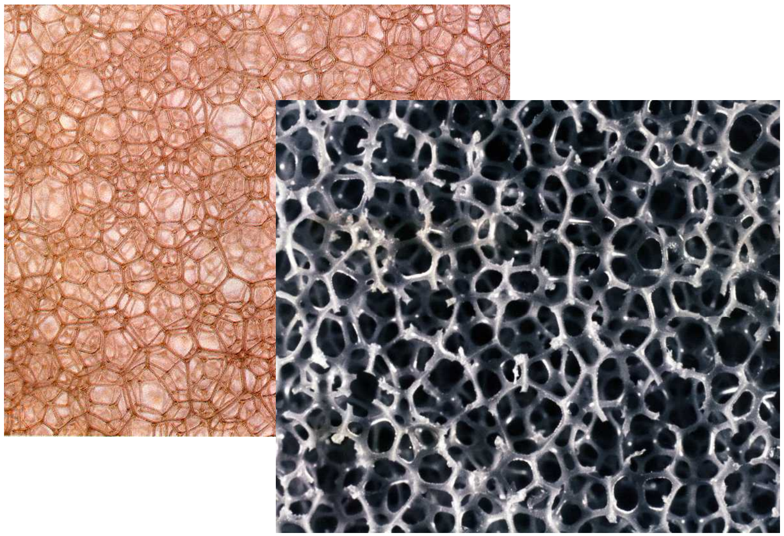
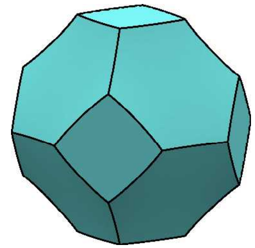
The Structure of Open-Cell Foams with Finite Density

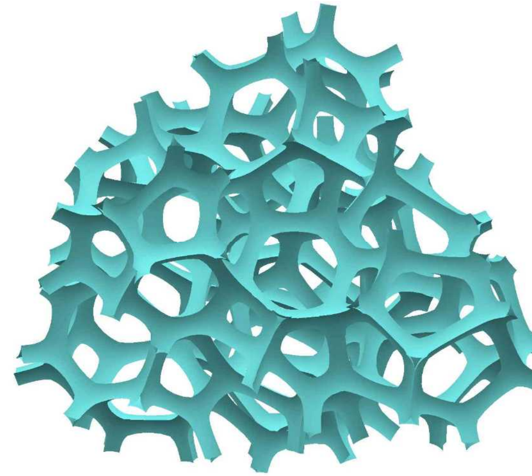
Andy Kraynik

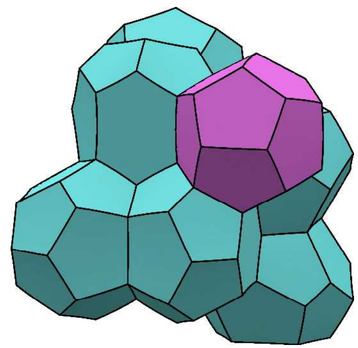
Sandia National Laboratories, Albuquerque

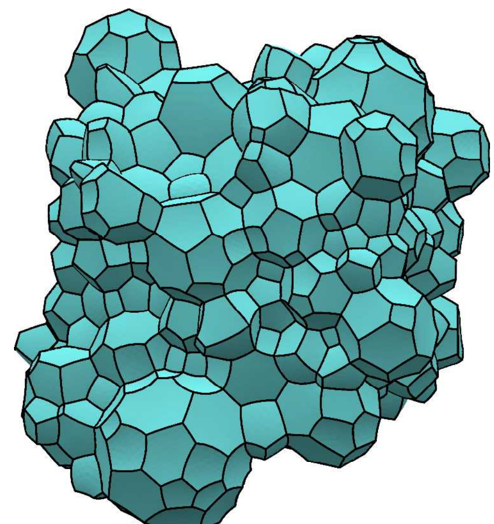
SAND2007-3378C

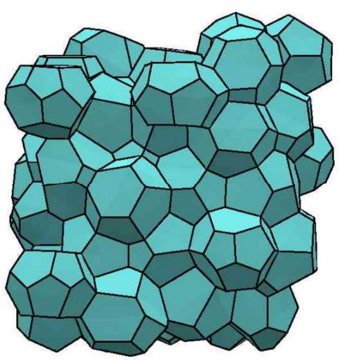


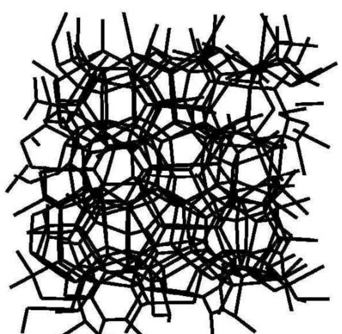












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Realistic models of foam structure enable

prediction of structure-property-processing relationships

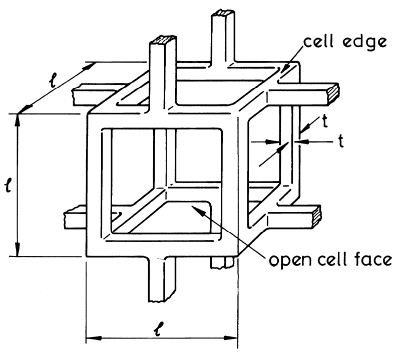
development of constitutive models

What are the important characteristics of foam structure?

How much do they influence foam properties?

Which models of foam structure are realistic?

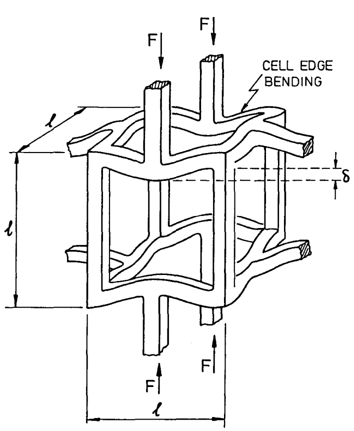
Which are useful?

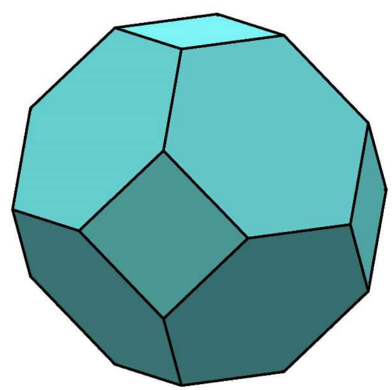


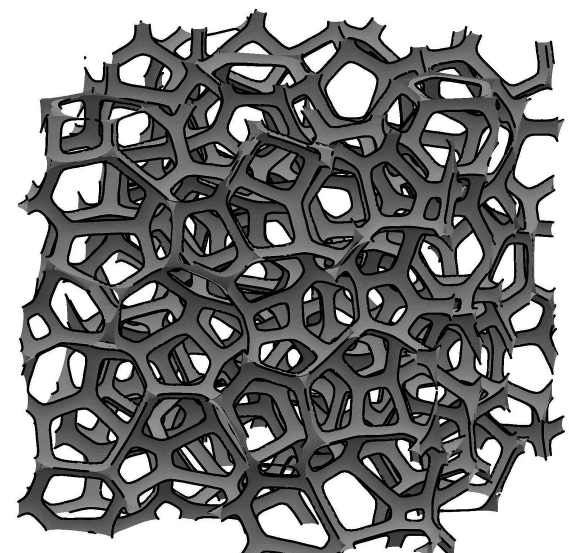
$$\frac{E^*}{E_s} \approx \left(\frac{\rho^*}{\rho_s}\right)^2$$

