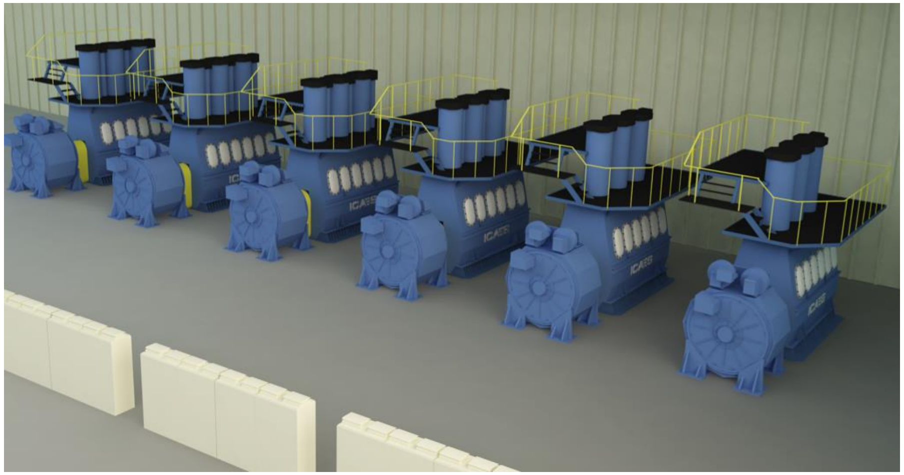
SustainX
SMARTER ENERGY STORAGE

ICAES

Foam Viscosity
Expansion Ratio & Texture



Test Setup

- BenchTop Test Stand
  - A variety of foams made: 400, 325, 230, 95, 52 ER
  - Foam pushed through a pipe smaller than foam gen 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):

