Imperial College London

UNDERSTANDING FROTH BEHAVIOUR WITH CFD

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Outline

- Froths and Foams
- Modelling of Flotation Froths
- 3 Case Studies
- Problems remaining

Froths and Foams

- Widely used
  – Food and drink
  – Personal products
  – Cleaning
  – Fire-fighting

- Biggest application is mineral separation:

  FROTH FLOTATION

MINING and MILLING before FLOTATION

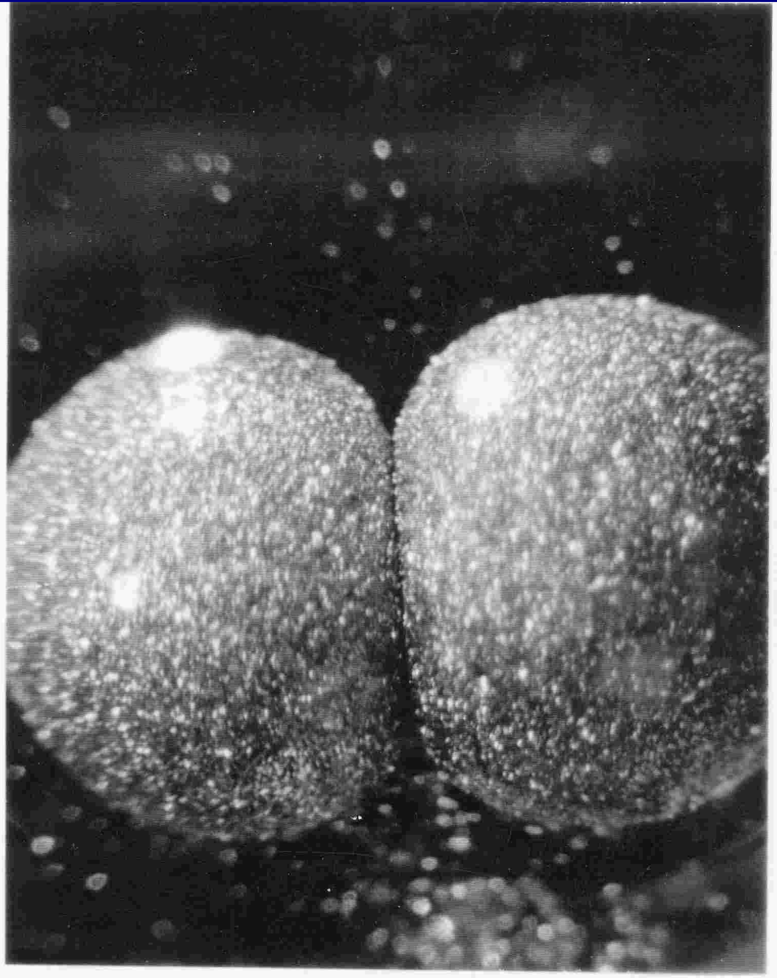
Mineral Separation using Froth Flotation

Conceptually simple:

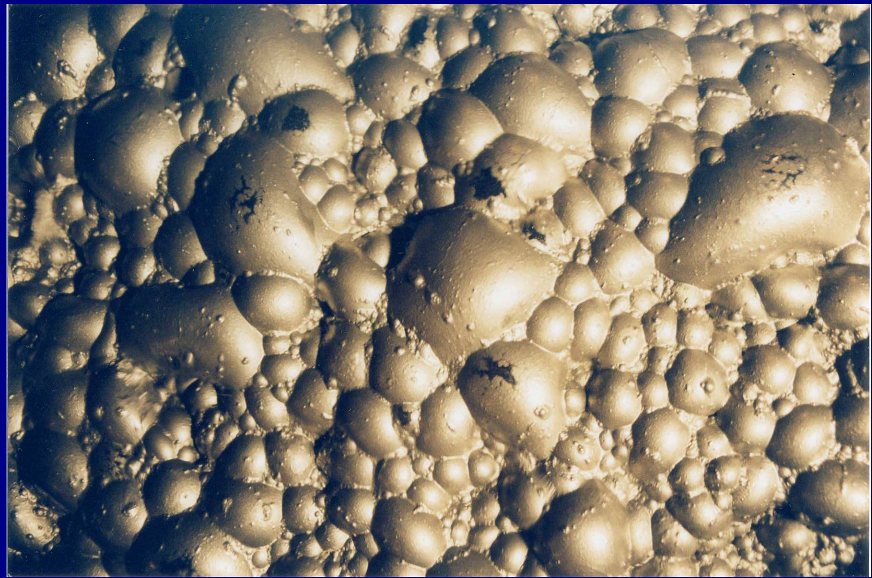
- Make the valuable mineral hydrophobic using surface chemistry, and add air bubbles
- Hydrophobic particles stick to the bubbles, and float to the surface.
- An overflowing froth is formed that holds the valuable particles
- The waste stays in the liquid and is disposed.

Chemically and physically complex.

The particles and the bubbles



Bubble coalescence
x 20



Flotation cells – bigger & bigger

Froth flow management:

launder layout
sloped walls
air rate
froth depth
washing

…. CFD model

Building a CFD froth model
What do we know about froth?

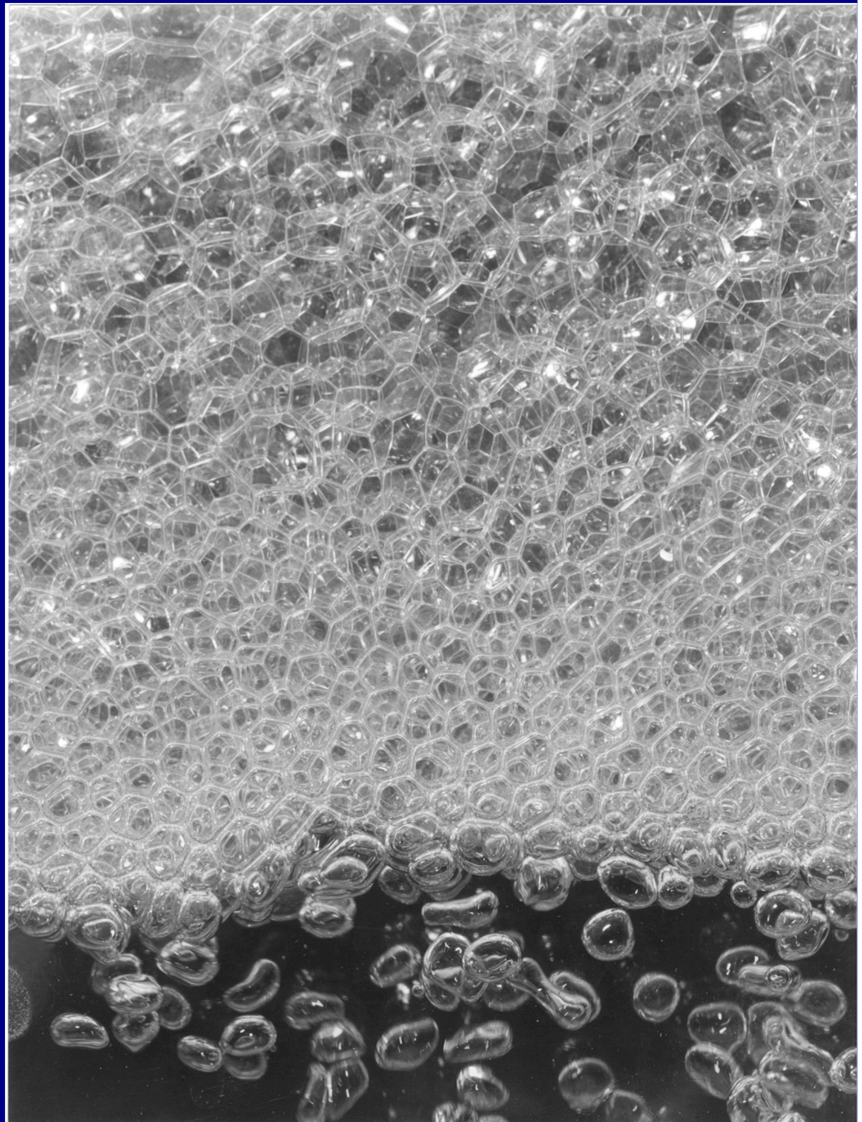
- Continuous, steady-state flowing system

- Bubbles move up & coalesce.
- Some overflow, some burst

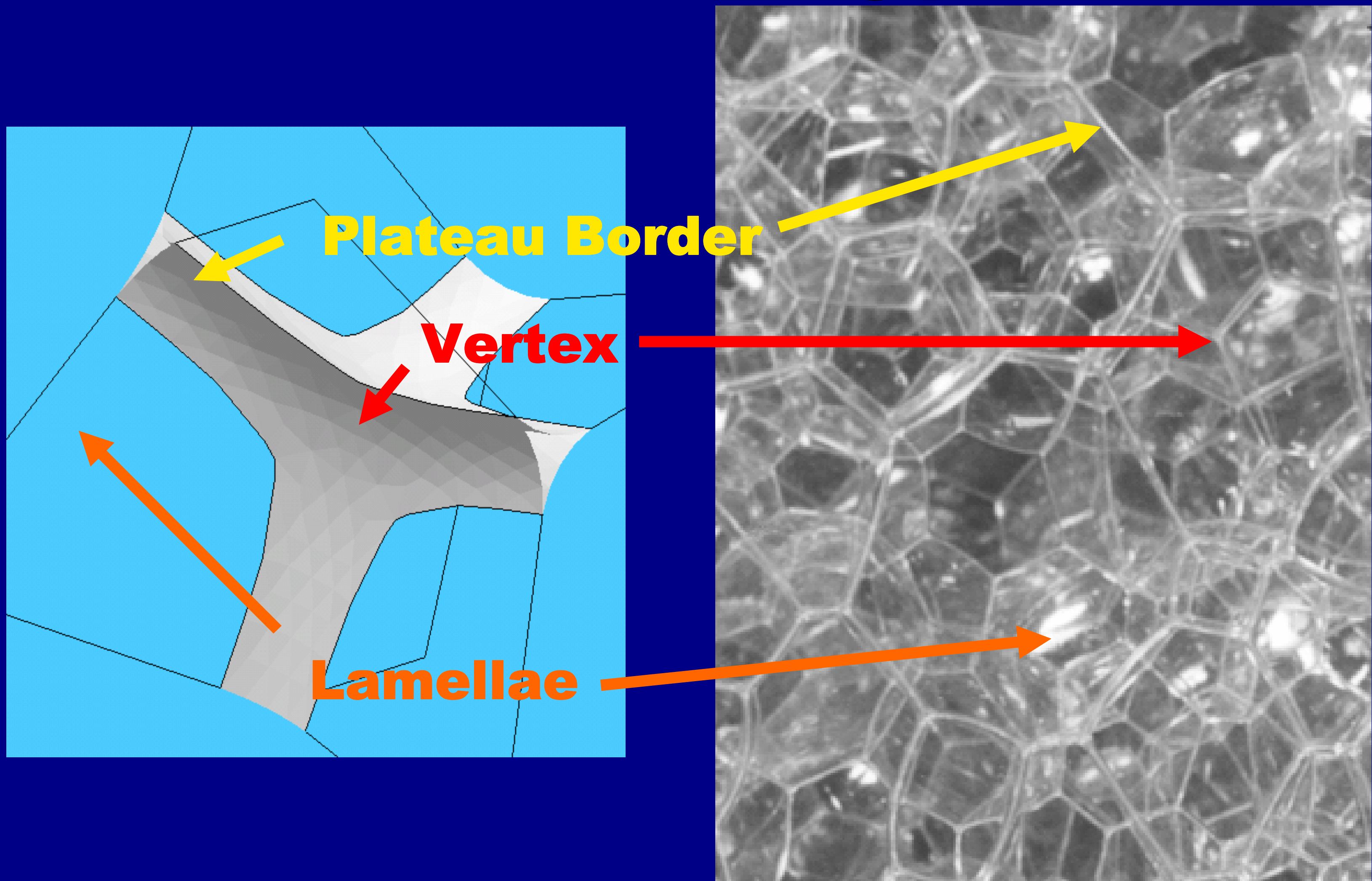
- Liquid content decreases upwards due to drainage