$$\frac{G^*}{E_s} \approx \frac{3}{8}\left(\frac{\rho^*}{\rho_s}\right)^2$$

$$\nu^* \approx \frac{1}{3}$$



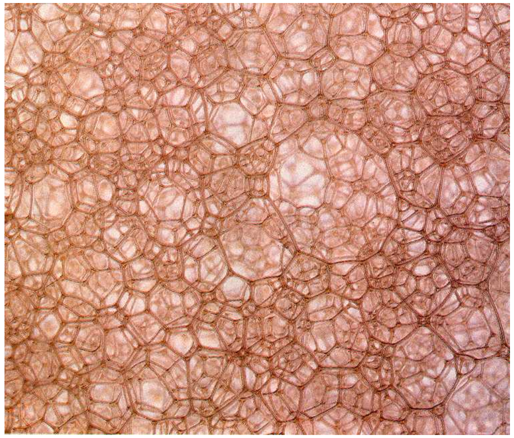




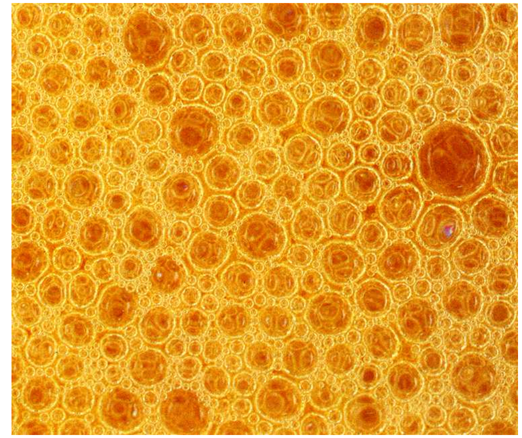
Familiar Foams

Low-Density Foams | Dense Foams

Liquid Foams

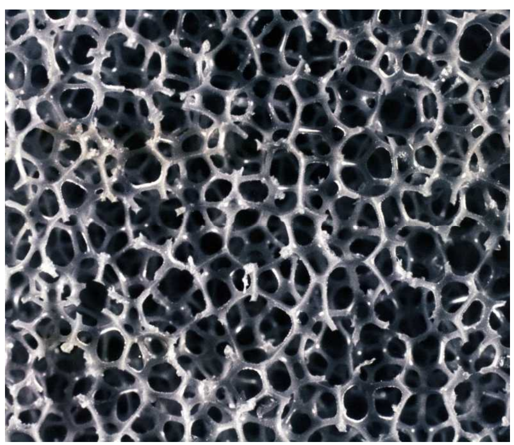


Soap Froth - “Dry” Foam
Drained Beer Foam

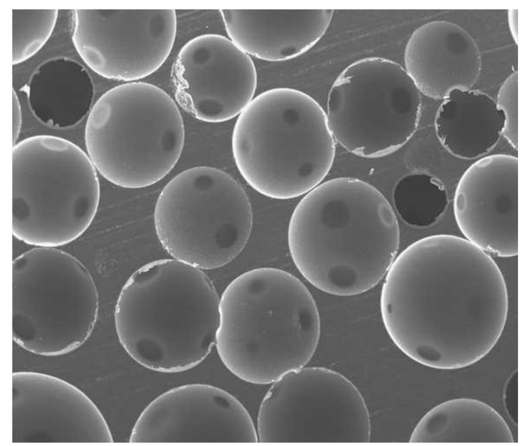


“Wet” Foam
Fresh Beer Foam

Solid Foams

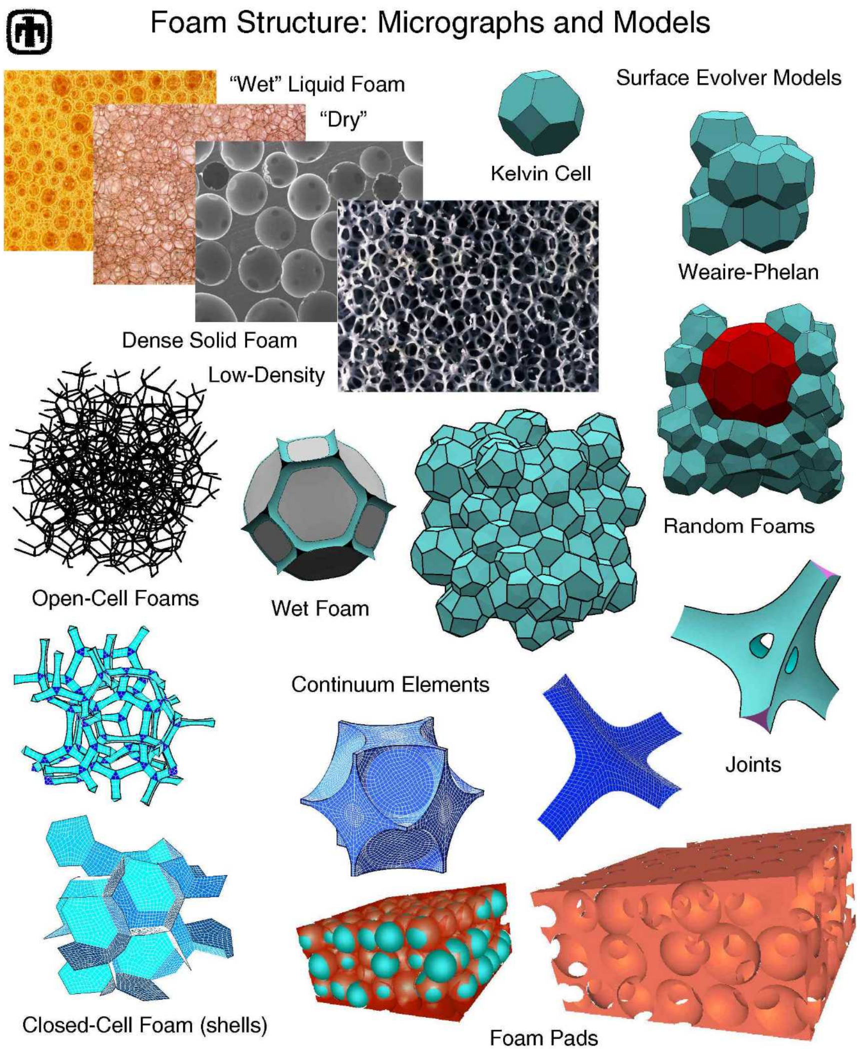


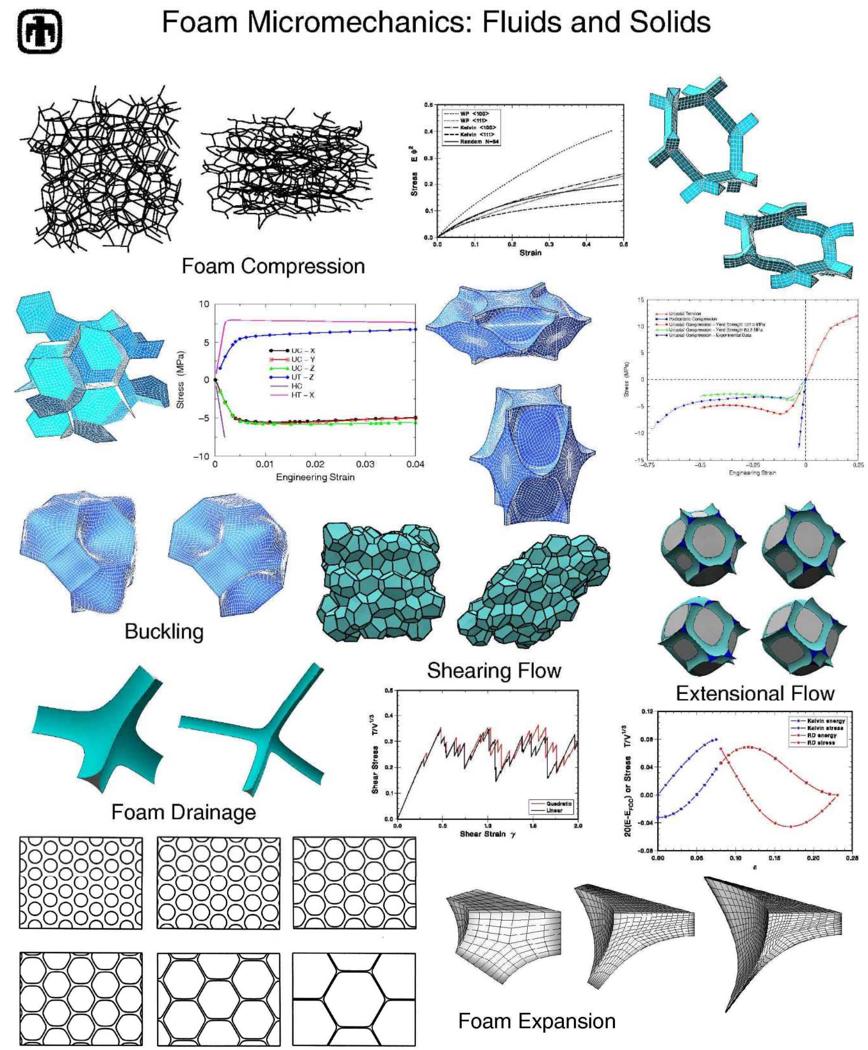
Low-Density Open-Cell Foam
Flexible Polyurethane Foam

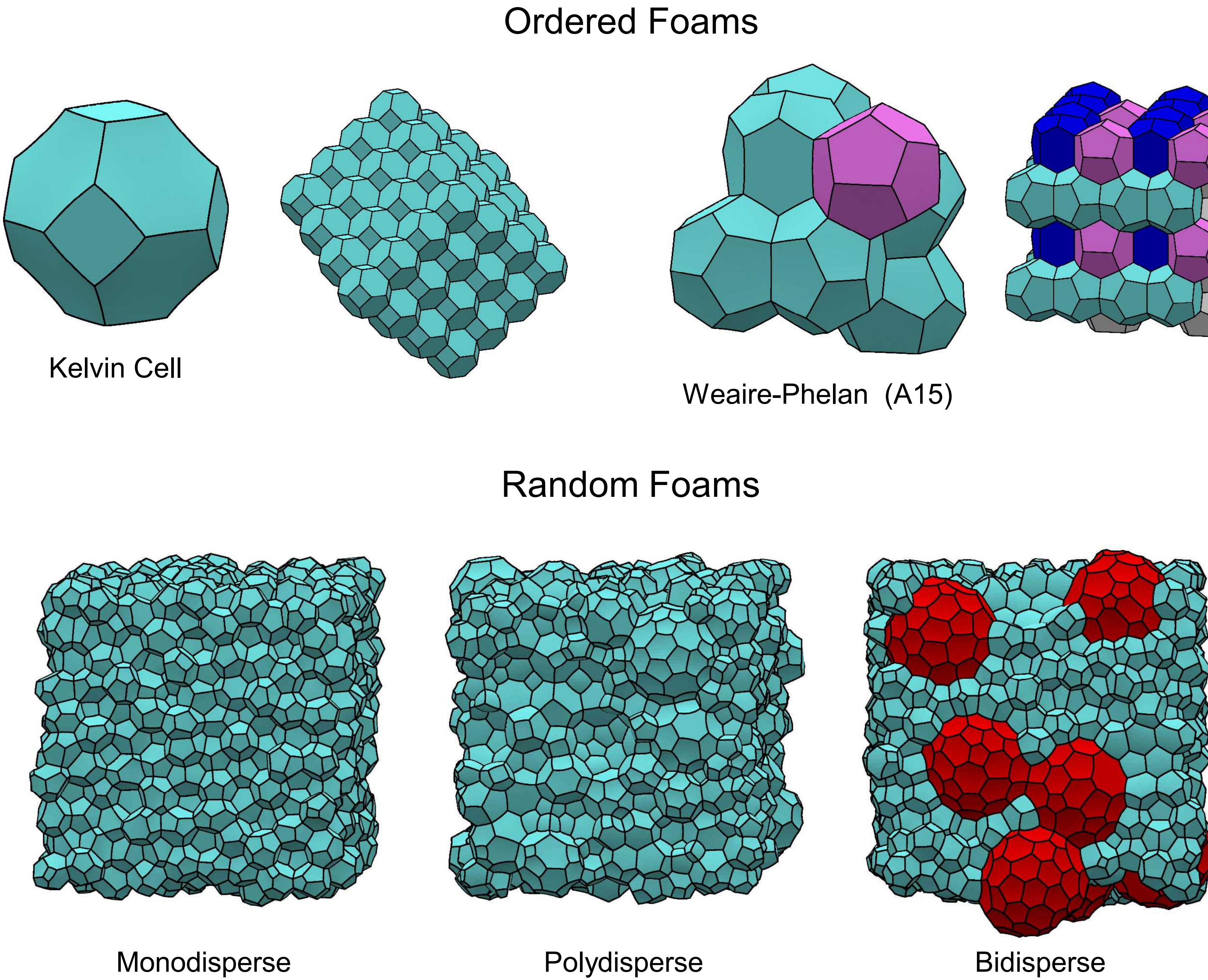


Dense Closed-Cell Foam
Rigid Polyurethane Foam

Predicting structure-property-processing relationships involves the fluid mechanics and solid mechanics of foams

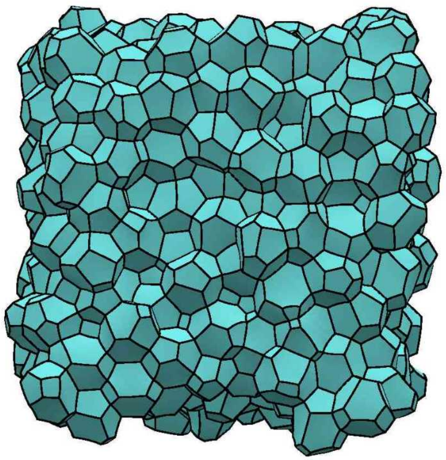




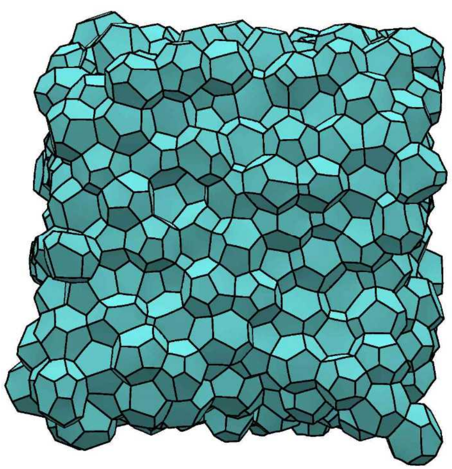

Ordered Foams
Kelvin Cell
Weaire-Phelan (A15)
Random Foams
Monodisperse
Polydisperse
Bidisperse

Cell Shapes in Random Monodisperse Foam

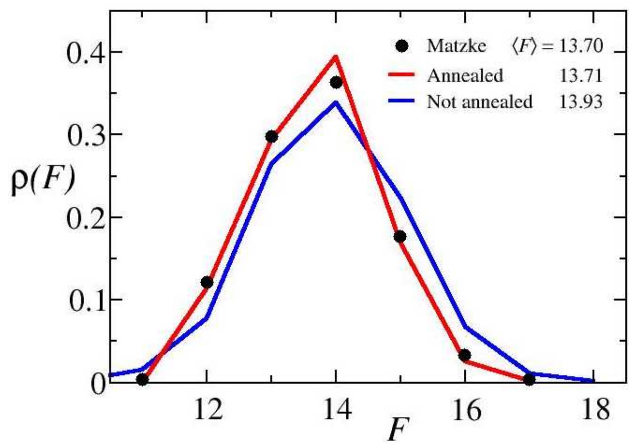
Kraynik, Reinelt & van Swol (2003) *Phys Rev E* **67**, 031403.

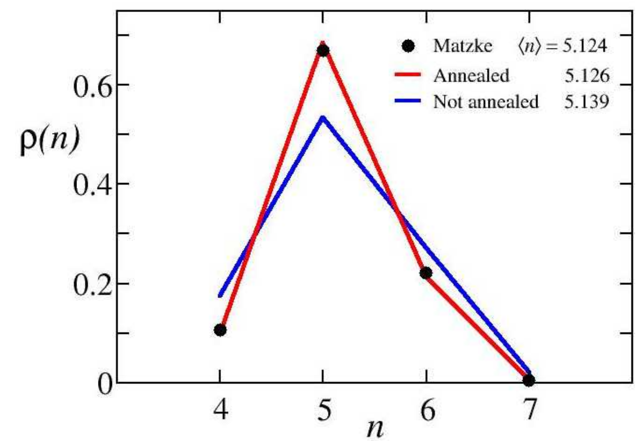


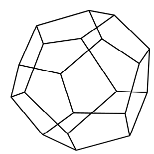
before annealing
E = 5.369



after annealing
E = 5.326







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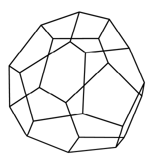

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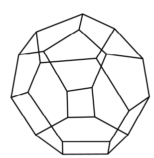
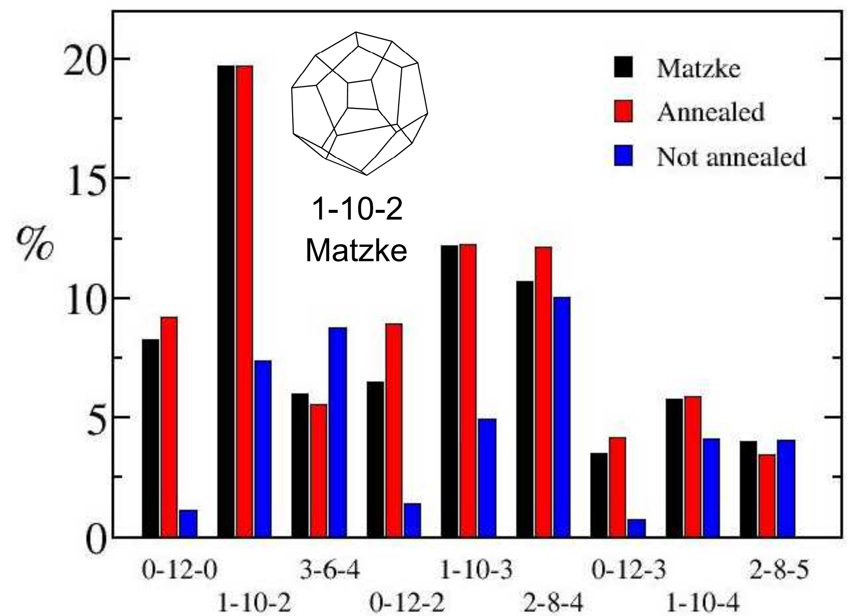