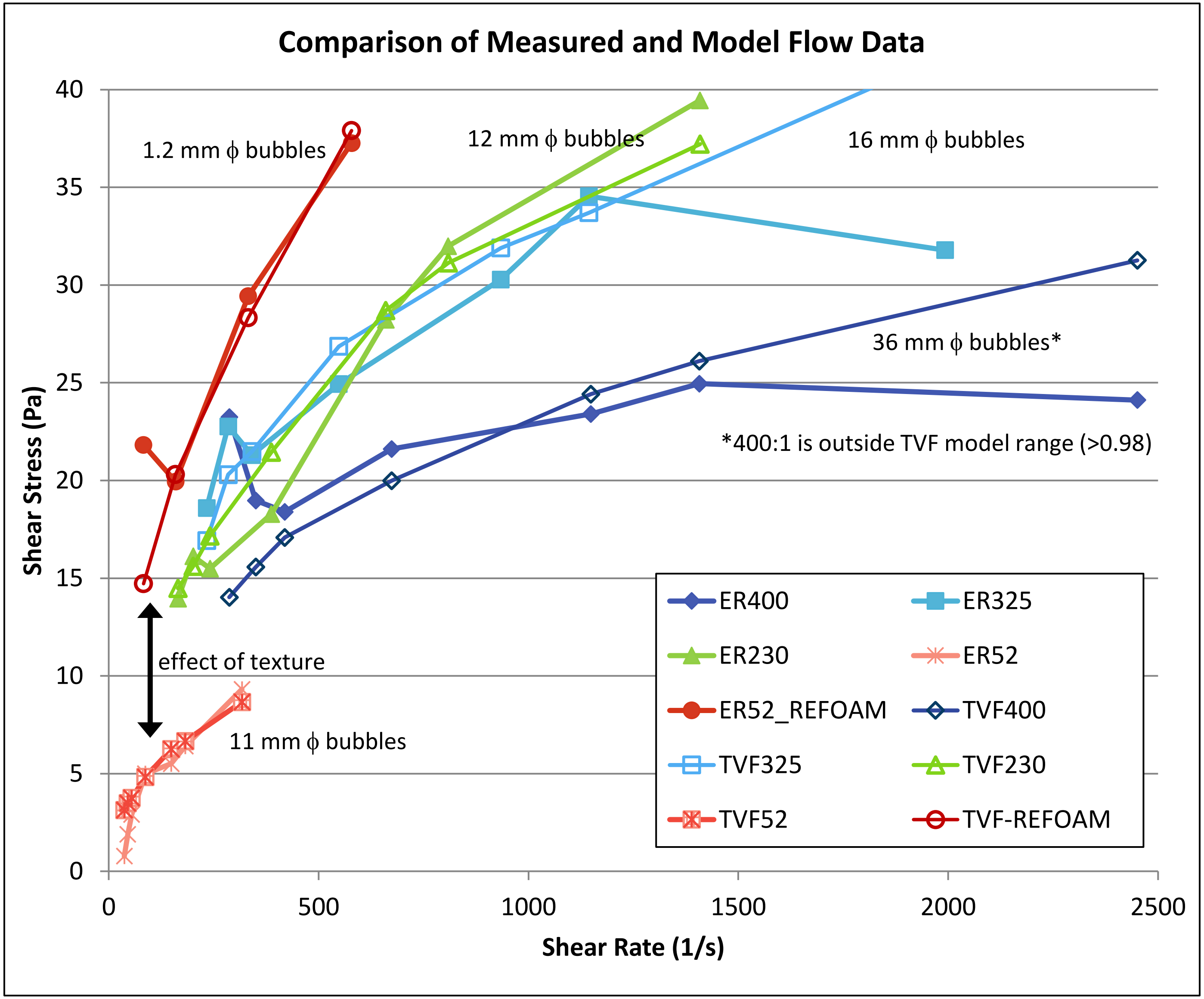
$$\tau = \frac{\Delta PD}{4L}$$

Shear rate (1/s):

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

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

Results



