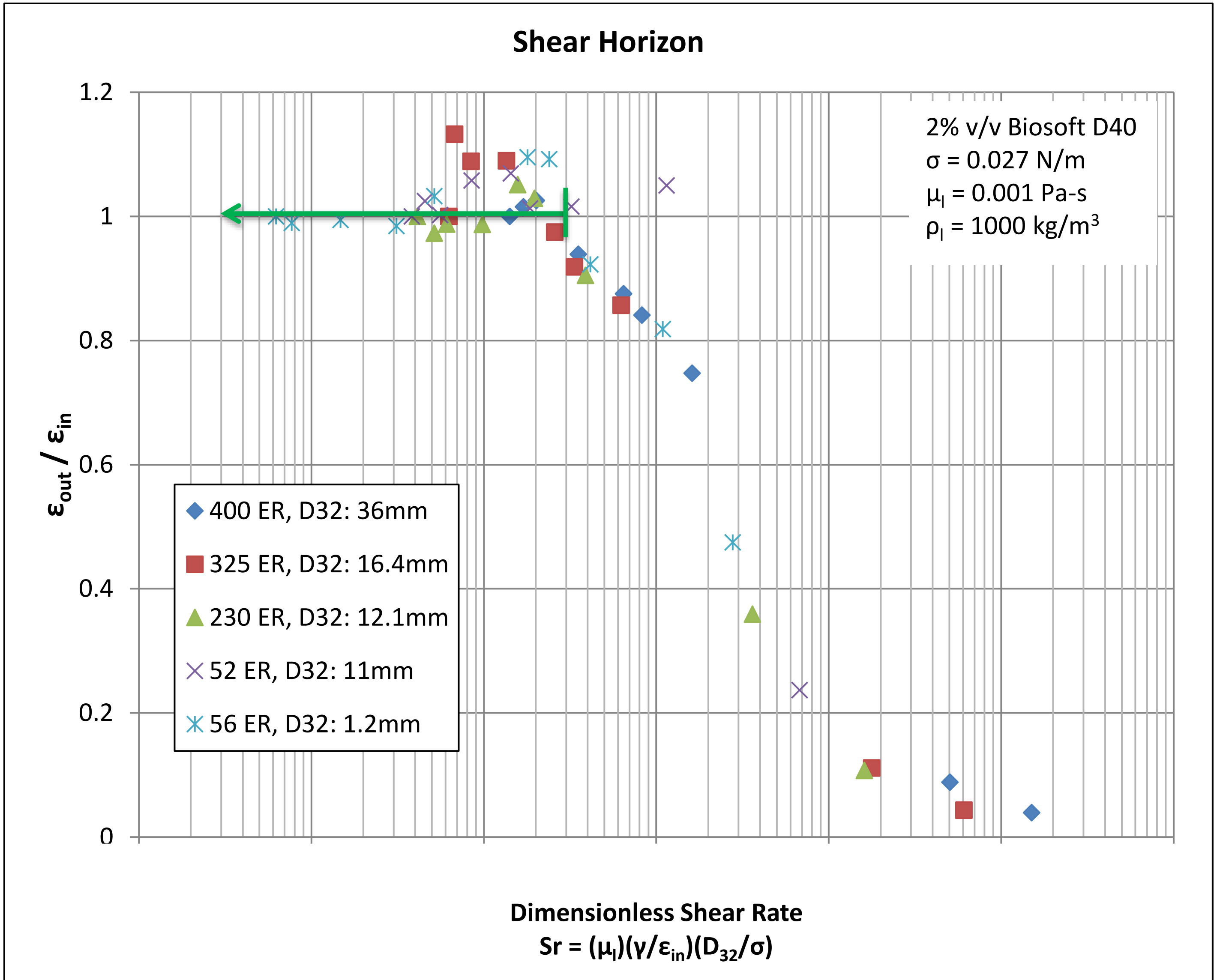
Wetter foams can withstand more shear before breaking down, i.e. wetter foams are more resilient

Shear Horizon vs. Expansion Ratio



Finer foams can withstand higher shear rates i.e. finer foams are more resilient

Dimensionless Shear Horizon (semi-log)