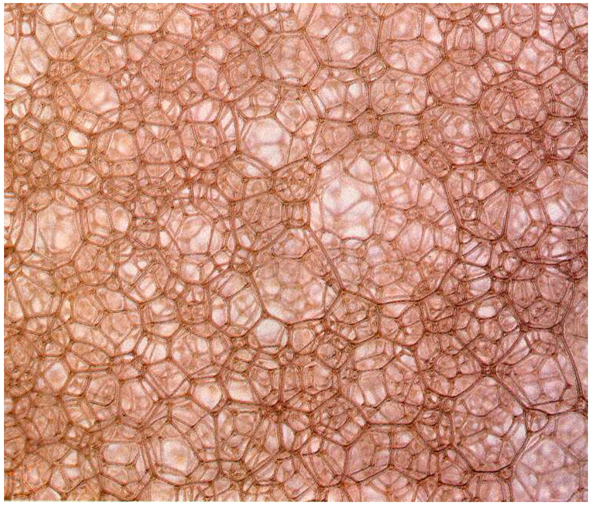
2-8-4

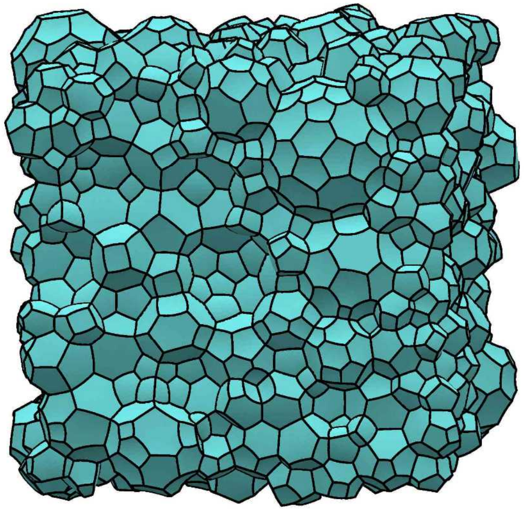


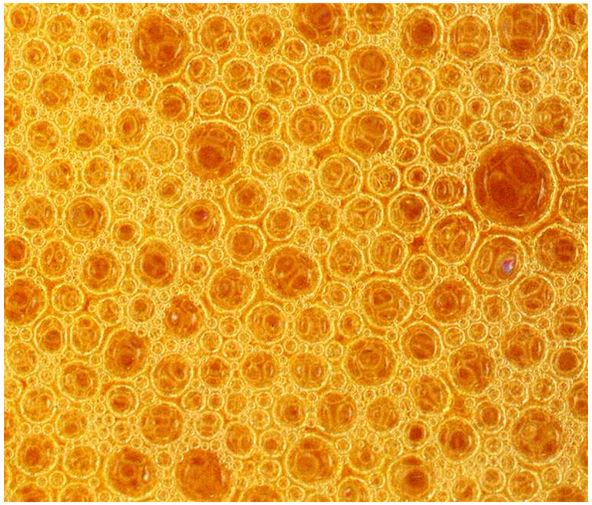
Random Foam Structure

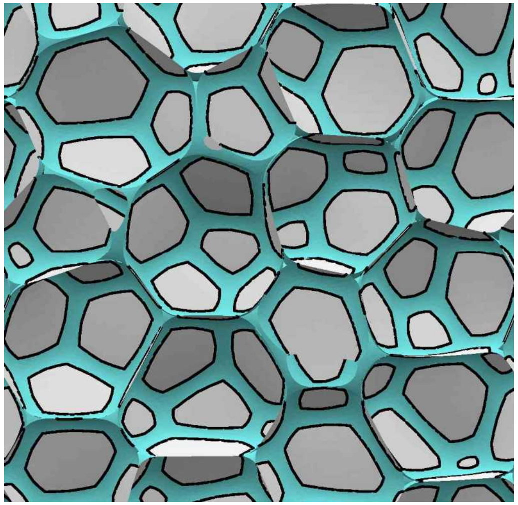
Liquid Foams

Surface Evolver Models

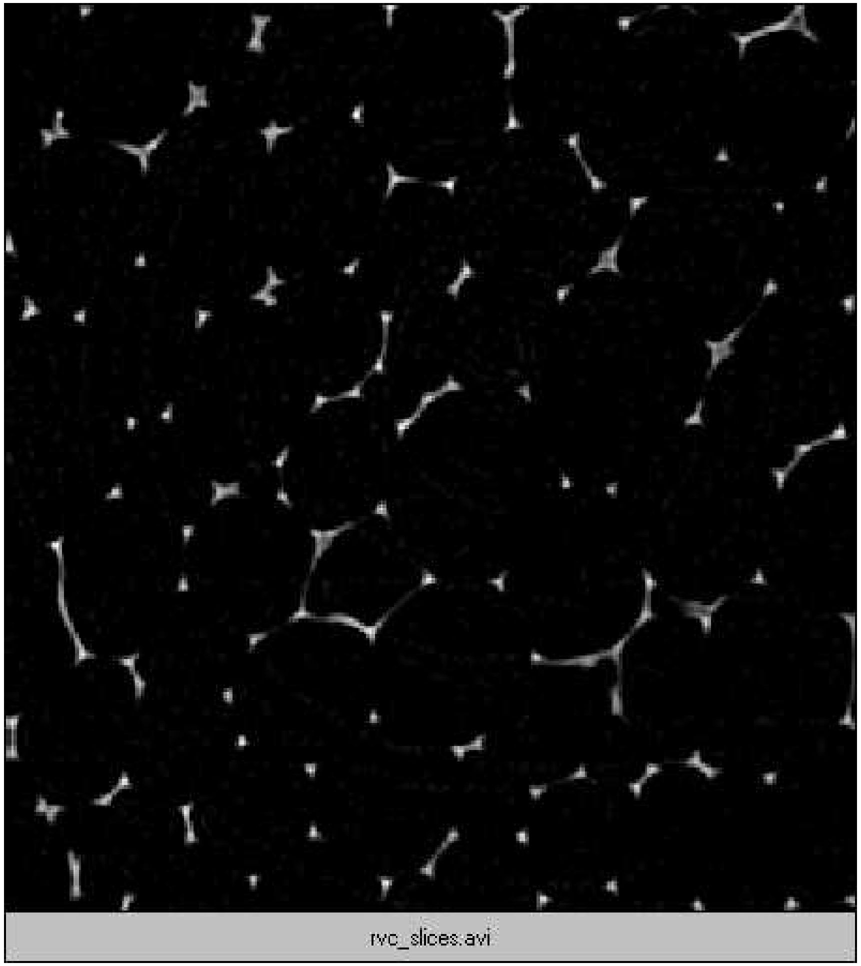


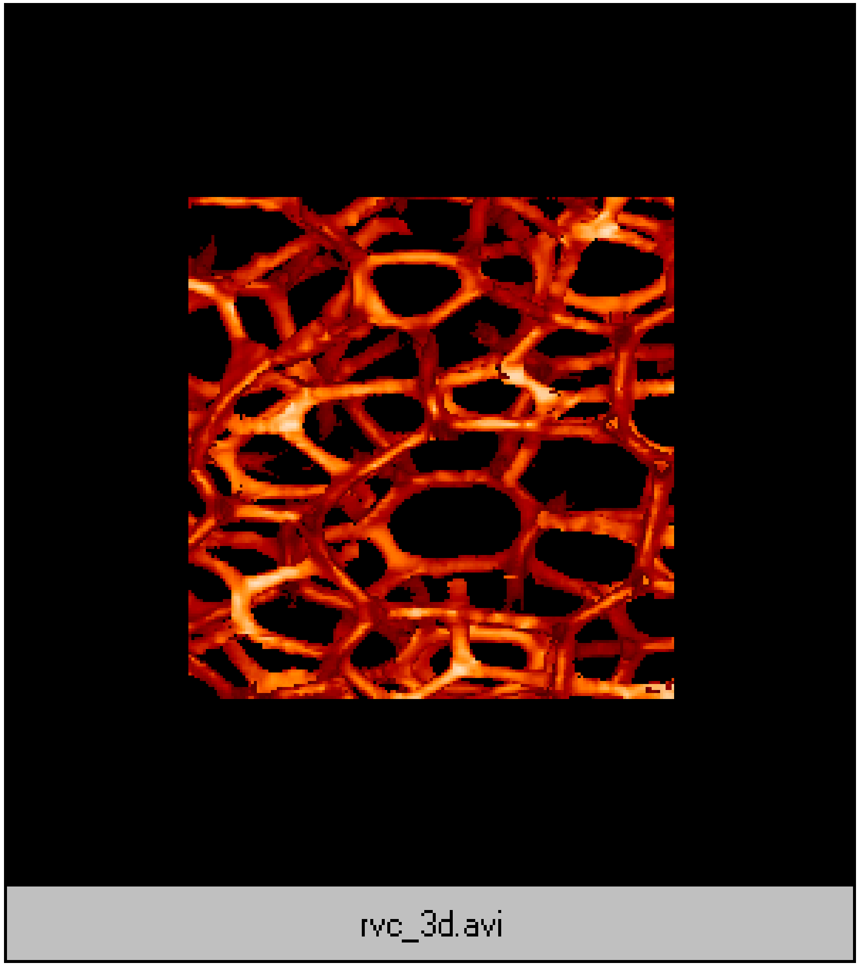






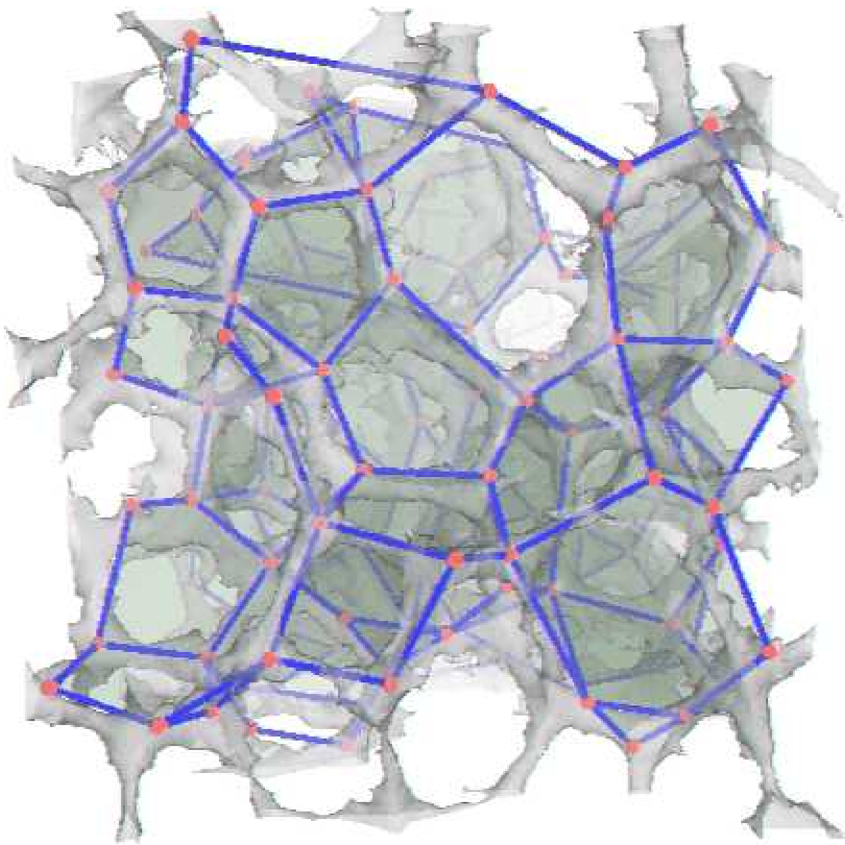
X-ray microtomography of open-cell foams