- Solids on bubble films and in liquid between bubbles

WELL-DEFINED STRUCTURE, DEFINED BY PHYSICS



Froth Structure and Terminology



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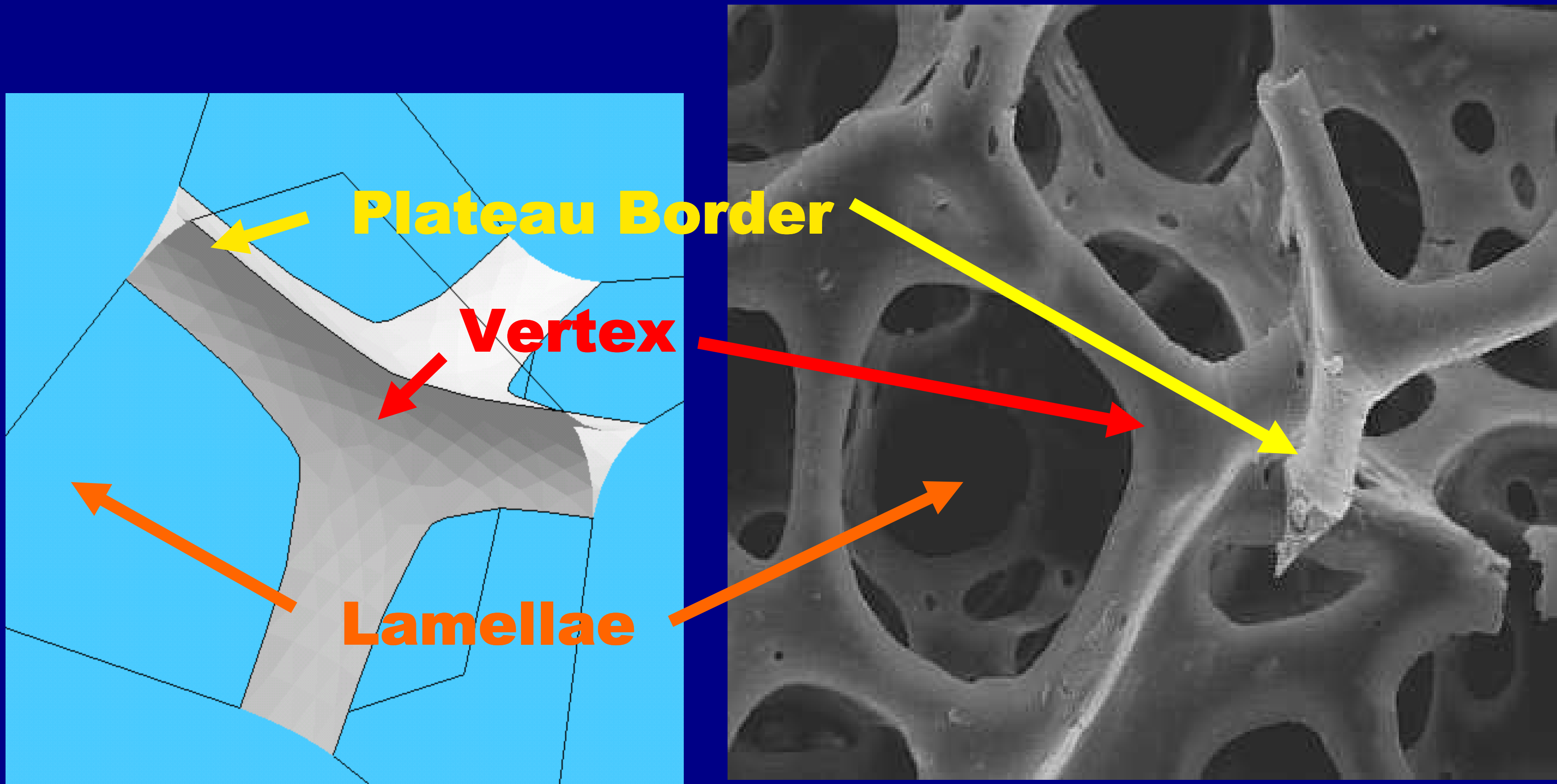
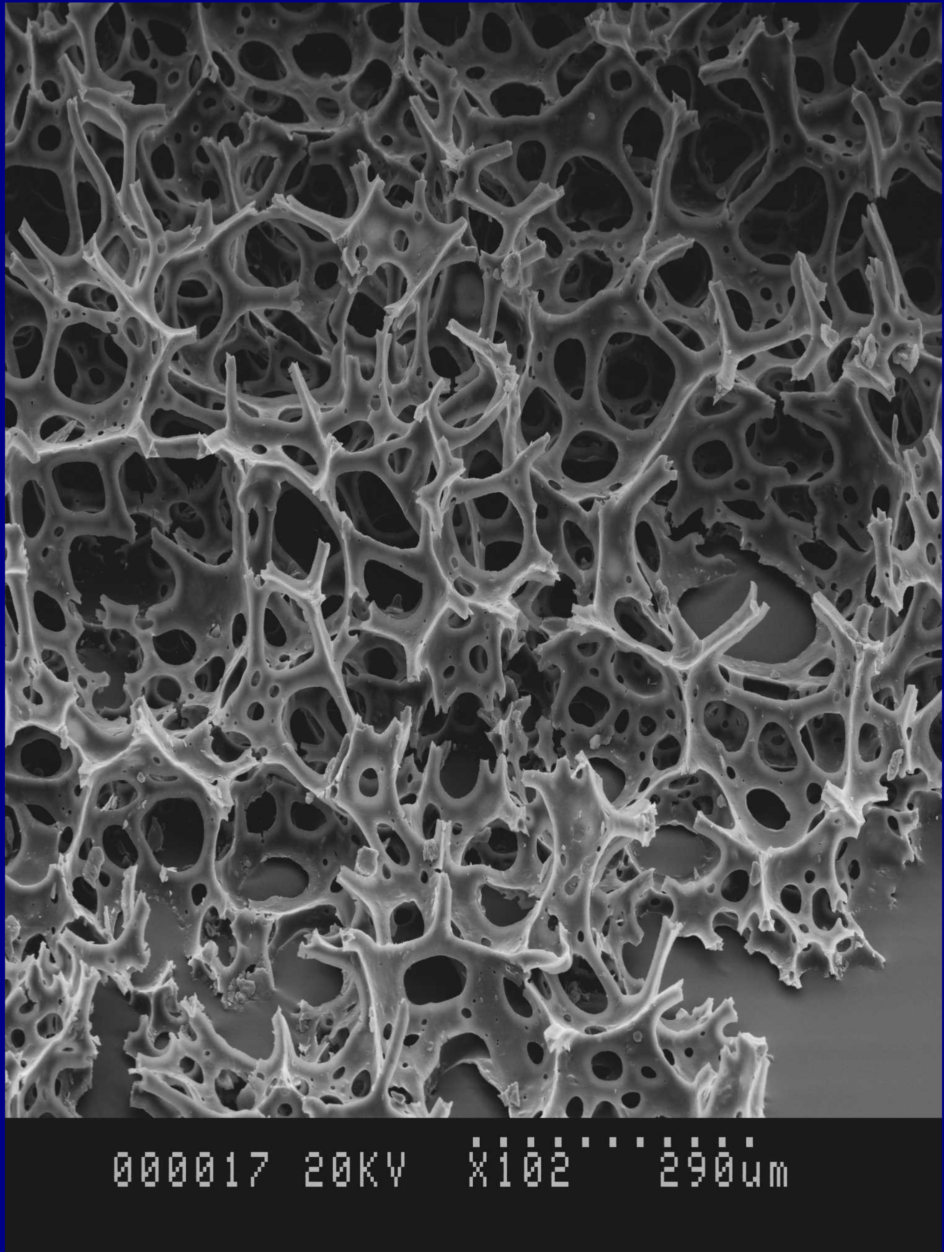
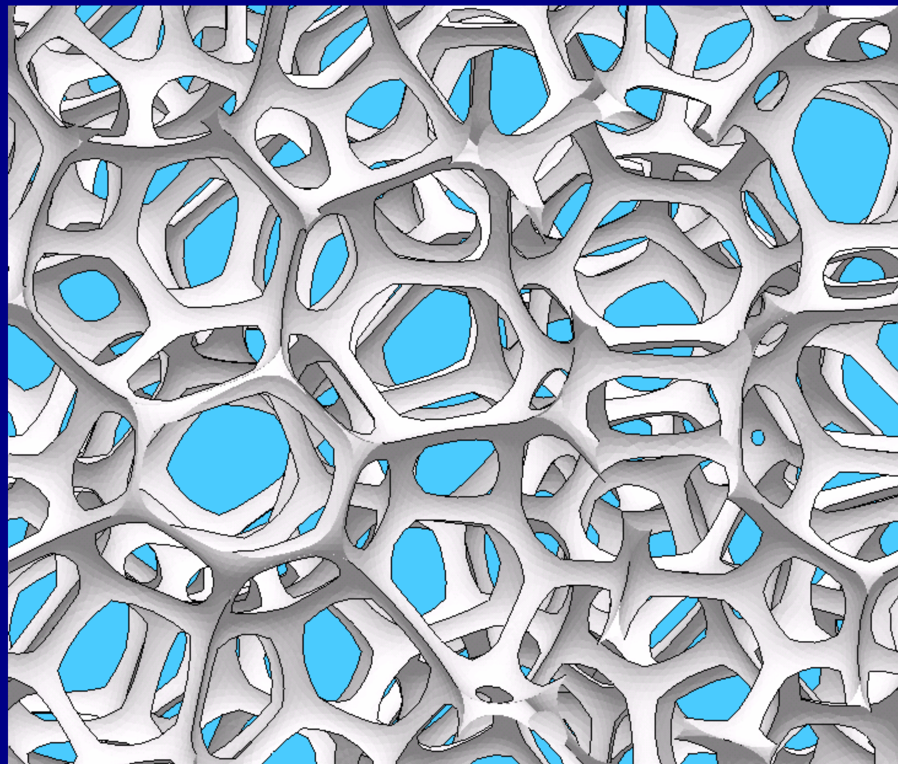
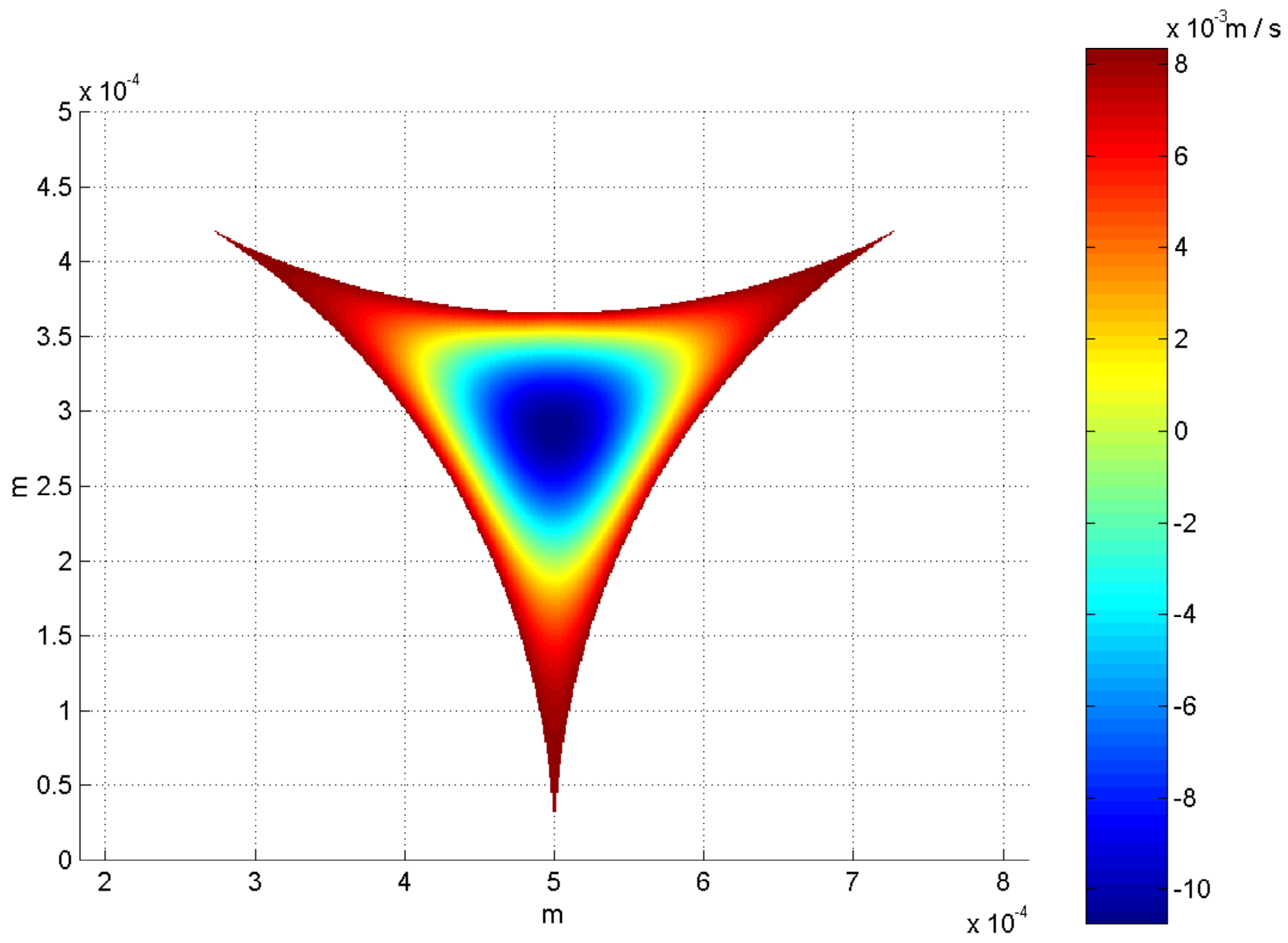