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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)

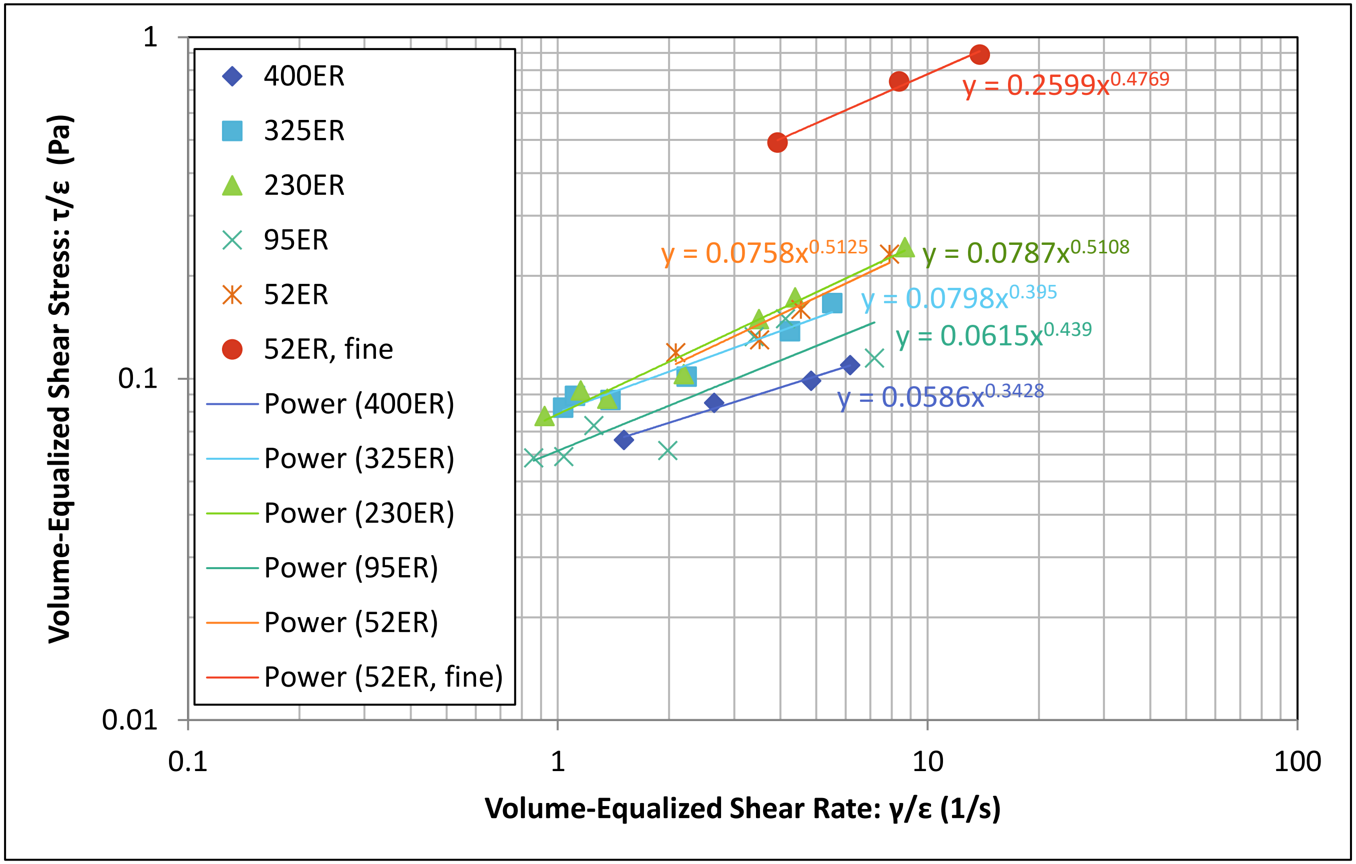
$$\tilde{\tau}_{VF} \approx 1.16\ Ca^{0.47}\ \Phi^{5/6}(\Phi - 0.74)^{0.1}/(1 - \Phi)^{0.5} \qquad (5)$$