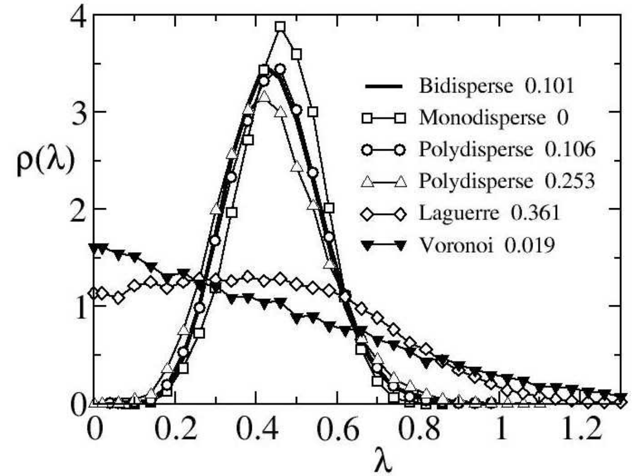


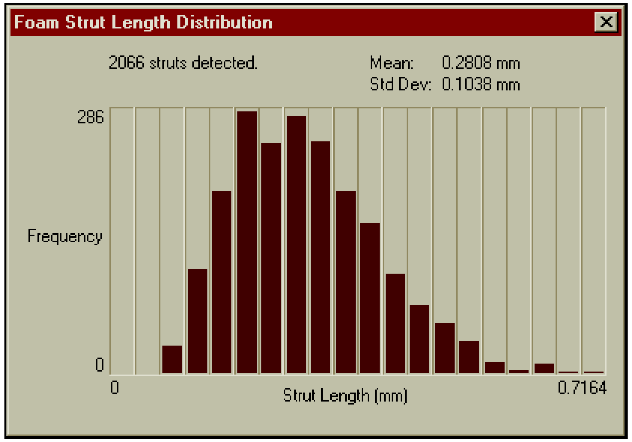


Jerry Seidler, Physics Department, University of Washington

Foam skeleton from image analysis of MRI and XMT data





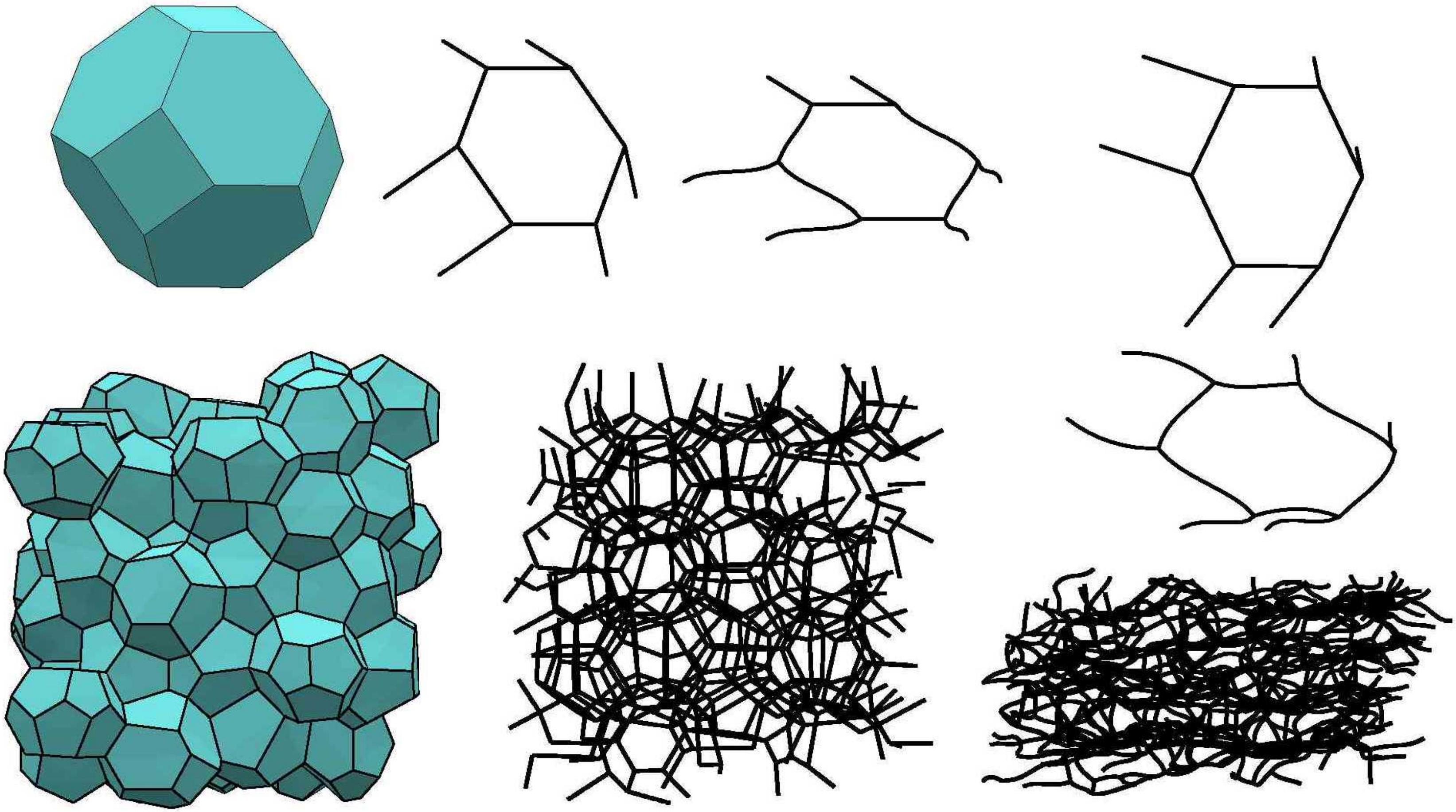


Strut length distribution

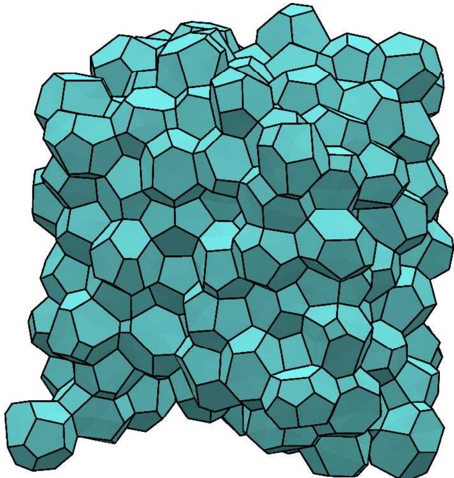
Matt Montminy, PhD thesis, Univ. Minnesota (2001)

M.D. Montminy, A.R. Tannenbaum and C.W. Macosko,
The 3D structure of real polymer foams, *J. Coll. Int. Sci.* **280** 202-211 (2004).