Plateau borders:
Liquid channels through foam



Plateau Border Velocity Profile

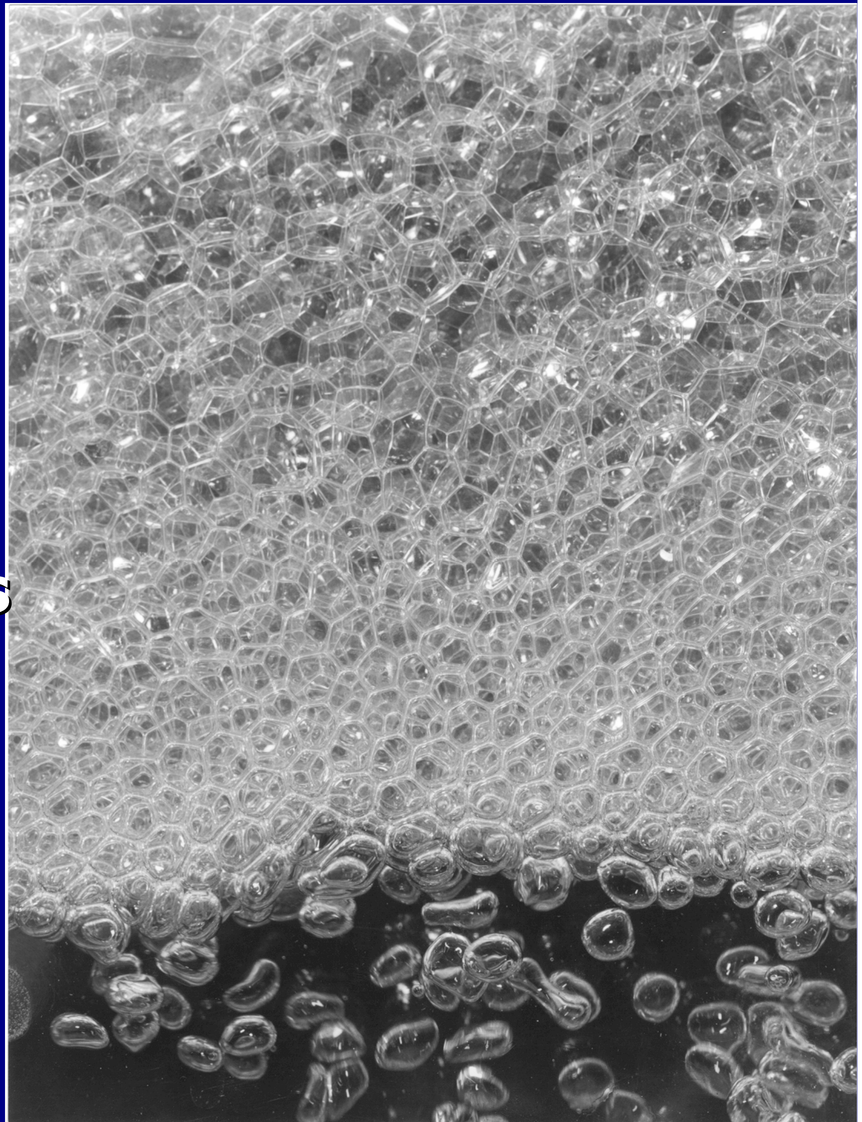


What is so difficult?

- Multiple flow scales
- Significant, rapid physical changes - coalescence

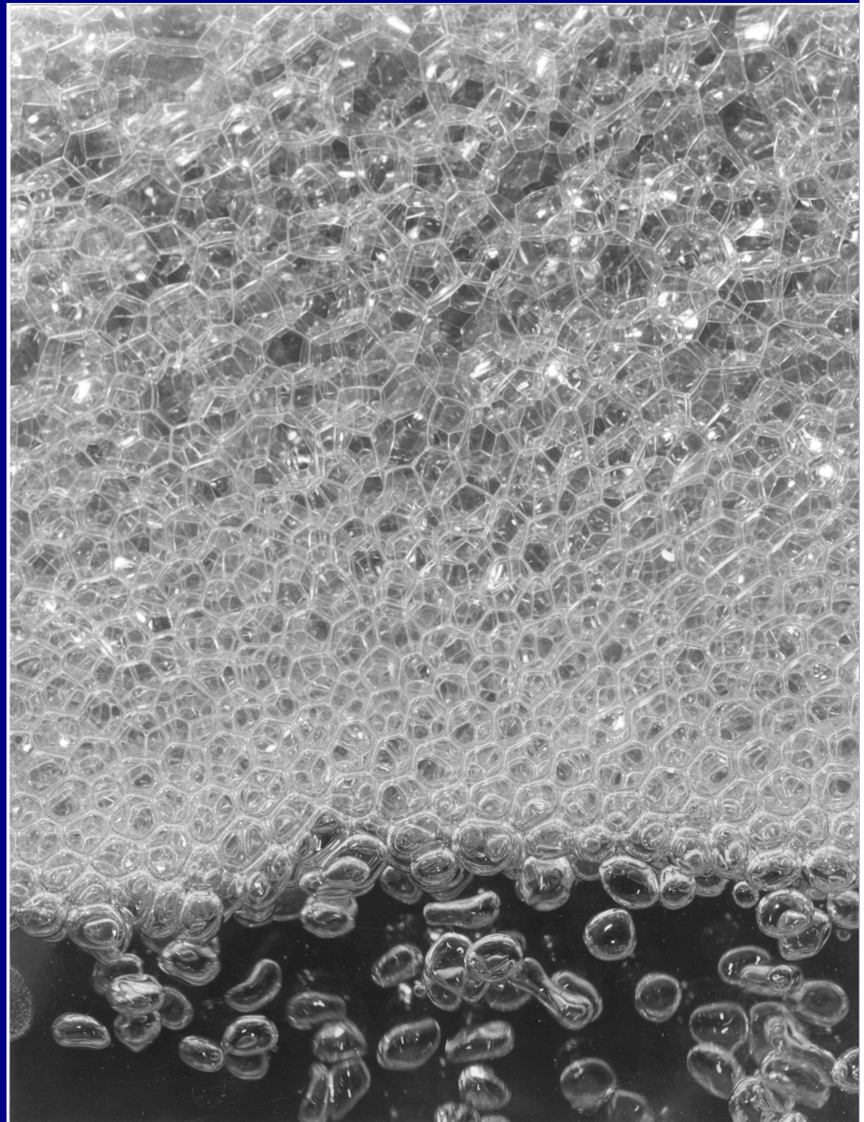
- Multiple, interacting phases
- Particles of different sizes, densities and hydrophobicities