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: $\varepsilon = \frac{\rho_l}{\rho_f}$

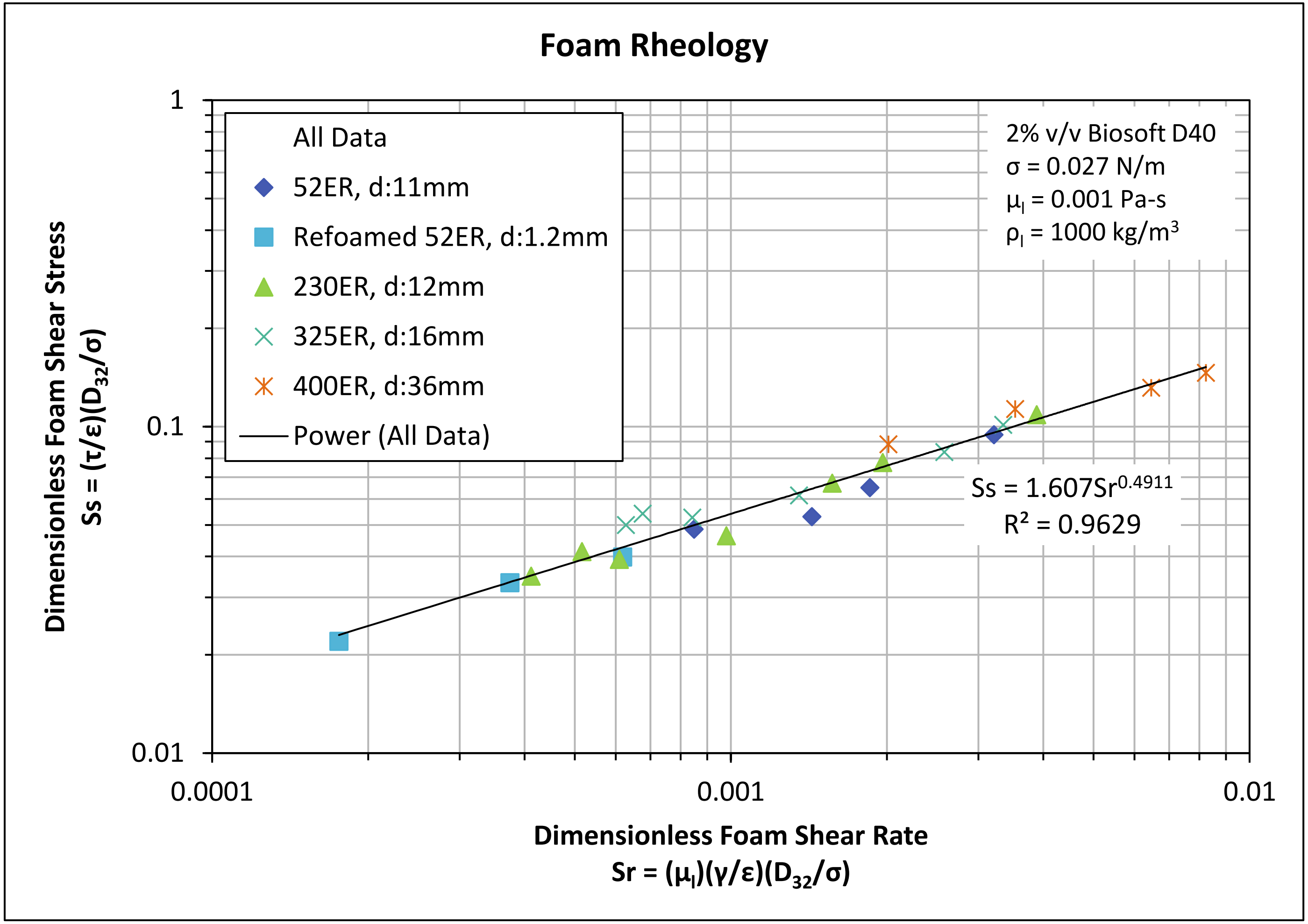
Foam density: $\rho_f = \Phi\rho_g + (1-\Phi)\rho_l$