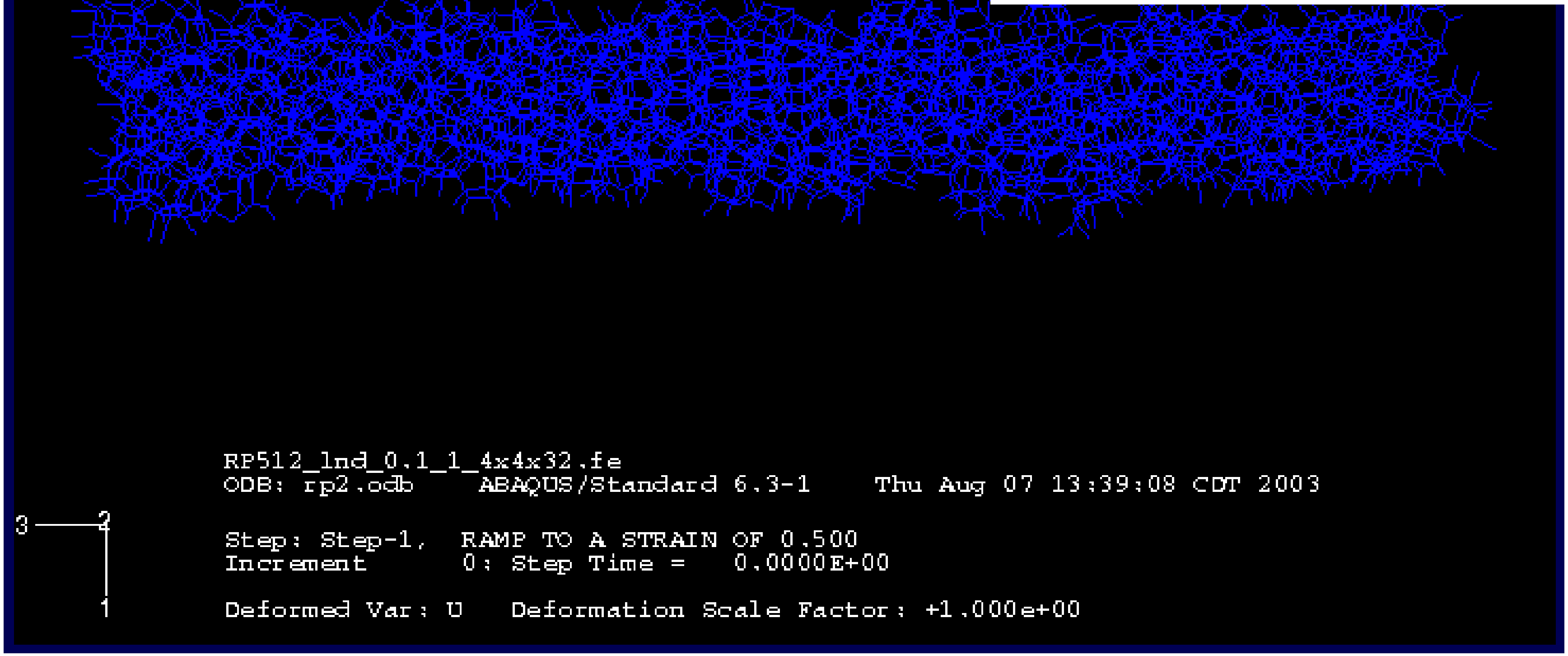
Modeling low-density open-cell foams

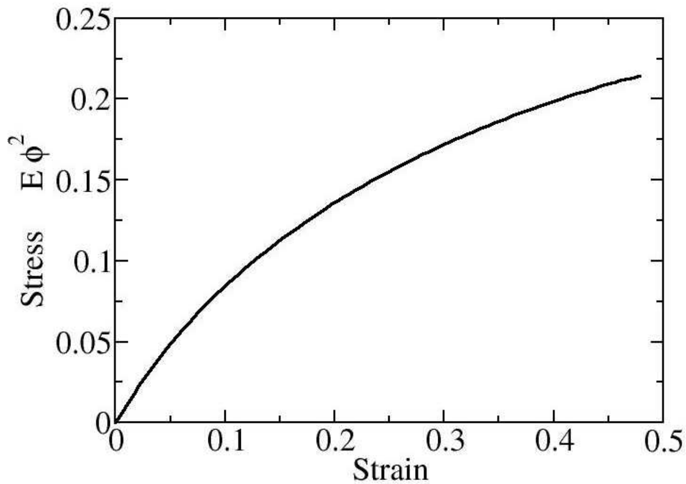


Simulation of Uniaxial Compression

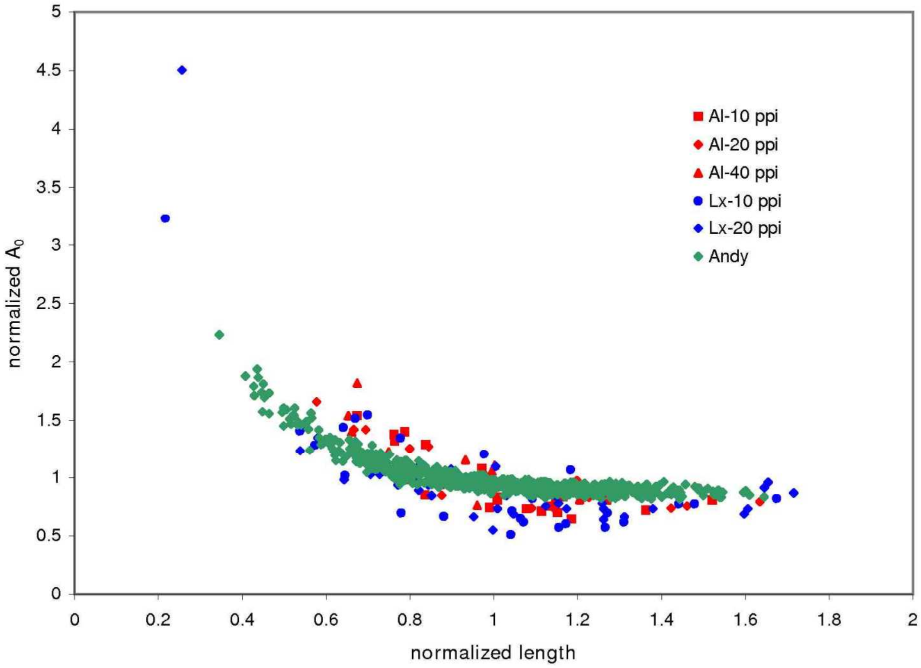


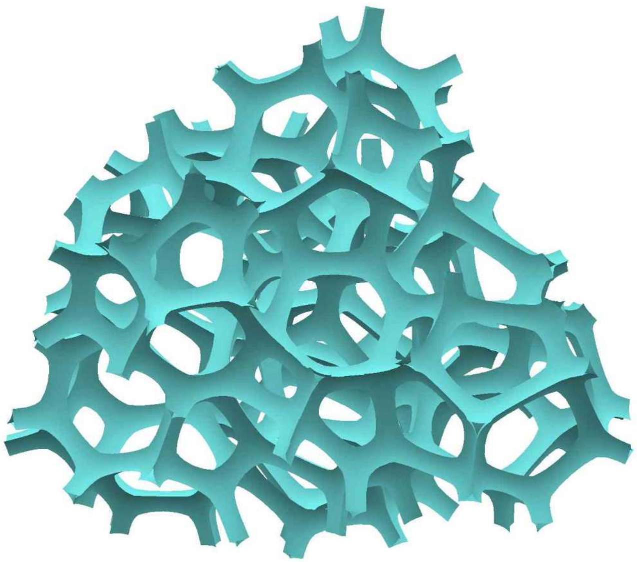
Animation by Mike Neilsen





Material Distribution in Struts

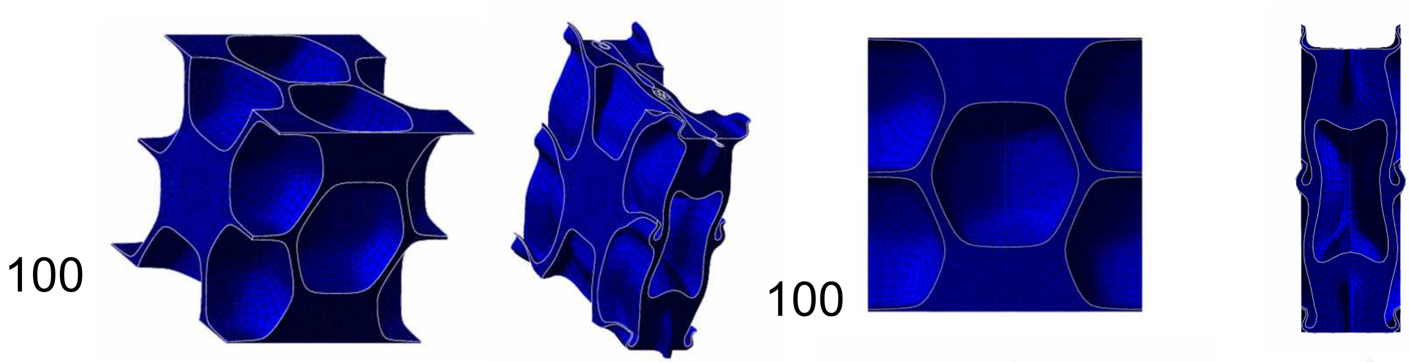


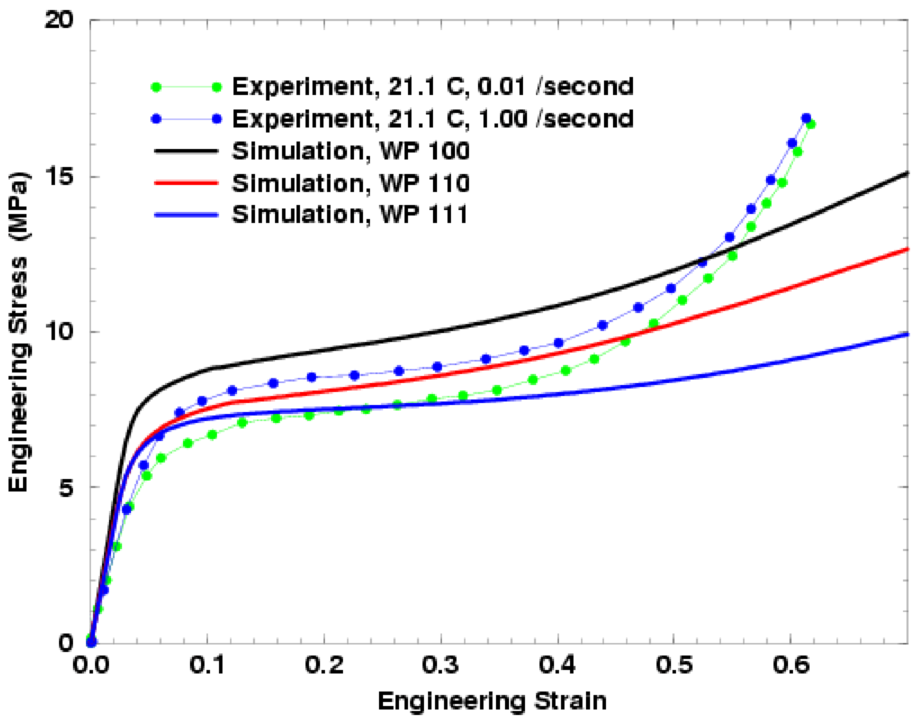


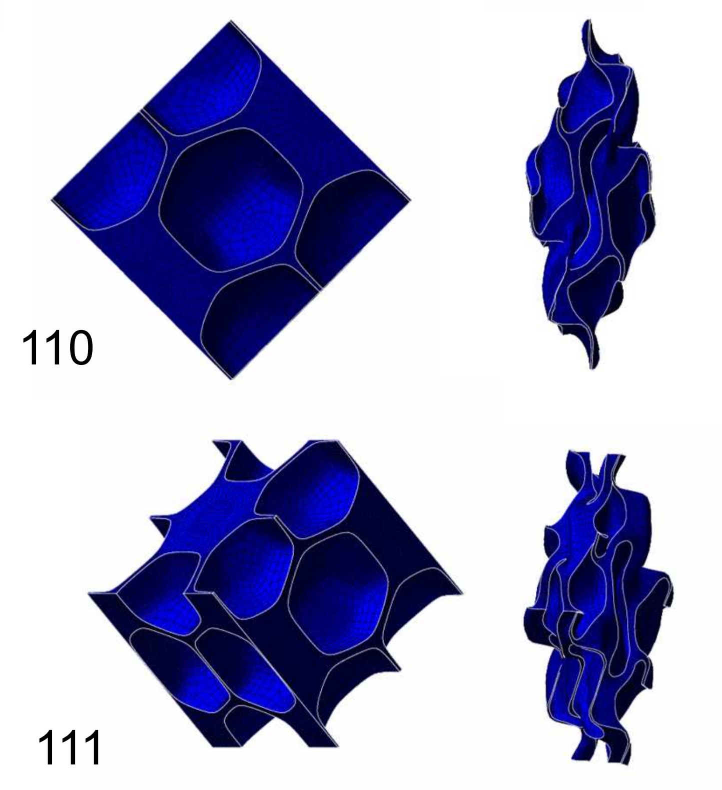
Kyriakides and Jang, UT, Austin

Uniaxial Compression of a Closed-Cell Weaire-Phelan Foam

E_s = 1600 MPa
ν_s = 0.40
σ_y = 50 MPa

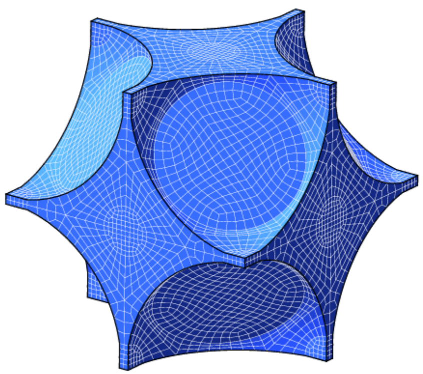


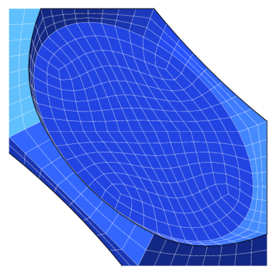


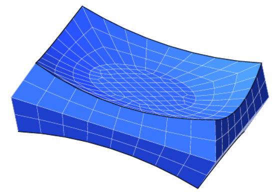


Microstructure of Closed-Cell Kelvin Foam

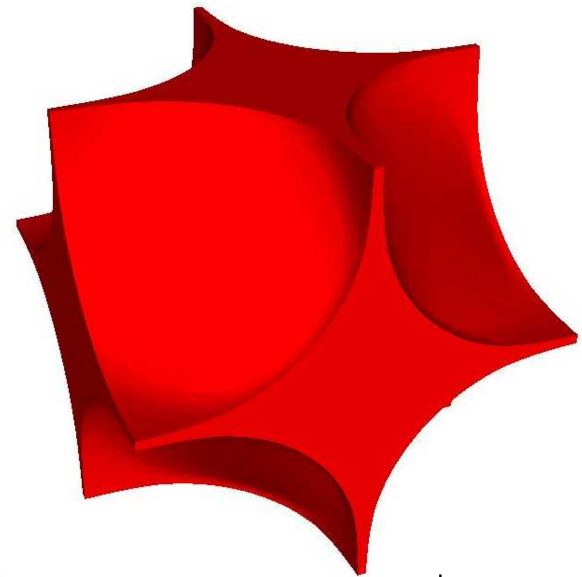
Simple model based on flat plates and spherical cavities





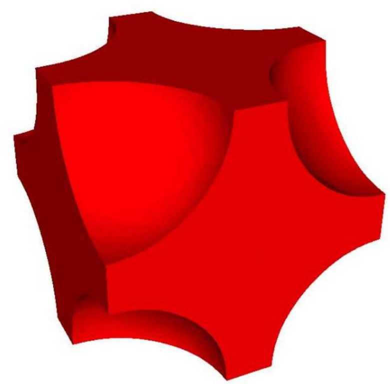


Mike Neilsen

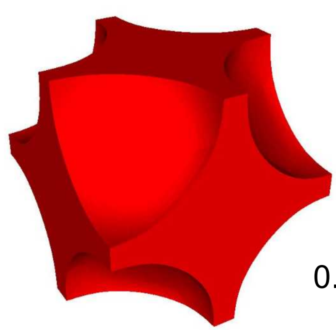


ϕ = 0.075

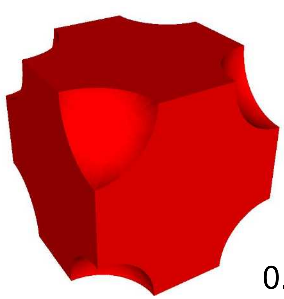
Use GOMA to model foam evolution by simulating bubble growth in viscous fluids.



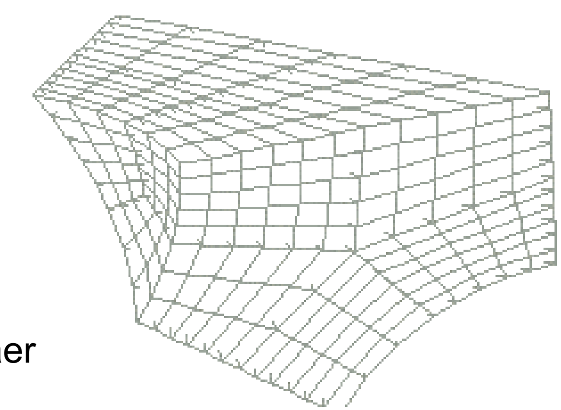
0.284



0.449

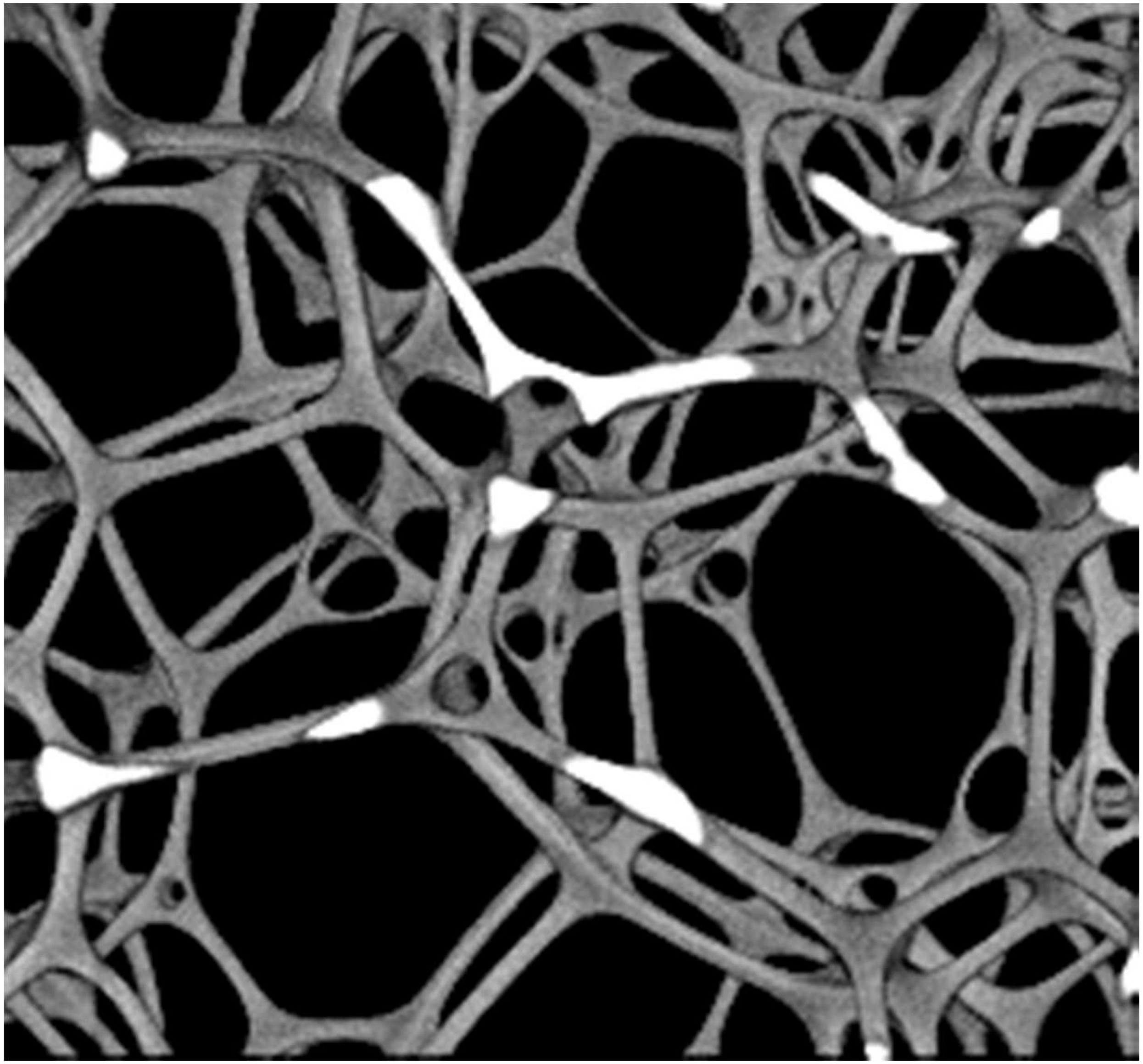


0.748



Animation by Tom Baer

Confocal microscopy of Plateau borders in emulsions

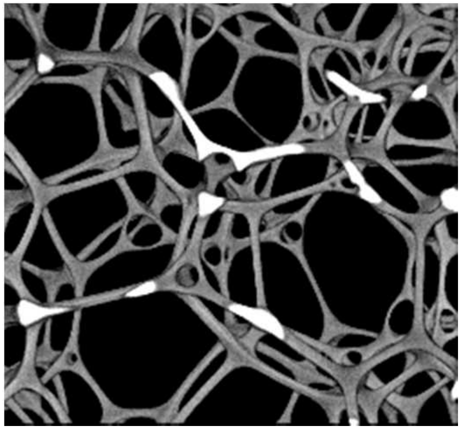


Eric Weeks, Physics, Emory University and Doug Wise, Physics, Harvard University

Surface Evolver Simulations of Wet Foams with 8% liquid

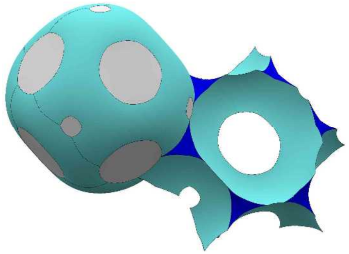
Sandia National Laboratories

Andy Kraynik
amkrayn@sandia.gov

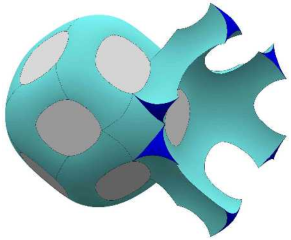


Confocal microscopy of Plateau borders in an emulsion

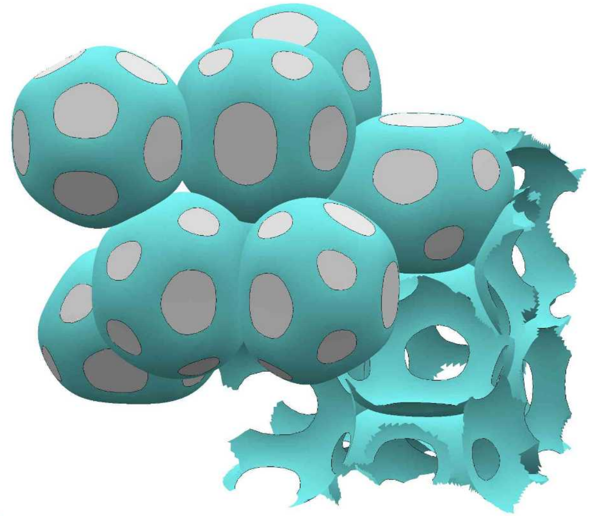
Eric Weeks (Emory), Doug Wise (Harvard)