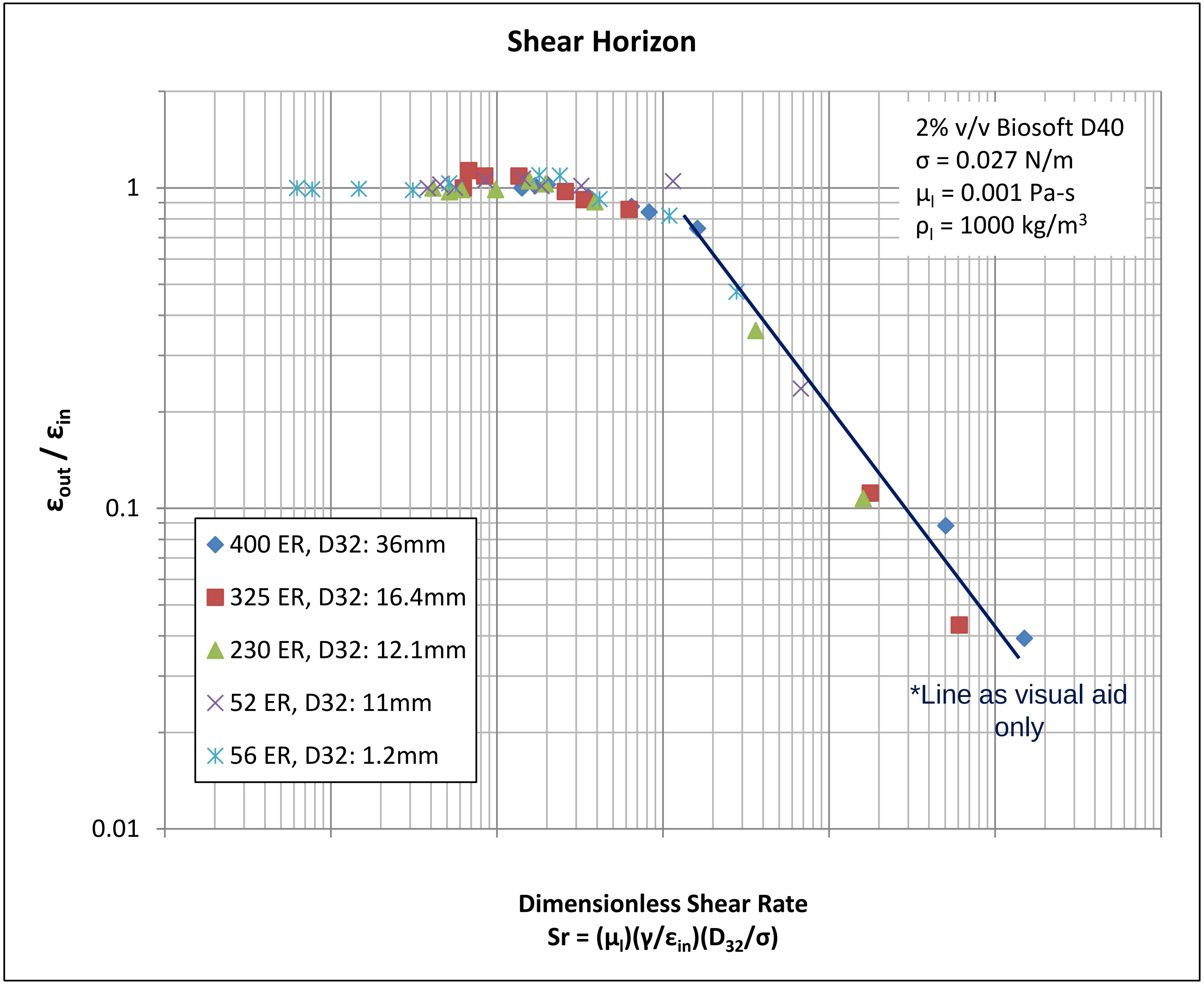


Foam Integrity: $\varepsilon_{out} / \varepsilon_{in}$ < 1 indicates the foam is breaking down from the shear

The semi-log version of this graph is useful for finding the maximum shear rate for keeping a foam intact

The limit is **Sr <= 0.002** for >95% intact foam

Dimensionless Shear Horizon (log-log)



The log-log version of this graph is useful for finding the shear rate for breaking down a foam