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



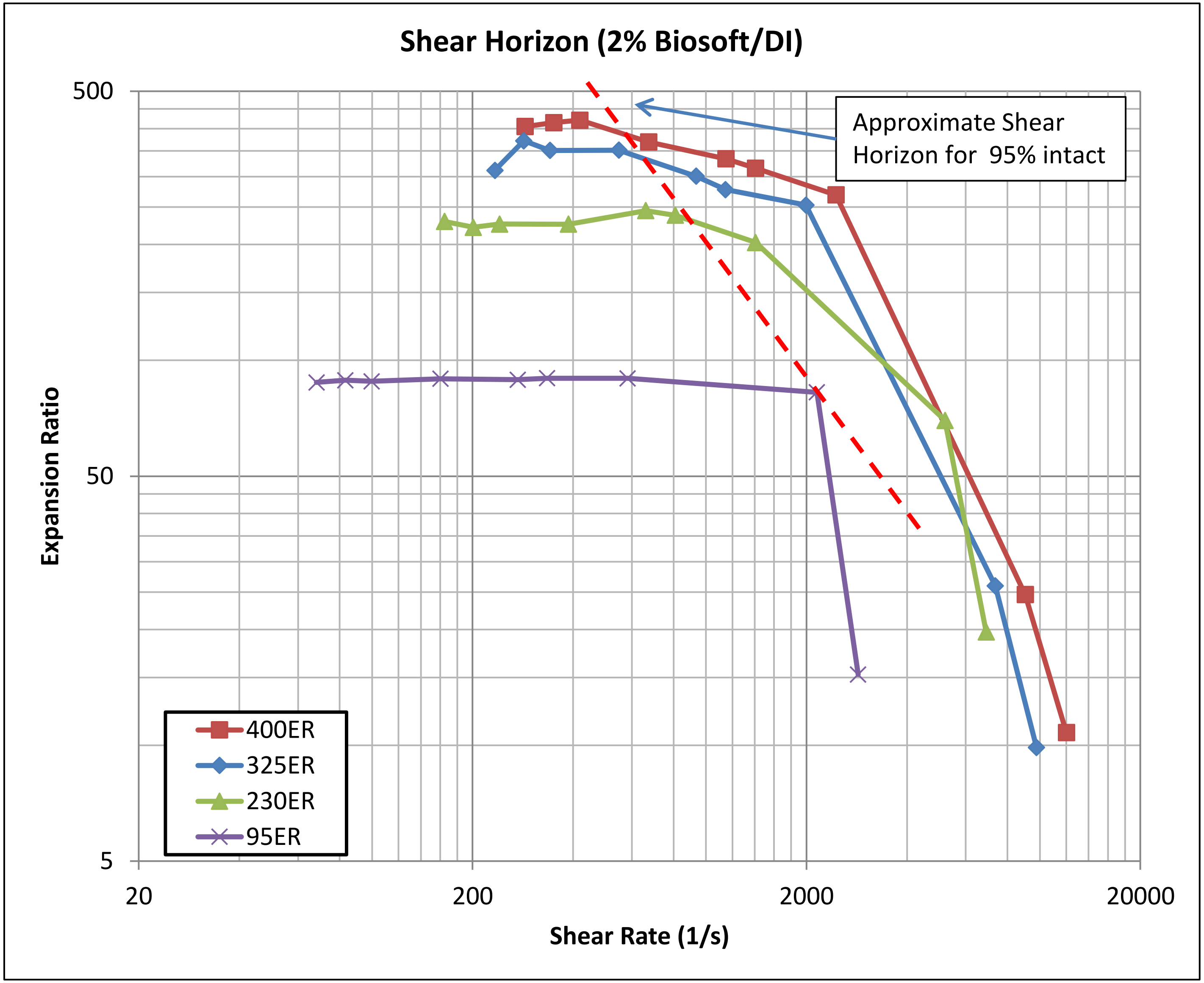
- Combine Capillary number with Volume-Equalization: All data sets are collapsed into one line!
  - Valid for $100 < \gamma < 1500$ 1/s
- Foam viscosity, μ_{app} can be predicted at any expansion ratio and texture
- Future viscosity & texture measurements will strengthen this model