MODEL EACH PHASE, AND COMBINE



A CFD Froth Model

- **Continuous, flowing**
  - Direction and velocity model
  - Physical boundaries
  - Fraction of bubbles overflowing
- **Liquid content & motion**
  - Drainage model
  - Bubble size effects
- **Solids motion**
  - Motion with bubbles
  - Free motion
  - Transfer

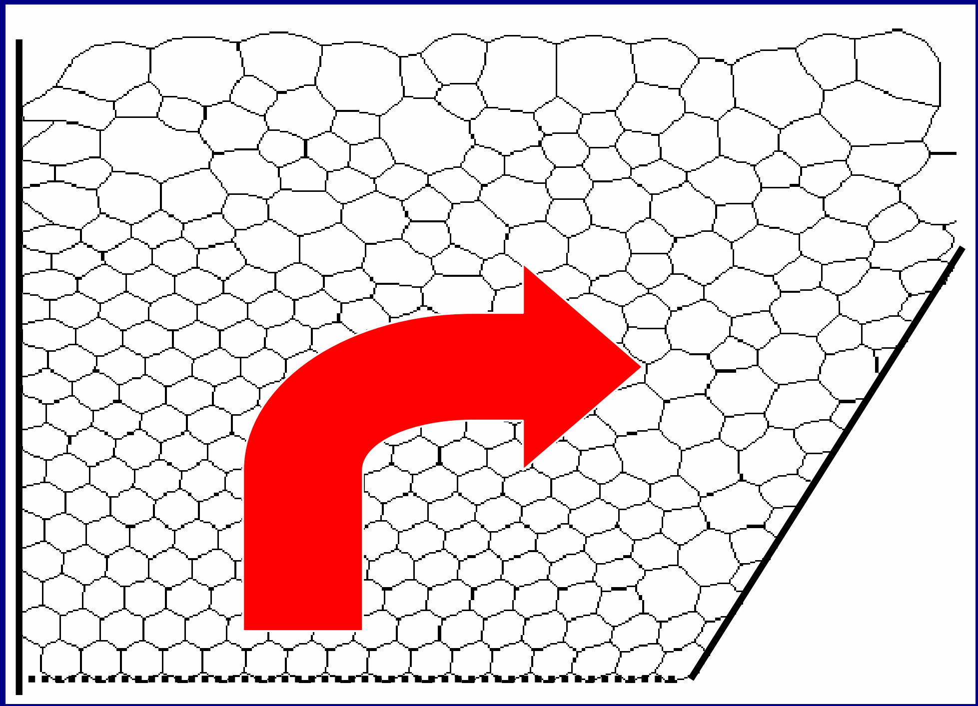


A CFD Froth Model:

Foam Flow and Bubble Motion

Bubbles assumed to be
- **Incompressible**
- **Irrotational**

Laplace equation
- **Vessel shape**
- **Bubble motion**



KEY BOUNDARY VALUE

Air entering the cell that overflows the weir:

AIR RECOVERY

A CFD Froth Model

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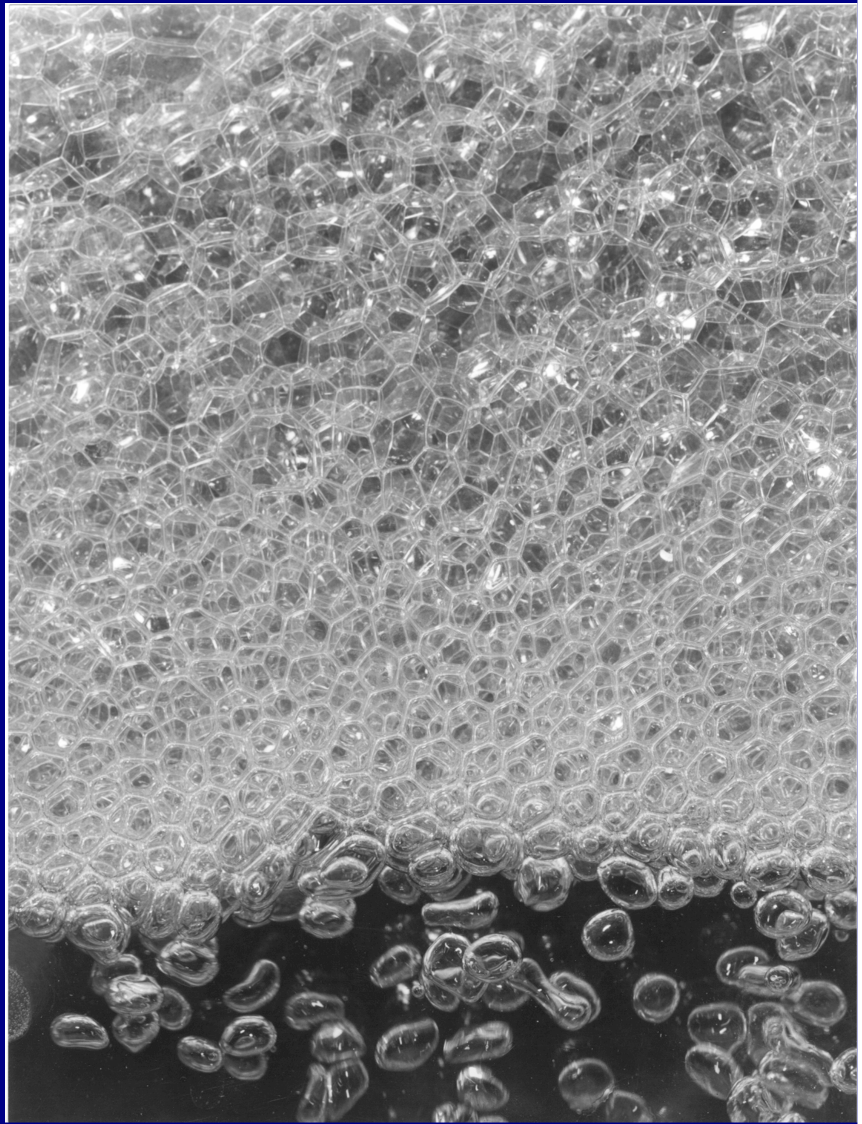


A CFD Froth Model:

Liquid Drainage

- **Three forces act on the liquid:**
  - ***Gravity***
  - ***Capillary***
  - ***Viscous dissipation***
- **Force balance**
- **Include bubble size change and foam motion**
- **Combine with continuity**

Liquid velocity:

$$\hat{u} = \begin{pmatrix} -\frac{k_2}{\sqrt{A}} \times \frac{\partial A}{\partial x} + v_x \\ -k_1 A - \frac{k_2}{\sqrt{A}} \times \frac{\partial A}{\partial y} + v_y \end{pmatrix}$$

Where: $k_1 = \frac{\rho g}{150\mu}$

$k_2 = \frac{C\gamma}{300\mu}$

A **= Plateau border area**
u **= Liquid velocity**
v **= Gas velocity**

Mathematical Model:

Liquid Drainage (2)

Continuity equation required to solve velocity equation:

$$\nabla.\left(\hat{u}\times A\times\lambda\right)=0$$

- **λ = Length of Plateau border per volume of foam**
- **λ allows for the effect of bubble size on liquid motion**

GOVERNING EQUATION

$$\lambda\left(-\frac{k_2}{2\sqrt{A}}\left(\frac{\partial A}{\partial x}\right)^2-k_2\sqrt{A}\frac{\partial^2 A}{\partial x^2}+\frac{\partial v_x}{\partial x}A+\frac{\partial A}{\partial x}v_x\right)$$

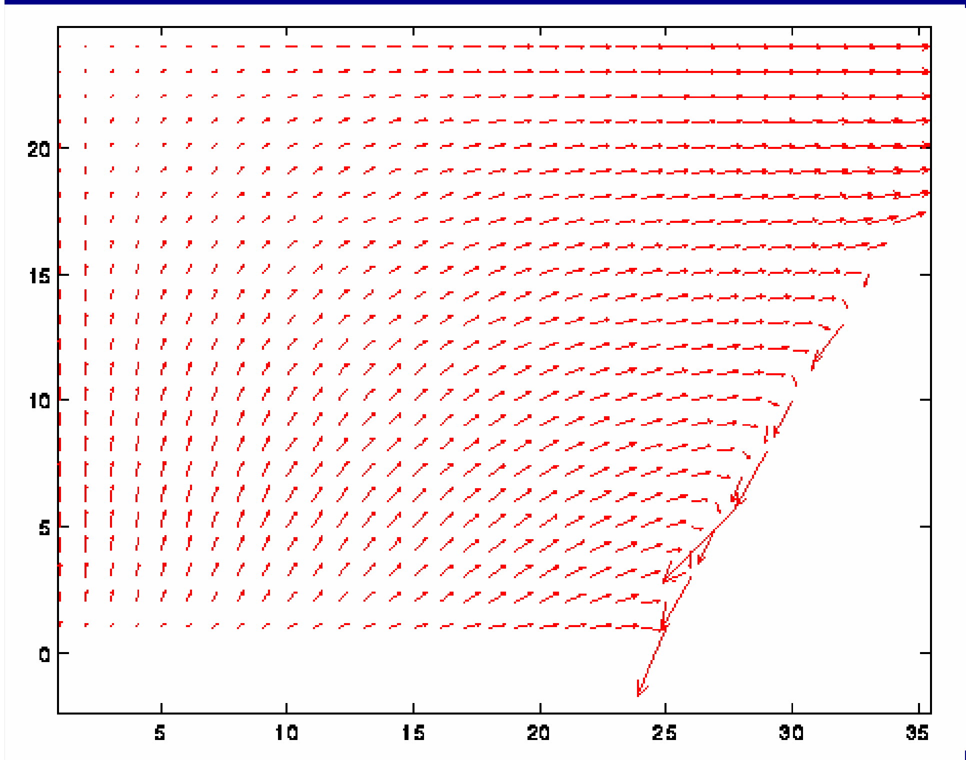
$$+\frac{\partial\lambda}{\partial x}\left(-k_2\sqrt{A}\frac{\partial A}{\partial x}+v_x A\right)$$