To break down a foam to 10%, **Sr ~ 0.3**

To break down a foam to 5%, **Sr ~ 1**

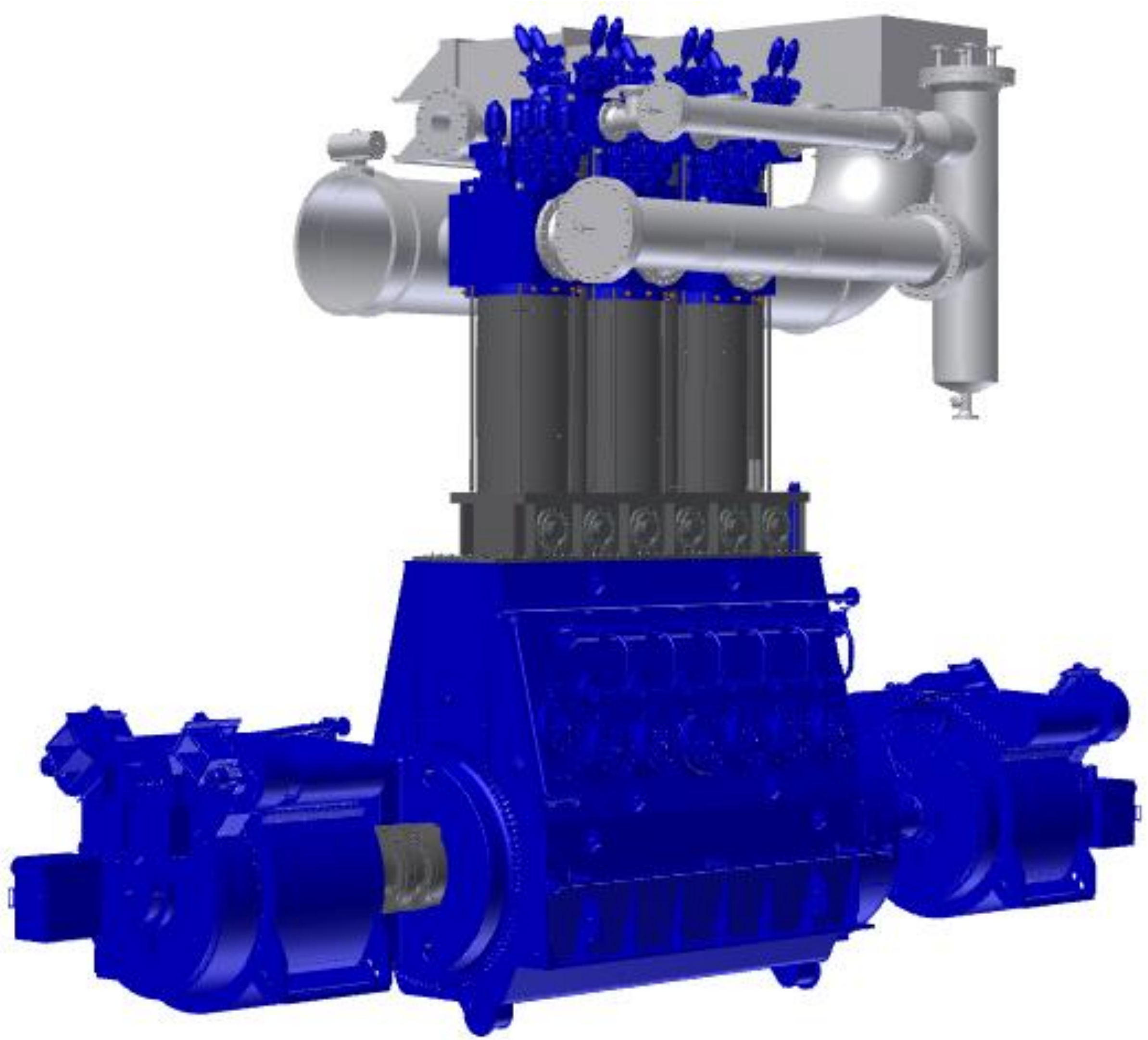
For foam to go from >95% intact to 5%
Sr: 0.002 → 1
i.e. 500x more shear needed

Sr is inversely proportional to the cube of the length scale (pipe diameter)
$Sr \sim 1/D^3$

Thus, D must shrink by ~8x

So to break foam via an orifice, the orifice must be nearly an order of magnitude smaller than the pipe transporting the foam

Sunapee



- 1.5MW compressed air energy storage power plant
- Reciprocating piston, 2-stage compressor & expander
- Wind turbine Permanent Magnet Machines coupled to a Marine diesel crankshaft
- Custom cylinders, heads, and valves

Sunapee

How can I benefit You?

- I can offer:
  - practical, hands-on engineering
  - a strong background in empirical testing
  - test stand design, operation, analysis
  - process design & simulation
  - fluid dynamics
  - chemistry
  - energy & mass balances
  - thermodynamic cycles
  - data analysis
  - project management
  - technology development
  - photography & videography
  - Excel & Matlab are my main squeeze, but I'd love to learn Simulink

References

- Ben Bollinger – formerly SustainX Chief Engineer & Co-Founder
  - Currently VP of Engineering at Malta
- Jeff Modderno – formerly SustainX Director of Fluid Systems
  - Currently Director of Mechanical Systems at Vionx Energy
- Dax Kepshire – formerly SustainX VP, General Manager, Co-Founder
  - Currently Director of Project Management at Fluence (Siemens & AES)

Thank You