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

Shear Horizon

- Foam Transport & Equipment Design
- Foam Breaking

Shear Horizon vs. Expansion Ratio

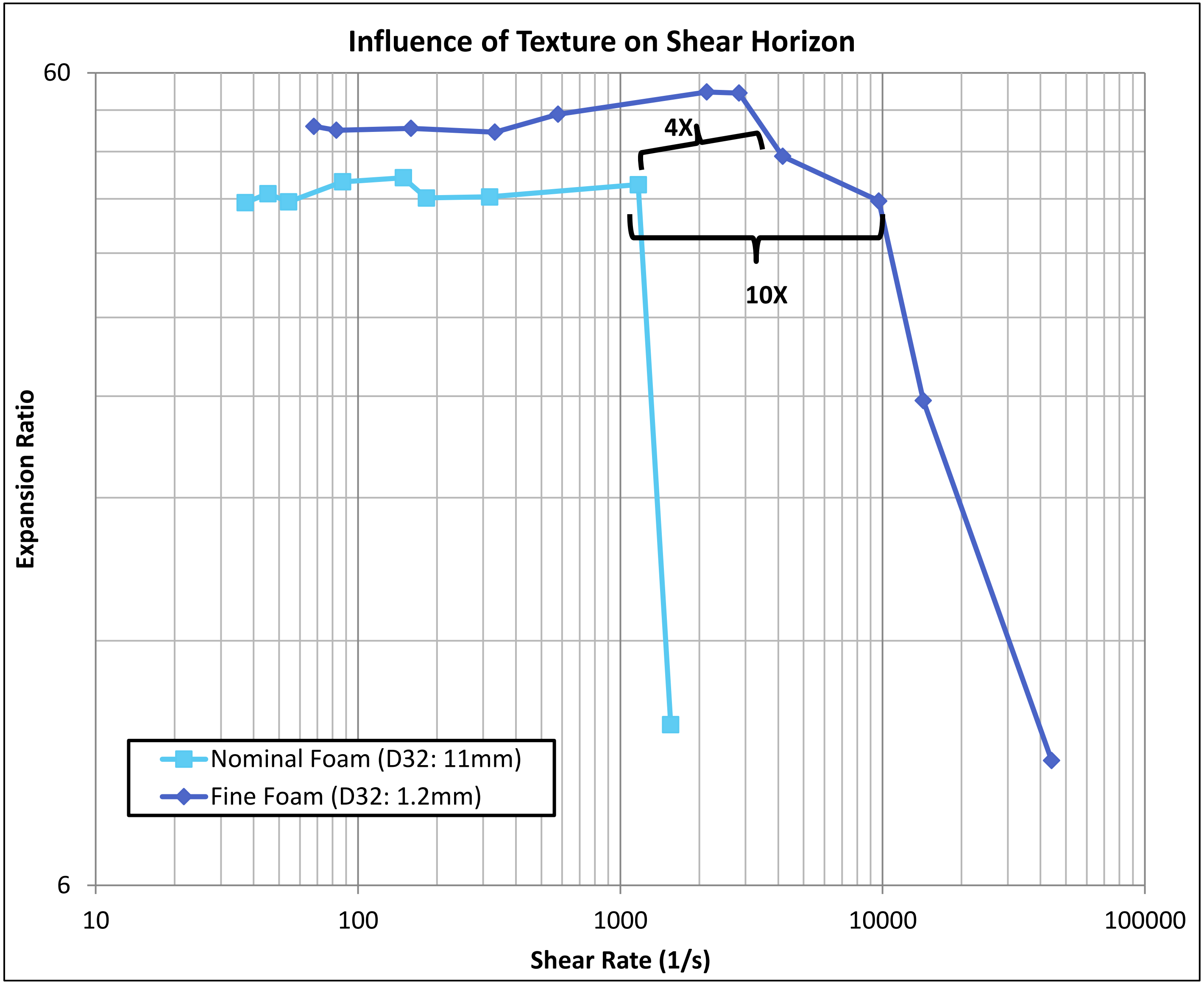


The Shear Horizon

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

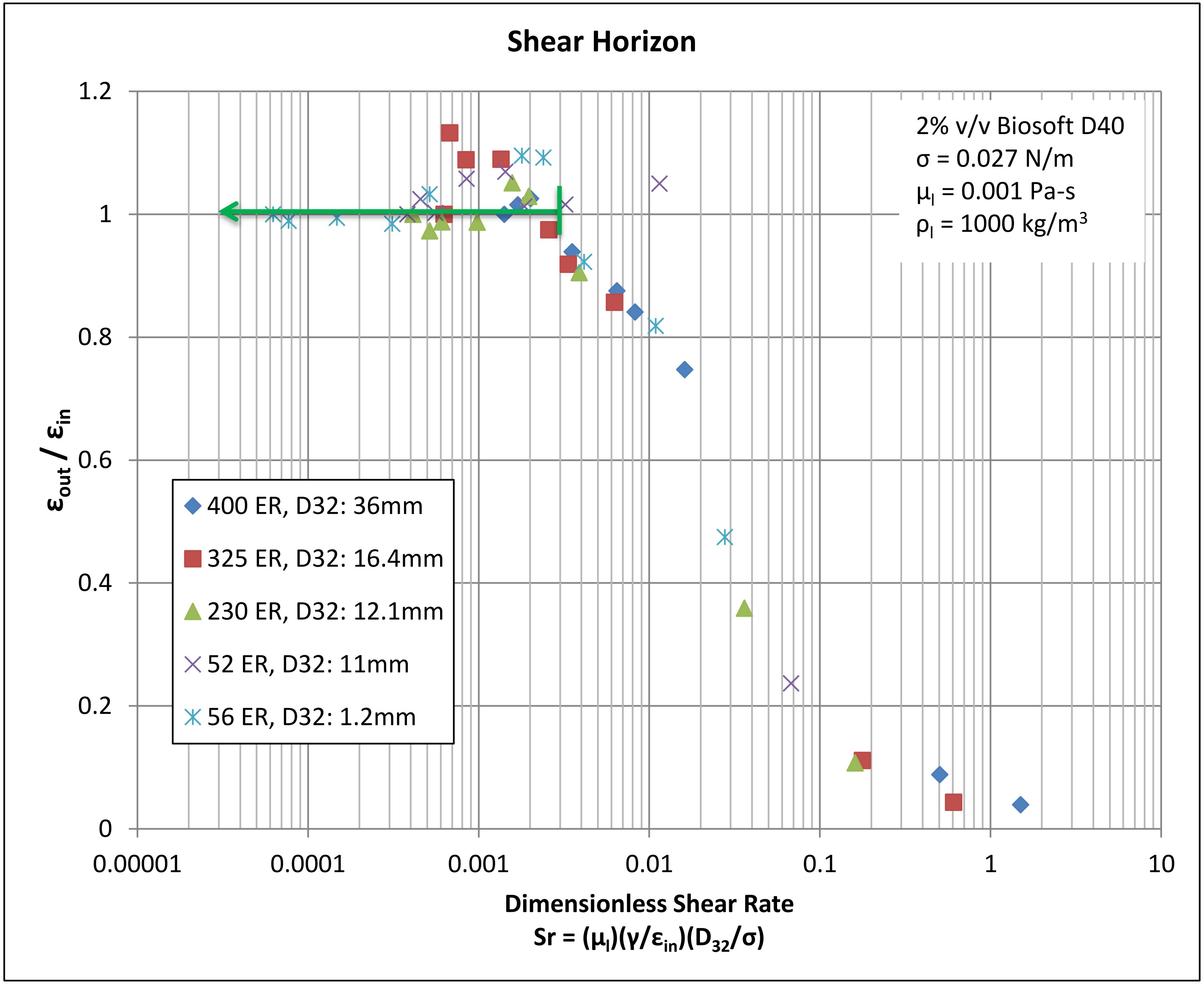
Wetter foams can withstand more shear before breaking down, e.g. wetter foams are more resilient