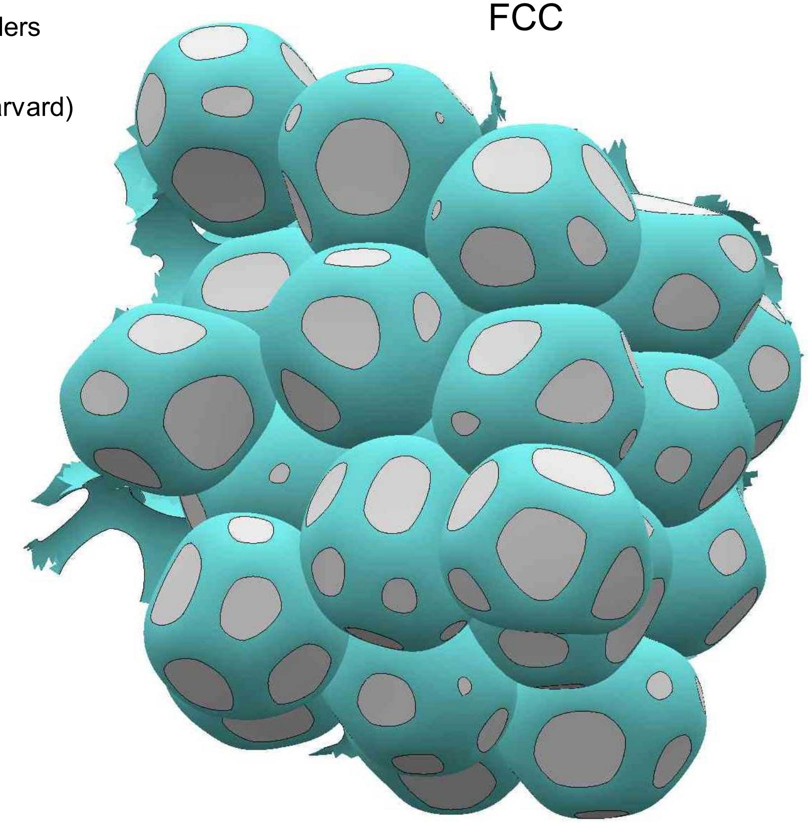
Kelvin



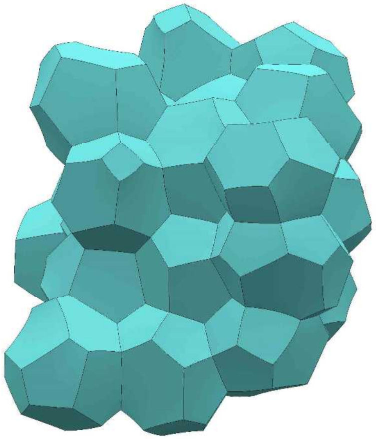
FCC



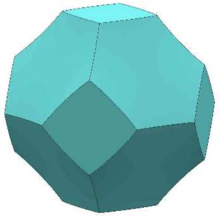
Weaire-Phelan



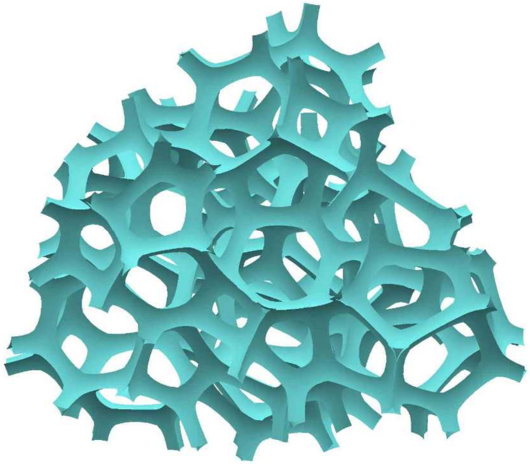
Random foam with 27 bubbles



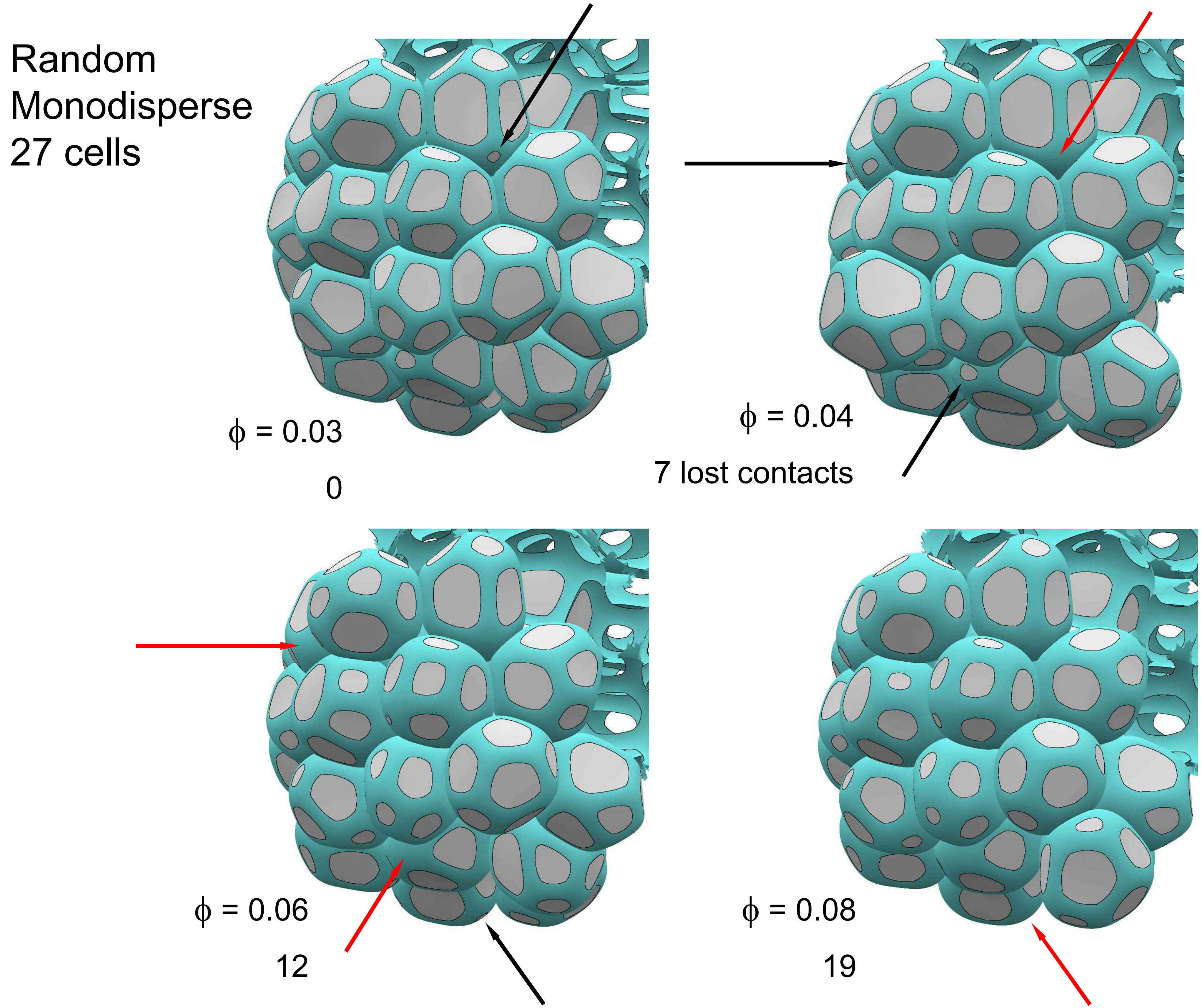
“Dry” Random foam with 27 cells



“Dry” Kelvin

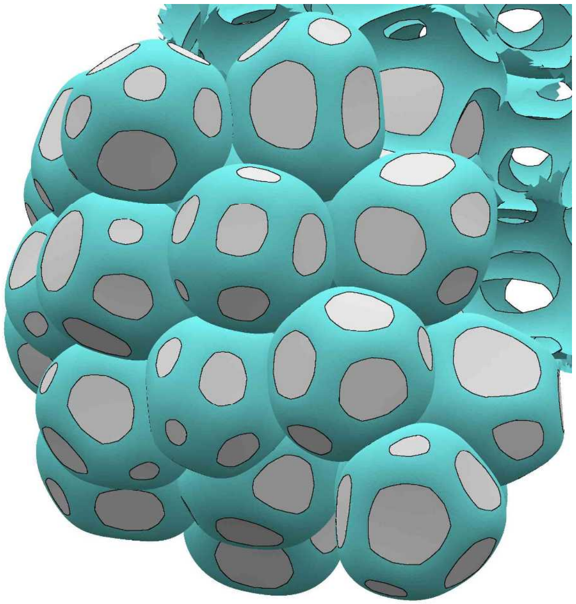


Plateau borders

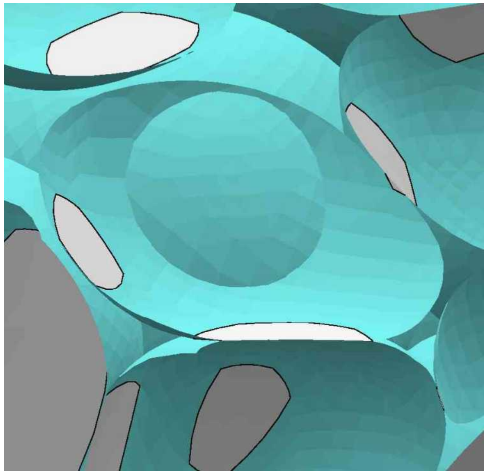


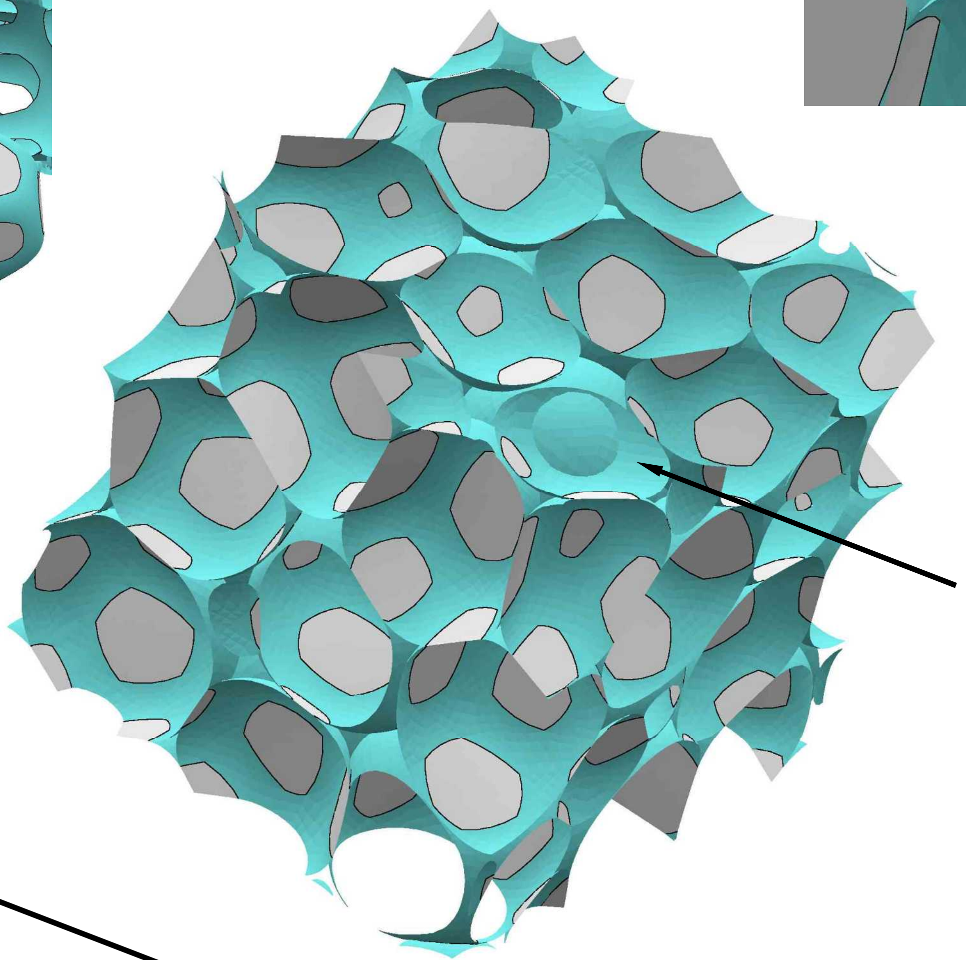
Random
Monodisperse
27 cells
ϕ = 0.03
0
ϕ = 0.04
7 lost contacts
ϕ = 0.06
12
ϕ = 0.08
19