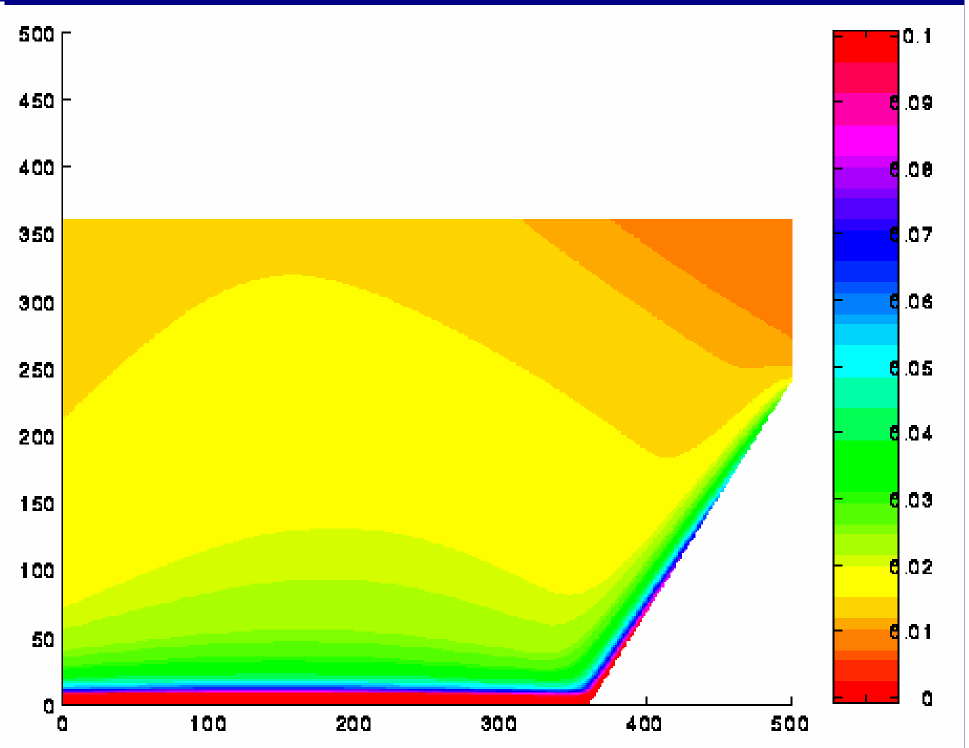
$$+\lambda\left(-2k_1A\frac{\partial A}{\partial y}-\frac{k_2}{2\sqrt{A}}\left(\frac{\partial A}{\partial y}\right)^2-k_2\sqrt{A}\frac{\partial^2 A}{\partial y^2}+\frac{\partial v_y}{\partial y}A+\frac{\partial A}{\partial y}v_y\right)$$

$$+\frac{\partial\lambda}{\partial y}\left(-k_1A^2-k_2\sqrt{A}\frac{\partial A}{\partial y}+v_y A\right)=0$$

A CFD Froth Model:

Liquid Motion and Content





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- Liquid content & motion
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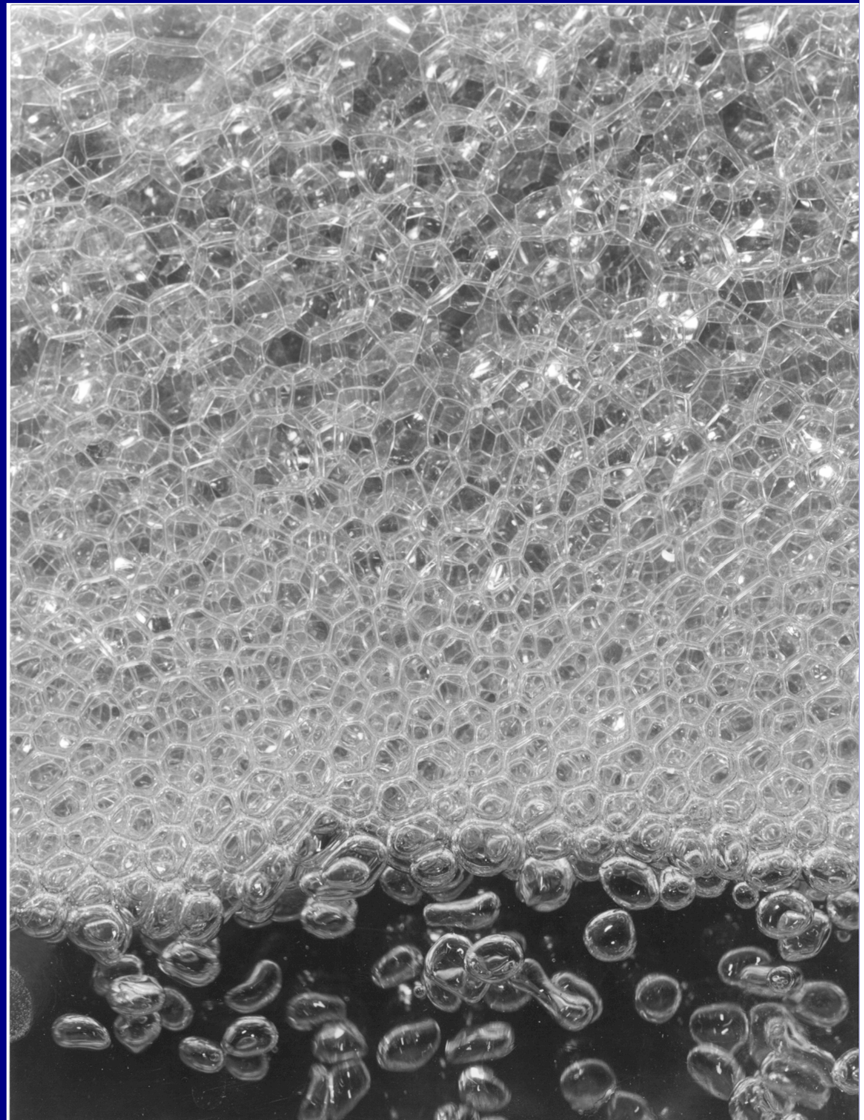
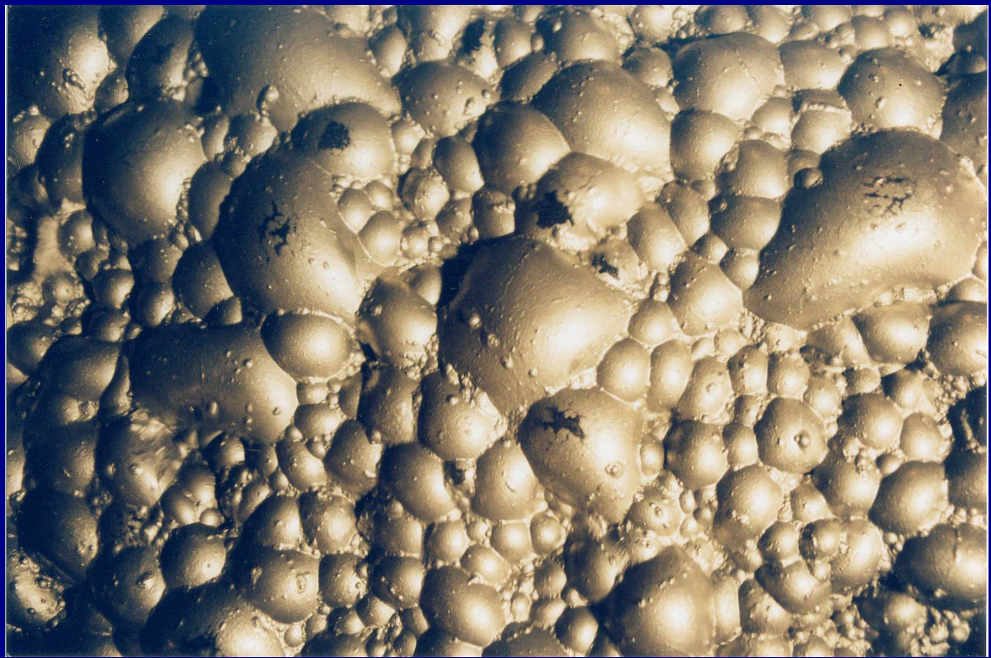
- **Solids motion**
  - **Motion with bubbles**
  - **Free motion**
  - **Transfer**