Shear Horizon vs. Expansion Ratio



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

Dimensionless Shear Horizon (semi-log)

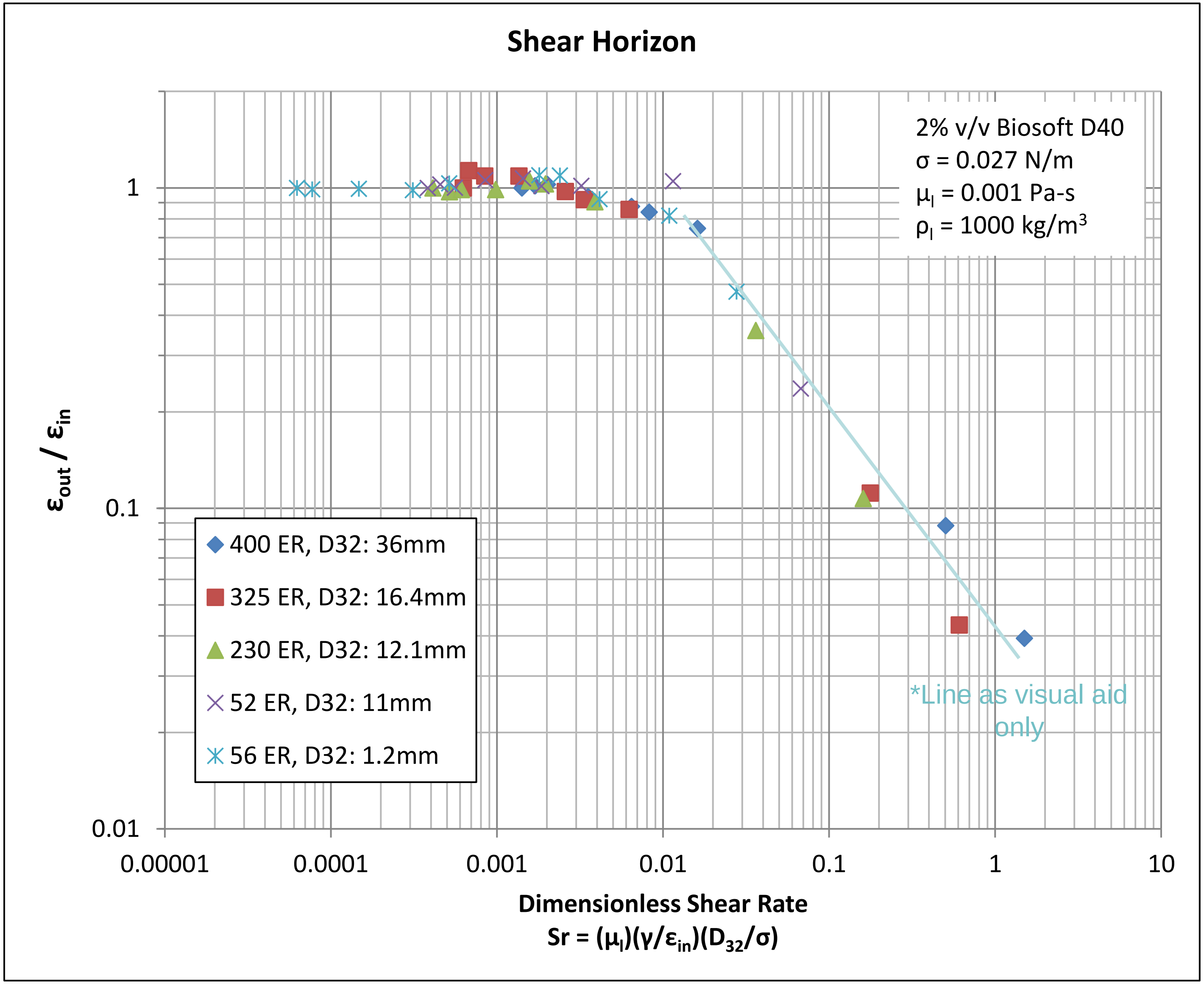


Foam Integrity: $\varepsilon_{out} / \varepsilon_{in} < 1$ indicates the foam is breaking down from the shear

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