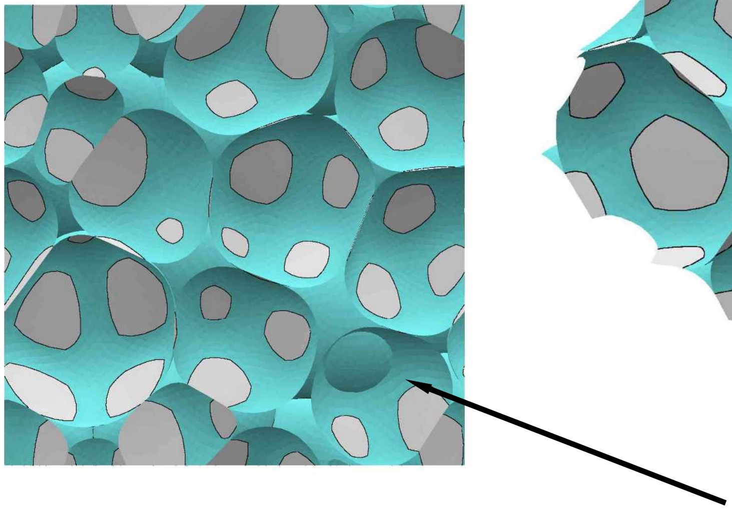
Bubble Overlap



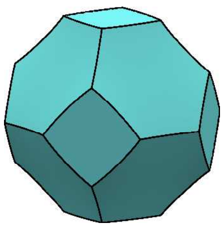
ϕ = 0.08   19 lost contacts

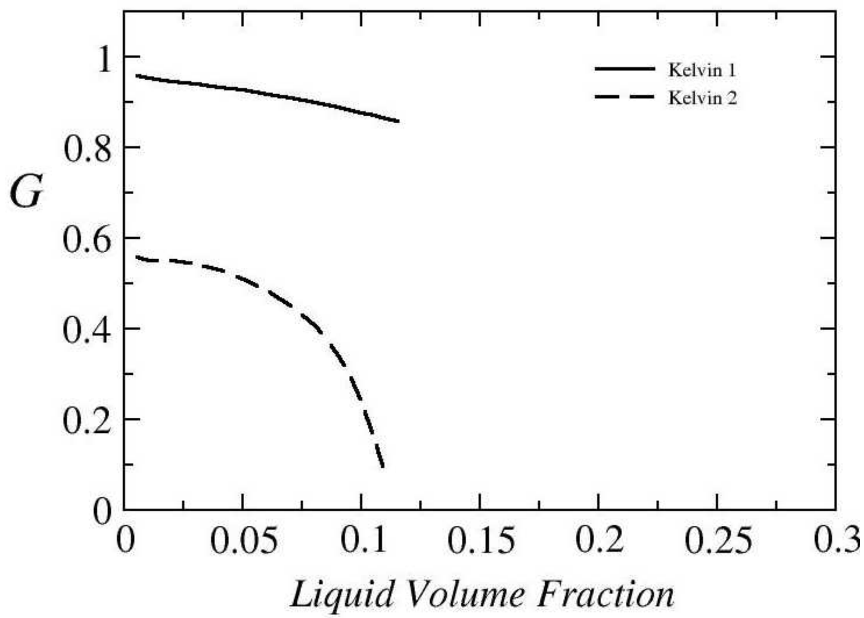


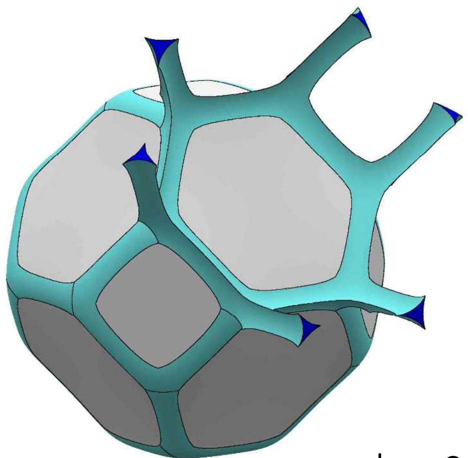




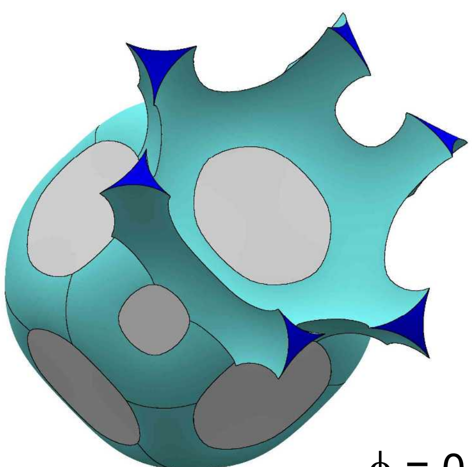
Wet Kelvin Foam
BCC



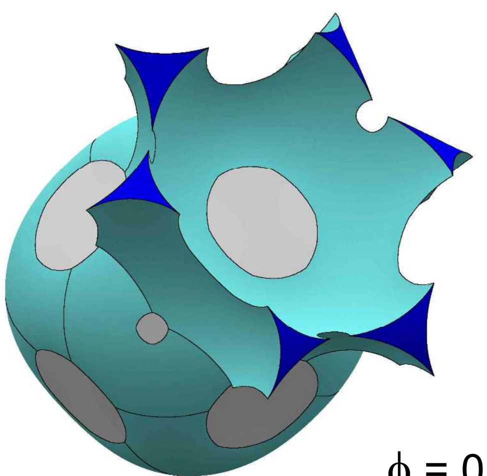




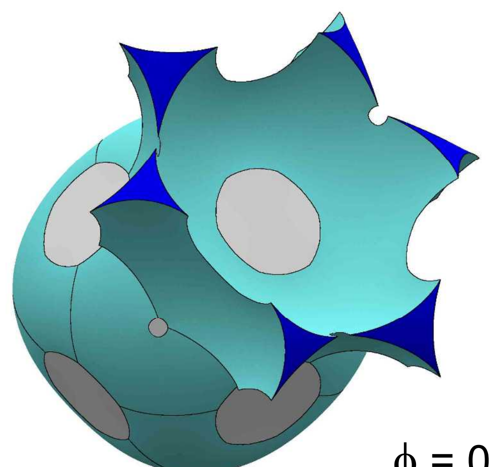
$\phi = 0.01$



$\phi = 0.05$

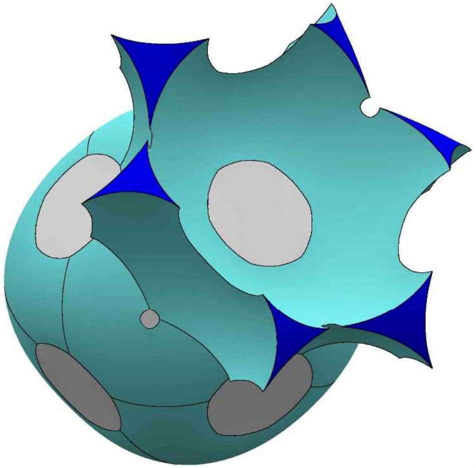


$\phi = 0.1$

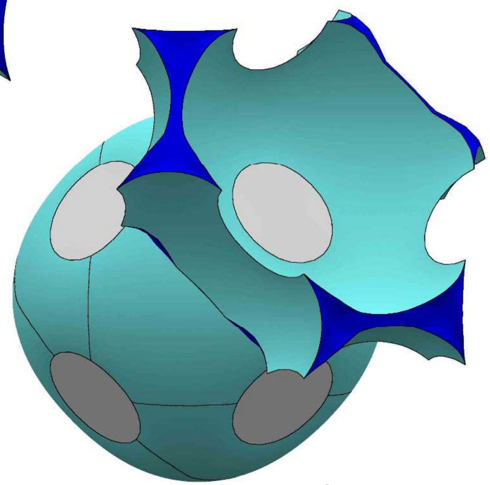


$\phi = 0.115$

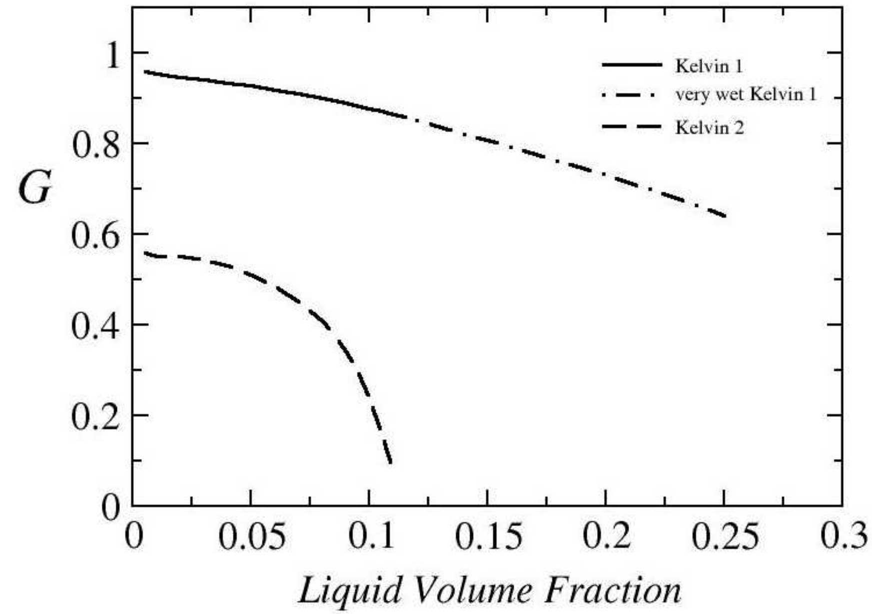
Very Wet Kelvin Foam

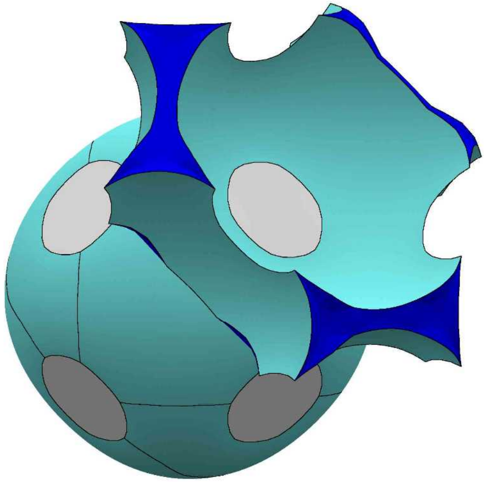


$\phi = 0.115$

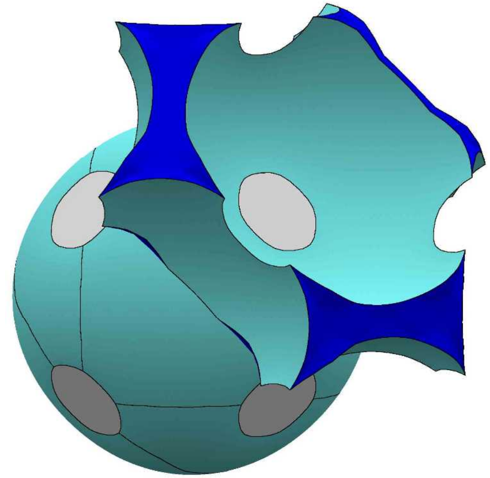


$\phi = 0.12$

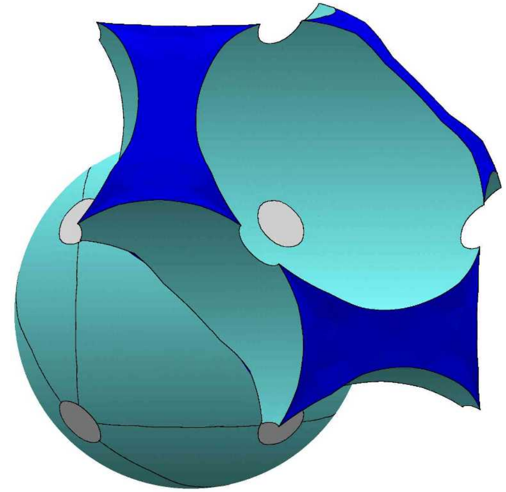




$\phi = 0.15$

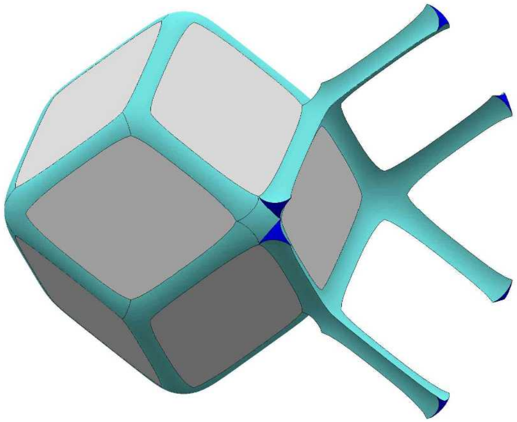


$\phi = 0.2$

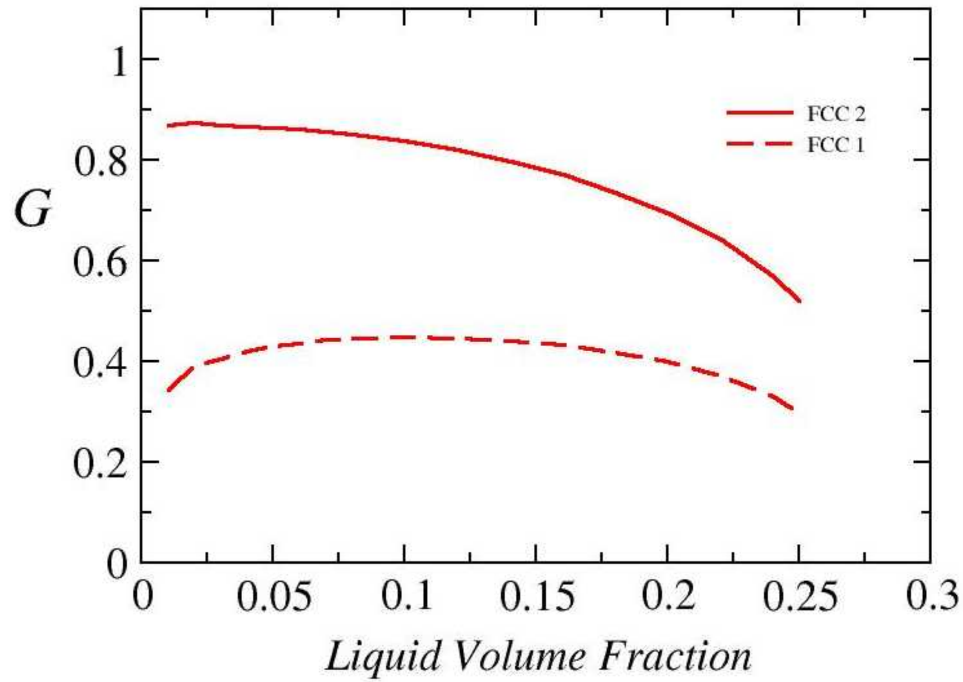


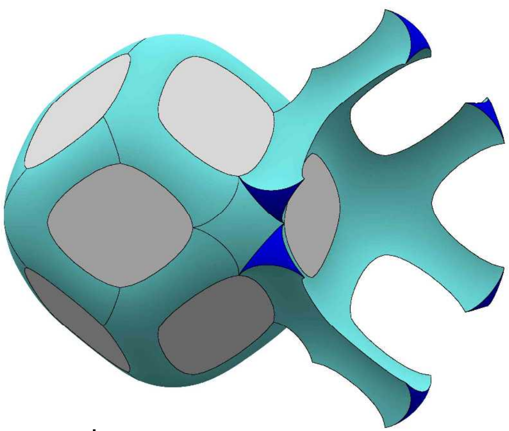
$\phi = 0.3$

Wet Rhombic Dodecahedra
FCC

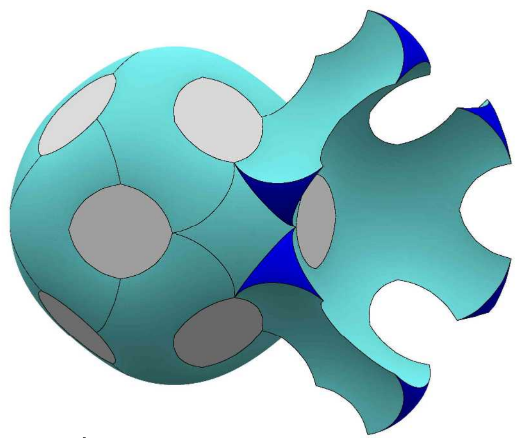


$\phi = 0.01$

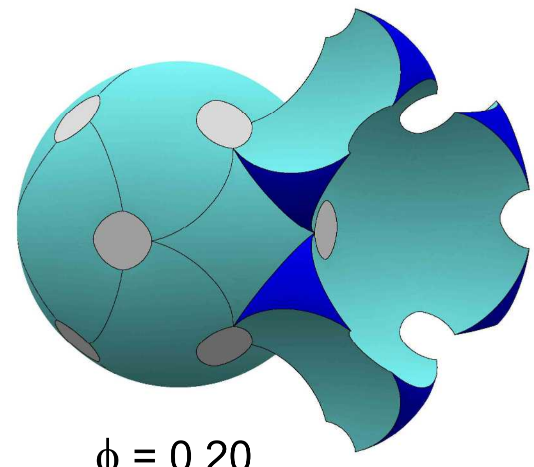




$\phi = 0.05$

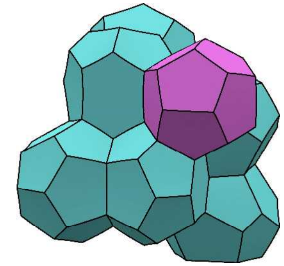