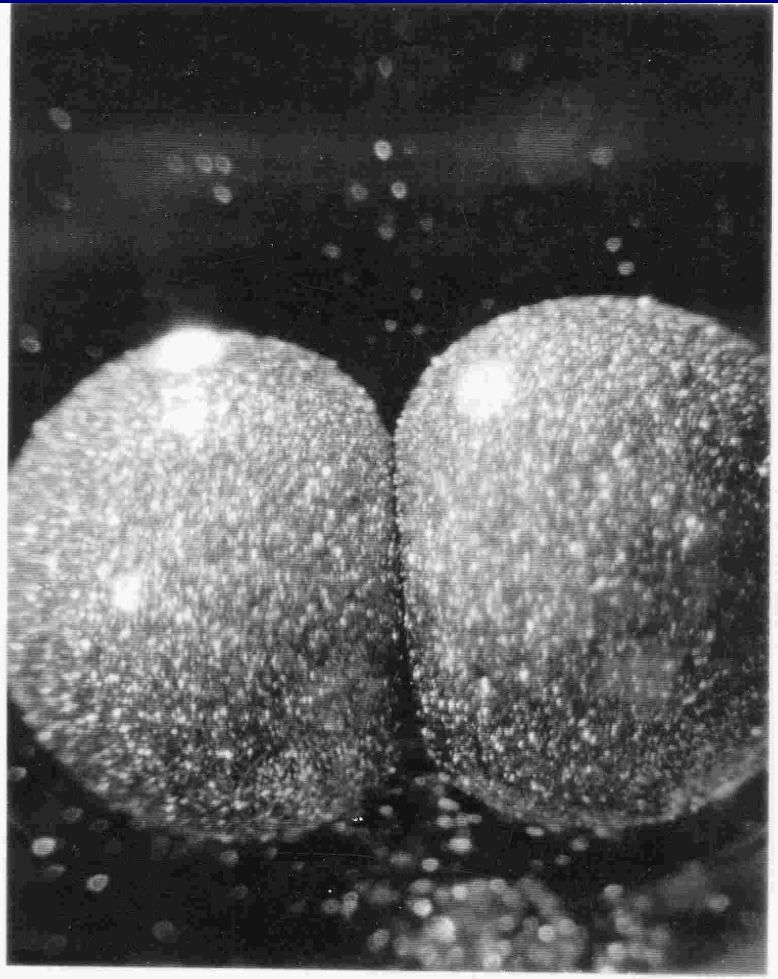


Solids Motion

1. Attached Solids

- Move with bubbles
- Detach at bursting surface or during coalescence





Bubble coalescence
x 20

Solids Motion

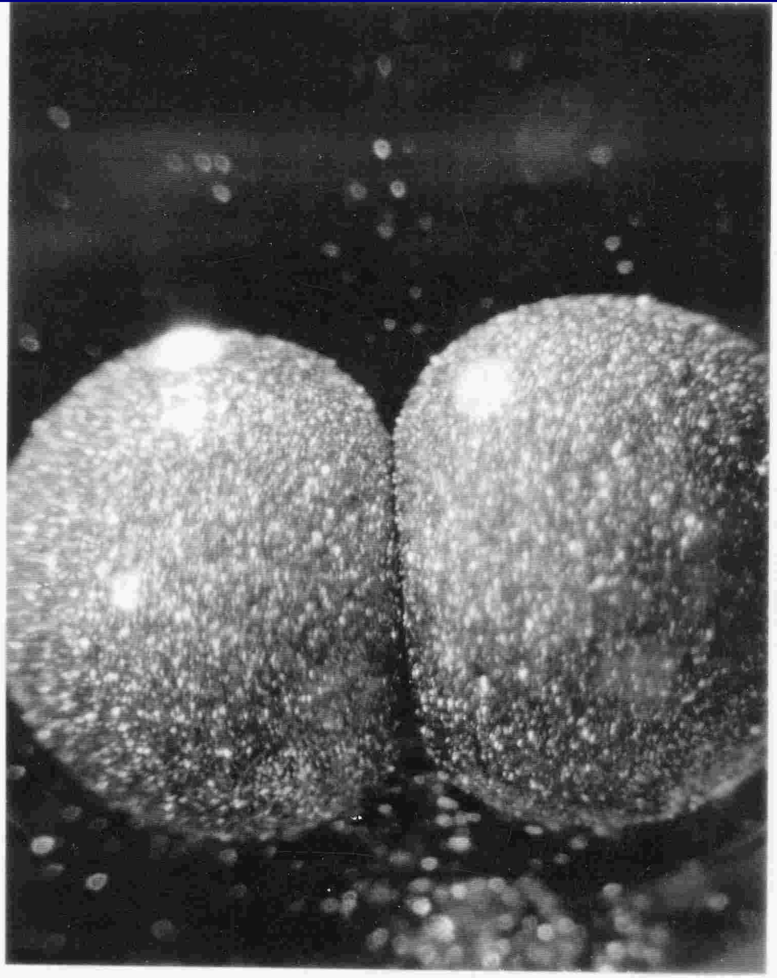
1. Attached Solids

- Move with bubbles
- Most detach

2. Unattached Solids:

- Enter froth by entrainment or from detachment
- Follow the liquid, settle and disperse

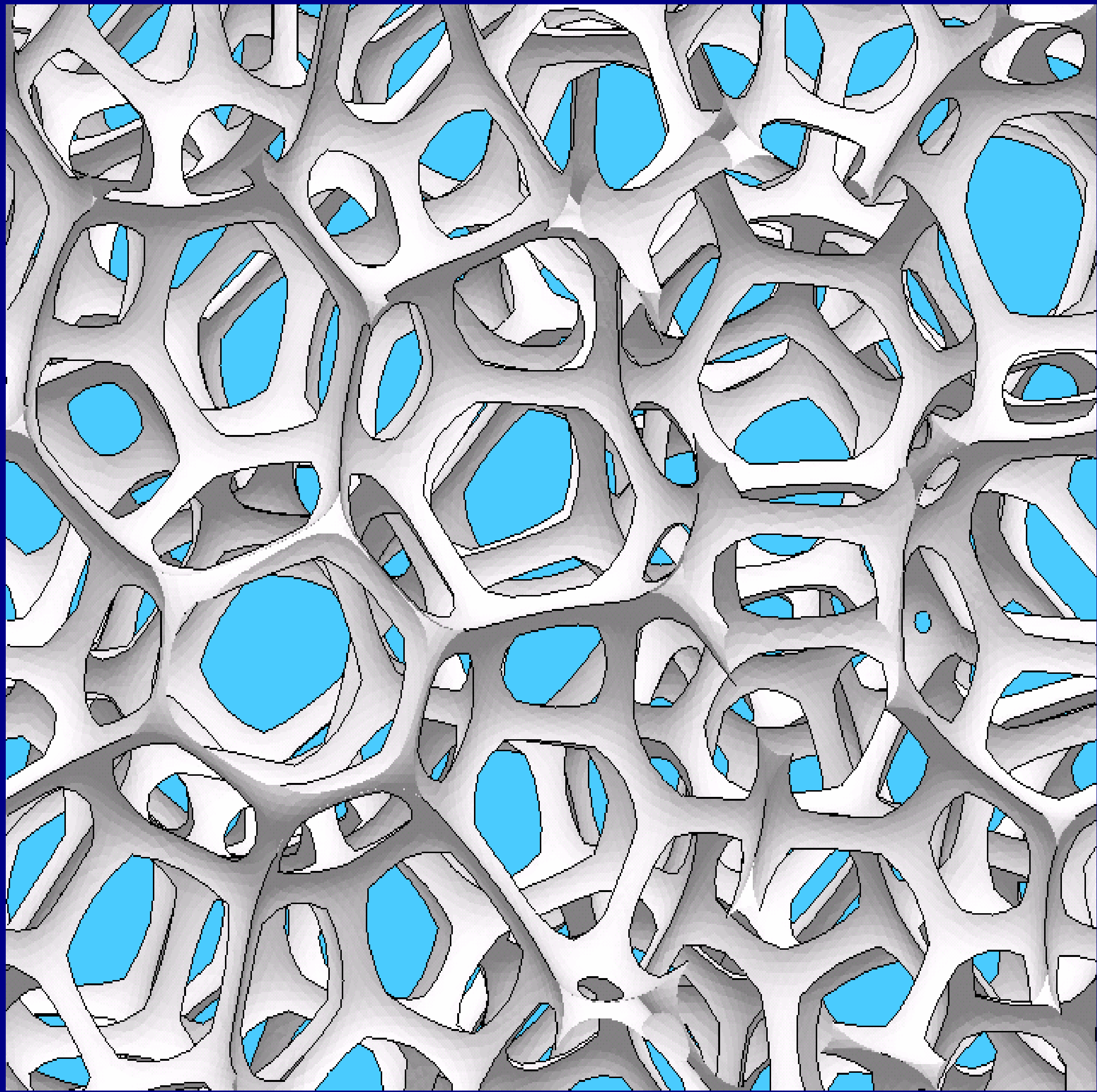
Dispersion is significant



Bubble coalescence
x 20

Plateau Border Network

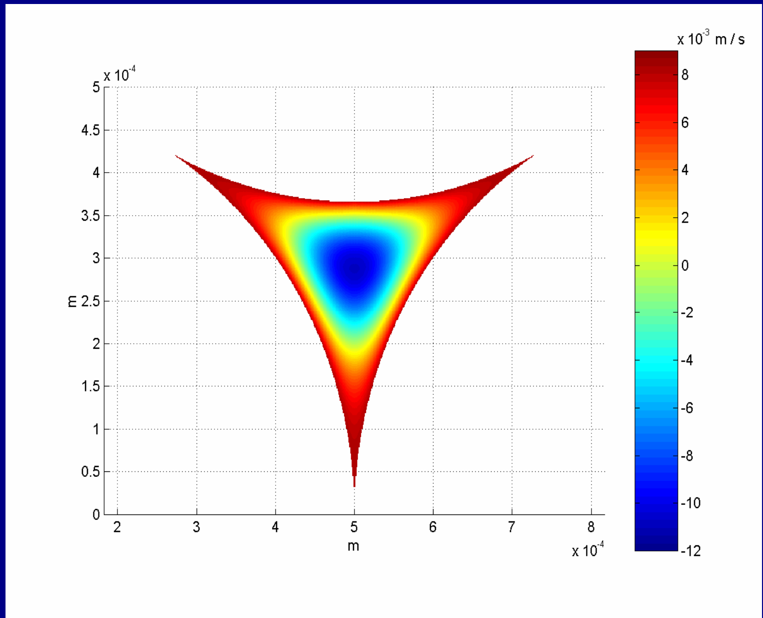
Random, mono-dispersed and periodic, 2% liquid



Topological layout for bubbles created by A. Kraynik, Sandia National Labs, USA

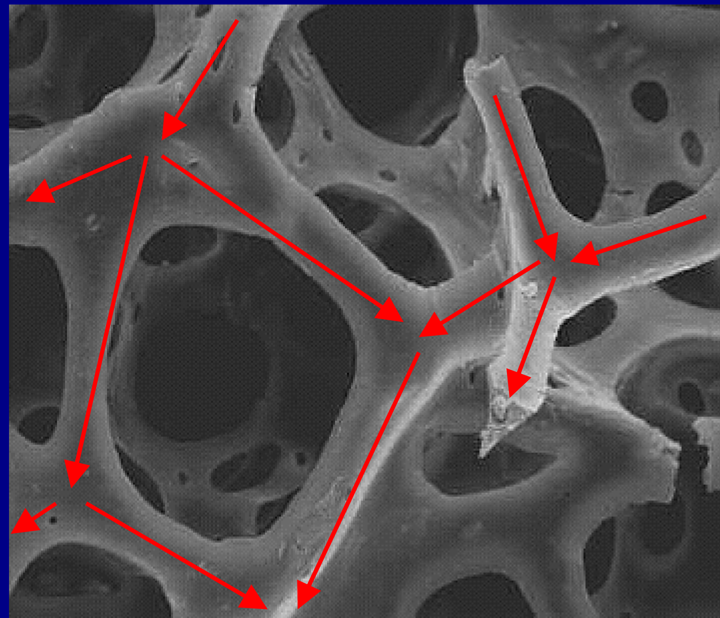
Particle Dispersion Mechanisms

Plateau border dispersion



- In direction of flow due to velocity gradient over Plateau border cross section