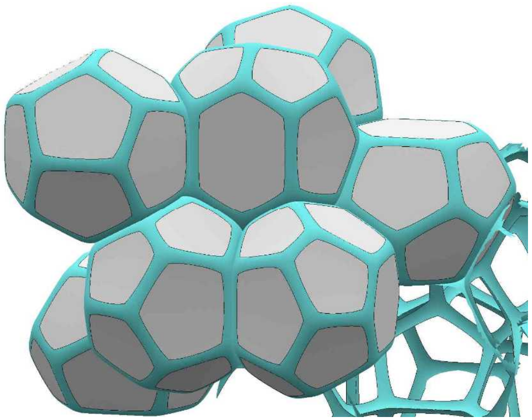
$\phi = 0.1$

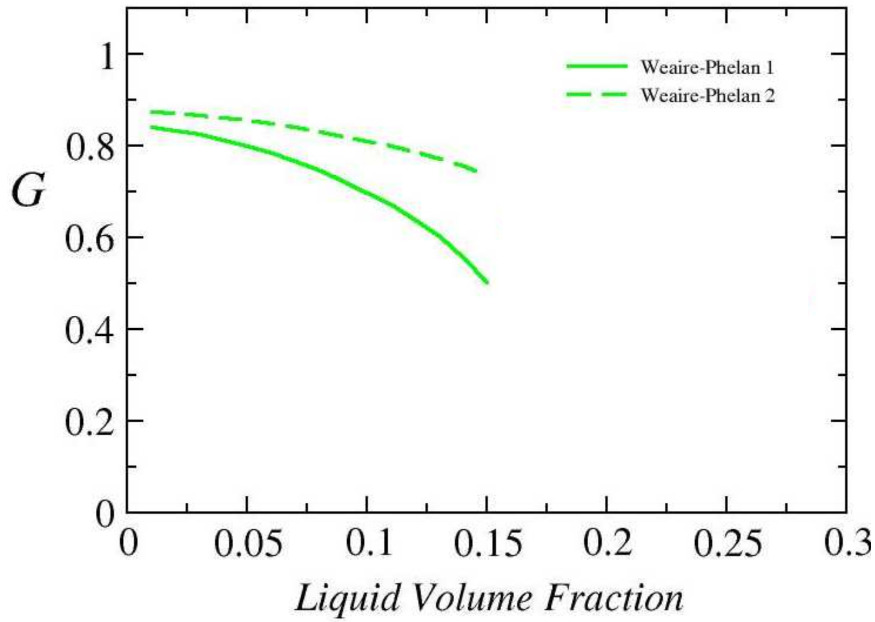


$\phi = 0.20$

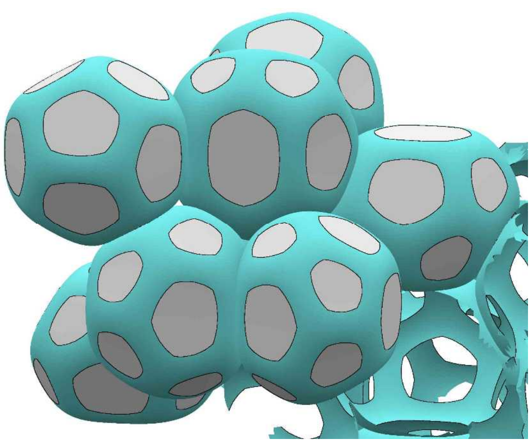
Wet Weaire-Phelan



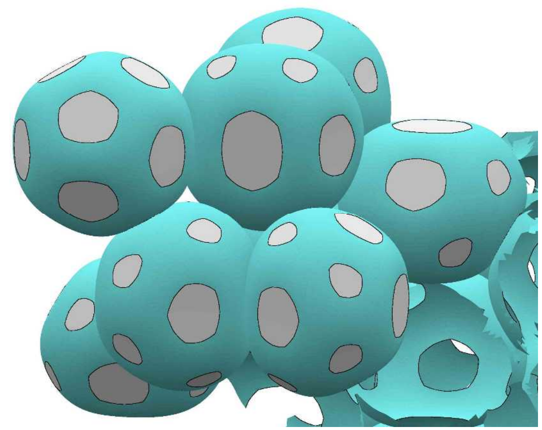




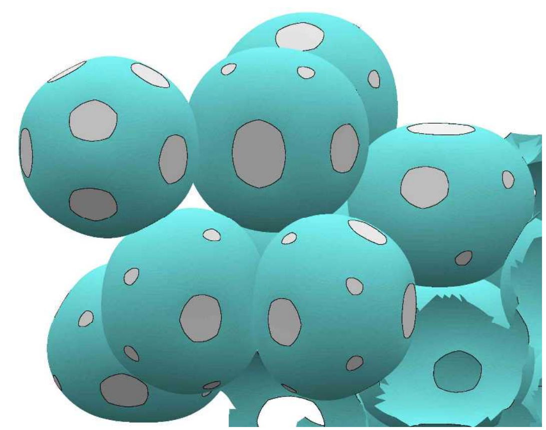
ϕ = 0.01



ϕ = 0.05

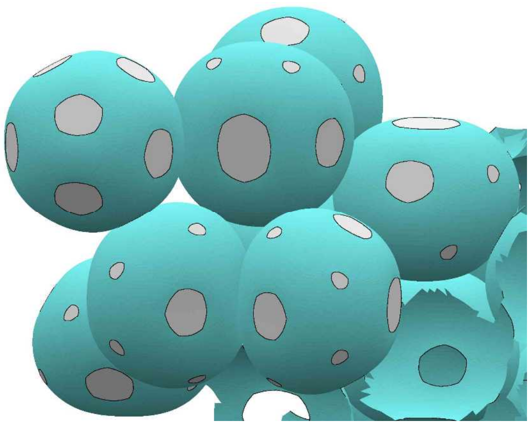


ϕ = 0.1

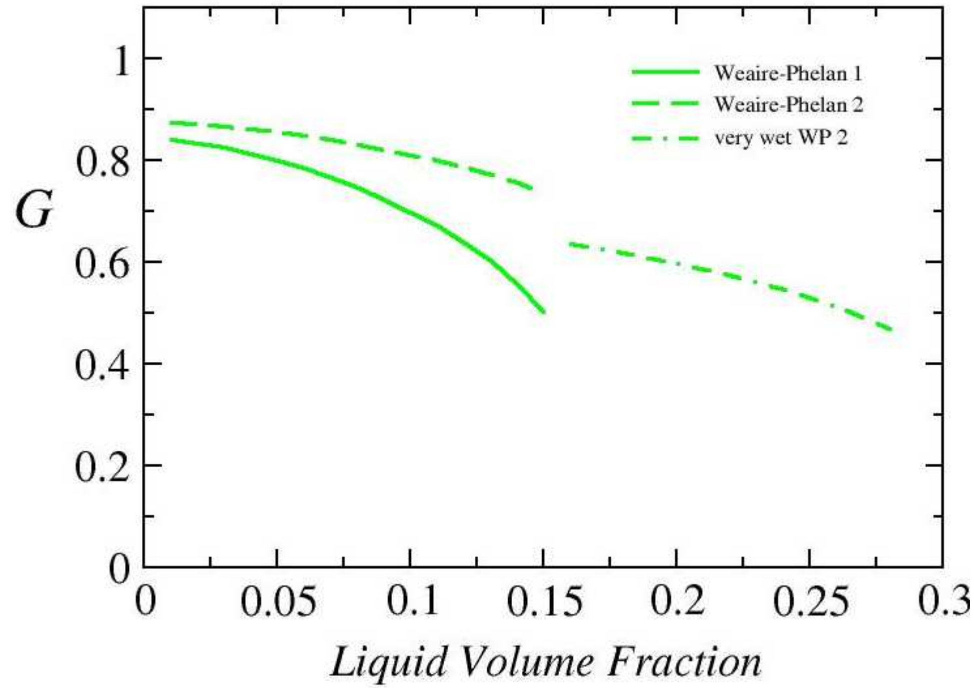


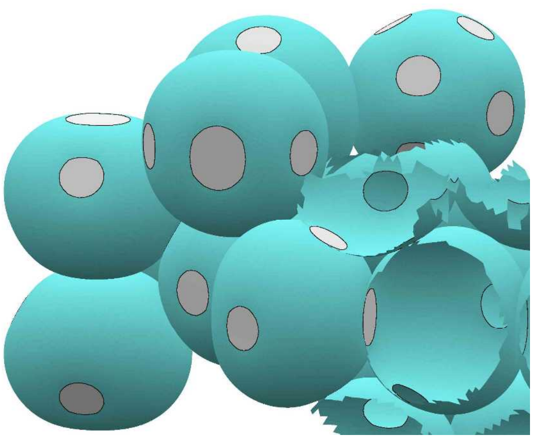
ϕ = 0.15

Very Wet Weaire-Phelan

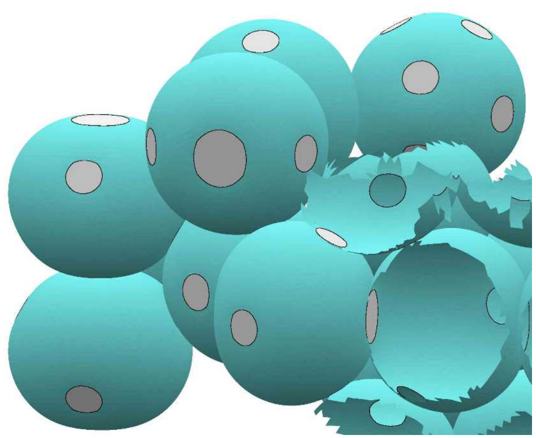


$\phi = 0.15$

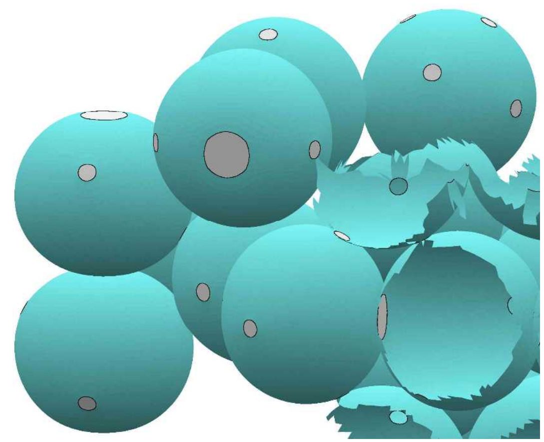




$\phi = 0.16$



$\phi = 0.2$



$\phi = 0.3$

Overview

Foams are ubiquitous materials but the connection between the macroscopic behavior and cell-level microstructure is poorly understood.

Accurate structure-property-processing relationships and constitutive models are needed to develop foams and predict response.

Complementary experiments and theoretical studies are needed to accomplish this goal.

Micromechanical analysis is used to predict the connection between foam structure and behavior.