Geometric dispersion



- Perpendicular to flow due to geometric layout of network

A CFD Froth Model:

Unattached Solid Motion

GOVERNING EQUATION FOR SOLIDS MOTION

$$-\left(\frac{\partial\left(u_x \times S_b\right)}{\partial x}+\frac{\partial\left(u_y \times S_b\right)}{\partial y}\right)\times Sconc_i=-\frac{\partial\left(v_{Settling,\,i}\times Cs_i \times A \times \lambda\right)}{\partial y}$$

$$-D_G \times \frac{\partial\left(d_b \times A \times \lambda \times \left|v_x - u_x\right| \times \frac{\partial Cs_i}{\partial y}\right)}{\partial y}-D_P \times \frac{\partial\left(d_p \times A \times \lambda \times \left|v_y - u_y\right| \times \frac{\partial Cs_i}{\partial y}\right)}{\partial y}$$

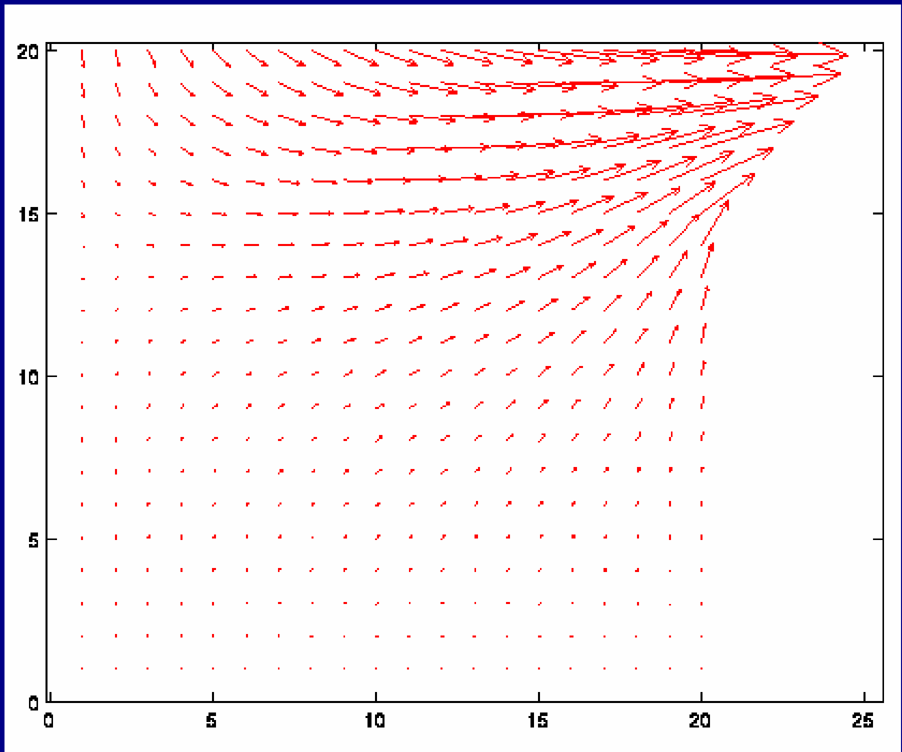
$$+\frac{\partial\left(v_y \times Cs_i \times A \times \lambda\right)}{\partial y}-D_G \times \frac{\partial\left(d_b \times A \times \lambda \times \left|v_y - v_{Settling,\,i} - u_y\right| \times \frac{\partial Cs_i}{\partial x}\right)}{\partial x}$$

$$-D_P \times \frac{\partial\left(d_p \times A \times \lambda \times \left|v_x - u_x\right| \times \frac{\partial Cs_i}{\partial x}\right)}{\partial x}+\frac{\partial\left(v_x \times Cs_i \times A \times \lambda\right)}{\partial x}$$

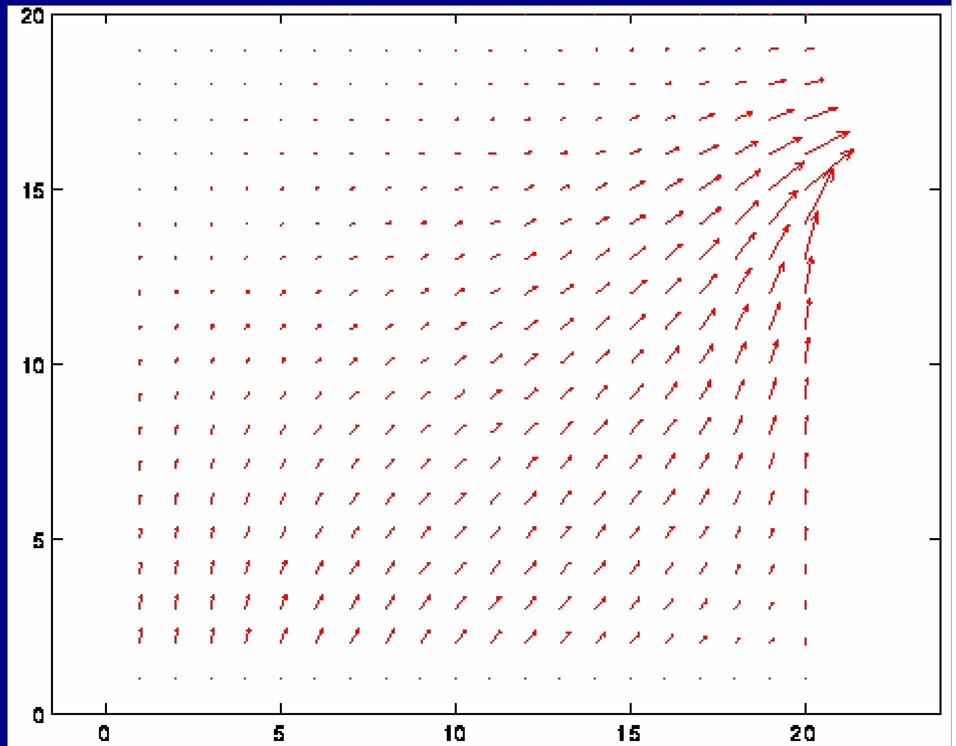
… require both dispersion coefficients

Mineral and Waste Motion:
Typical results

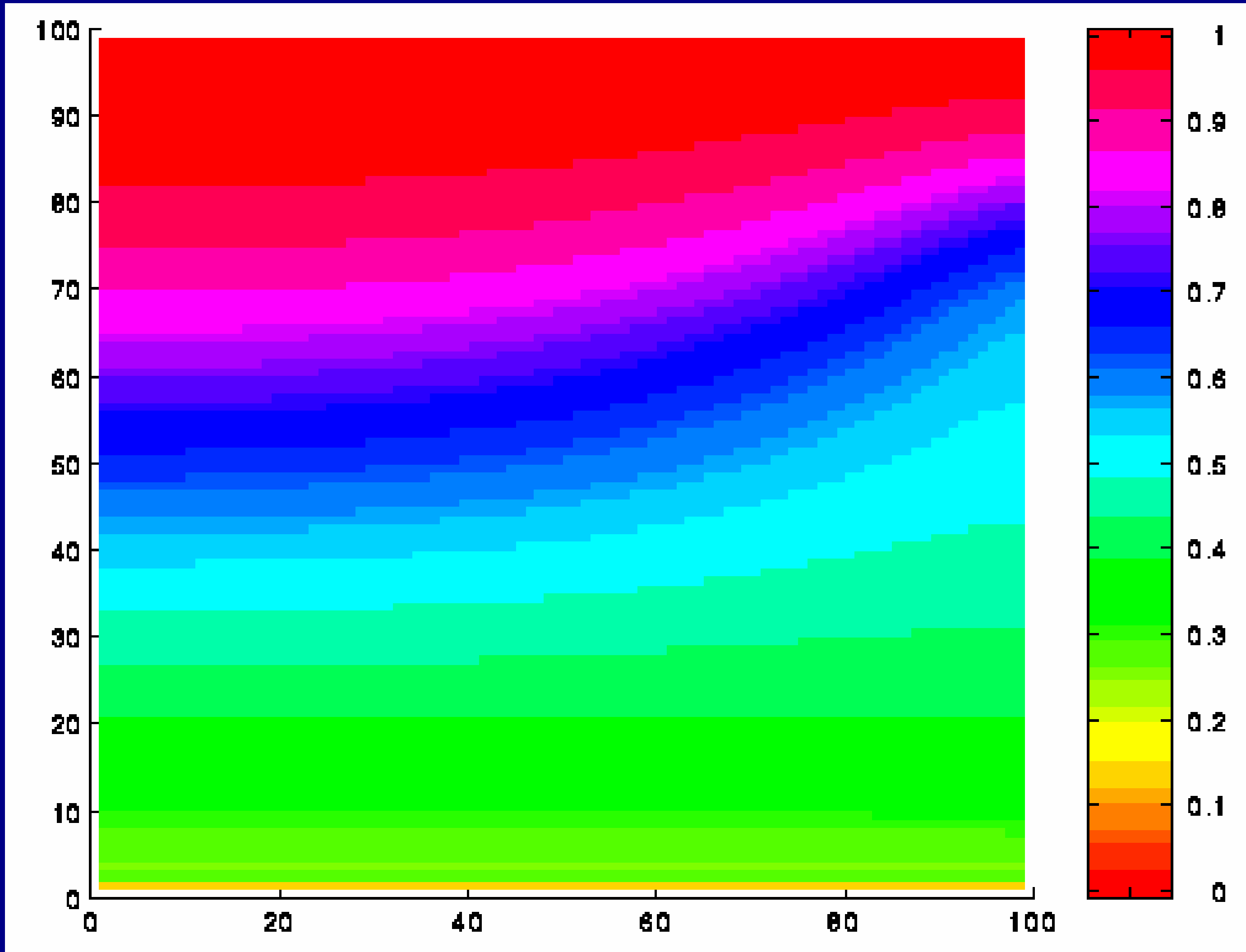
Valuable Mineral



Waste mineral



Mineral Ratio (grade) in froth & overflowing



3 Froth Case Studies

- Understanding
- Design
- Operation

Case Study 1: Understanding

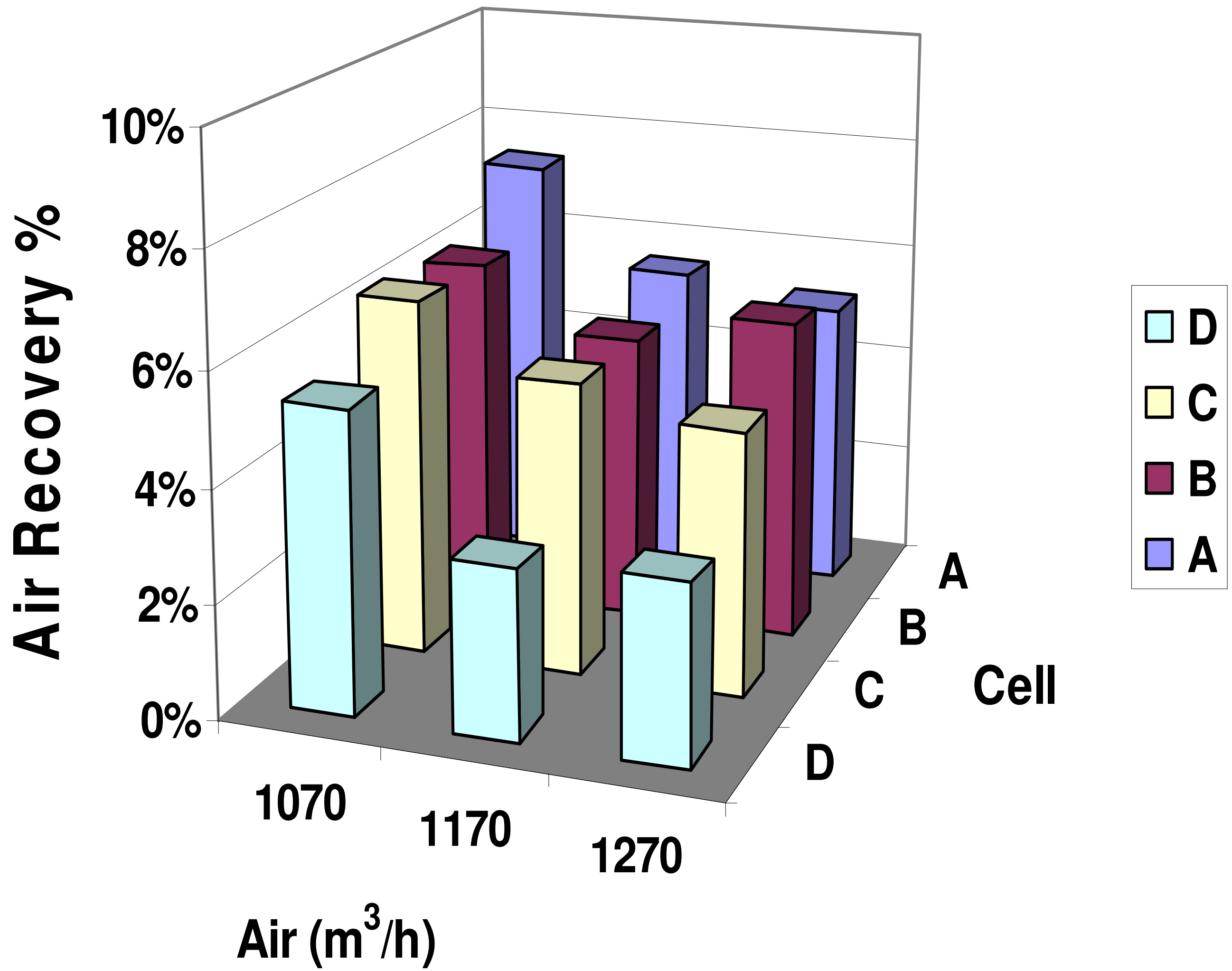
Solve the equations explicitly for overflowing water rate

Overflowing water rate = $k(v_g^2/d_b^2)\alpha(1-\alpha)$

- α is fraction of air that does not burst
- Important CFD boundary condition

- Experiments show it is low and a problem
- Techniques now being developed for on-line industrial measurement

Air Recovery α



Case Study 1: Understanding

Solve the equations explicitly for overflowing water rate

Overflowing water rate = $k(v_g^2/d_b^2)\alpha(1-\alpha)$

- **Froth depth** is missing from the equation
- Often used for controlling water rate
- Coupled effect – deeper froths have bigger bubbles overflowing d_b^2

Case Study 2: Design

Compare the performance of different launder layouts:

- **Doughnut launder:**

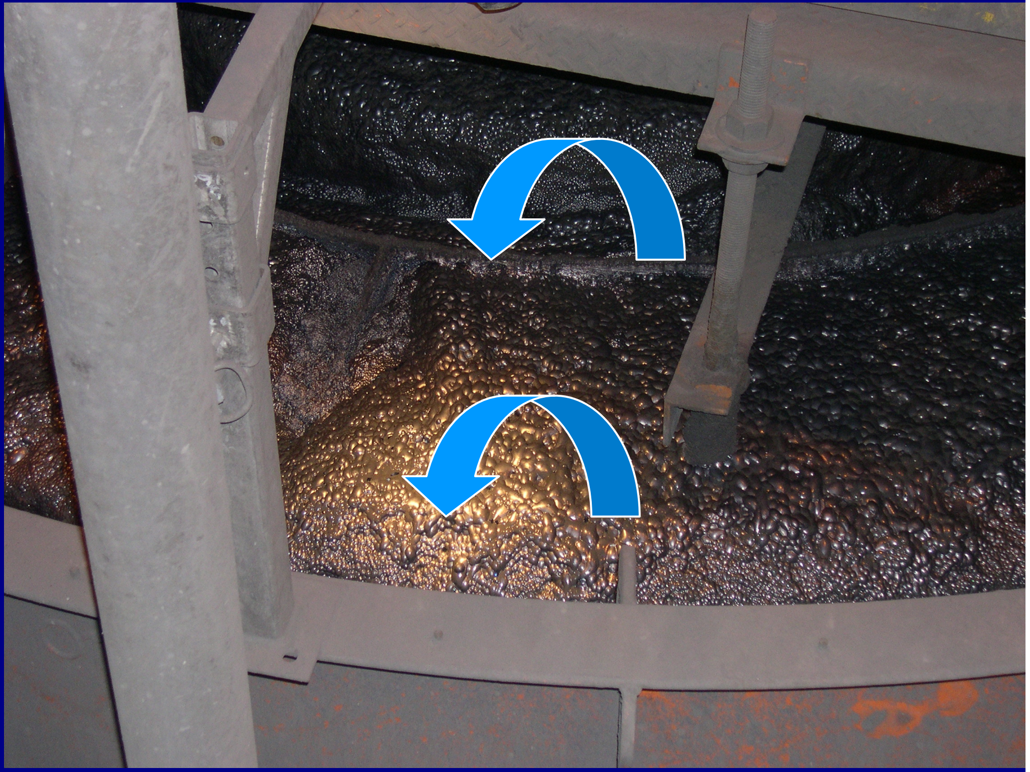
  froth is crowded in- and outwards to a single launder inside the cell

- **Two Ring launders:**

  froth crowded to an internal launder from the centre, and out from there to another at the cell wall

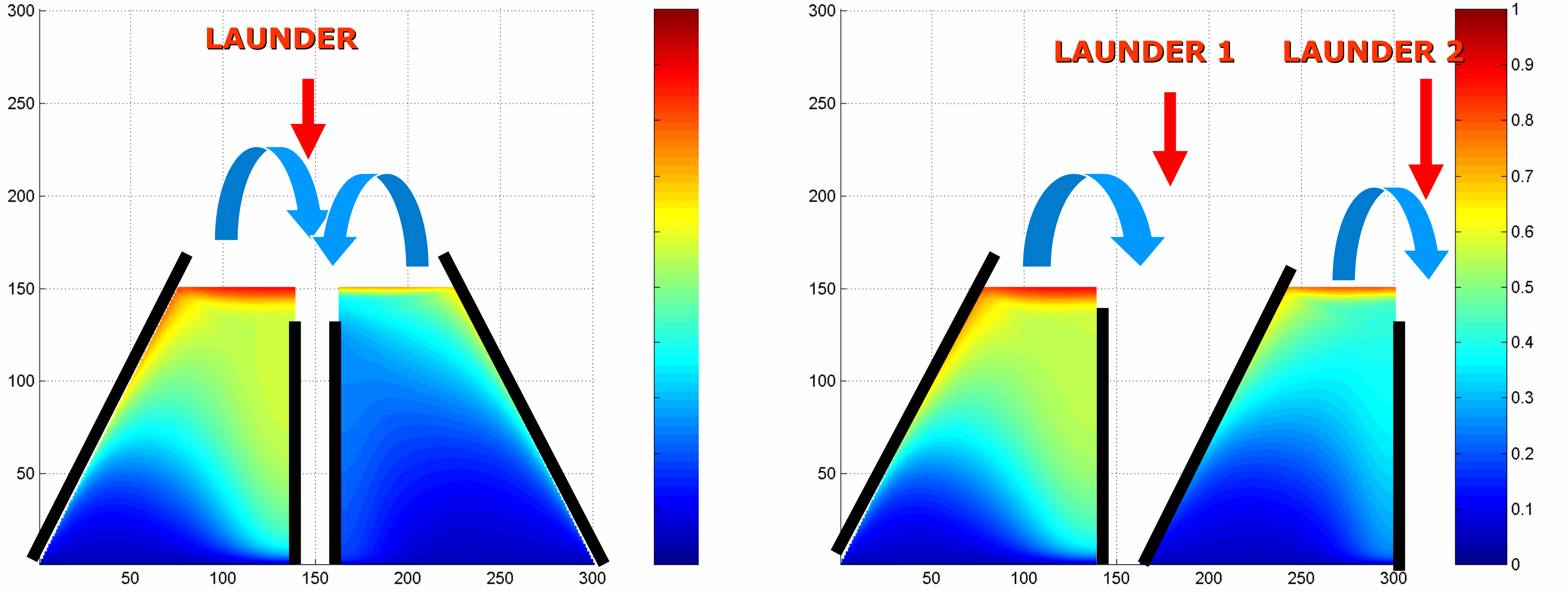
Internal "donut" launder

Internal & external ring launders



Crowder & Launder Design:

Effect of forcing froth inwards or outwards



DONUT LAUNDER

RING LAUNDERS

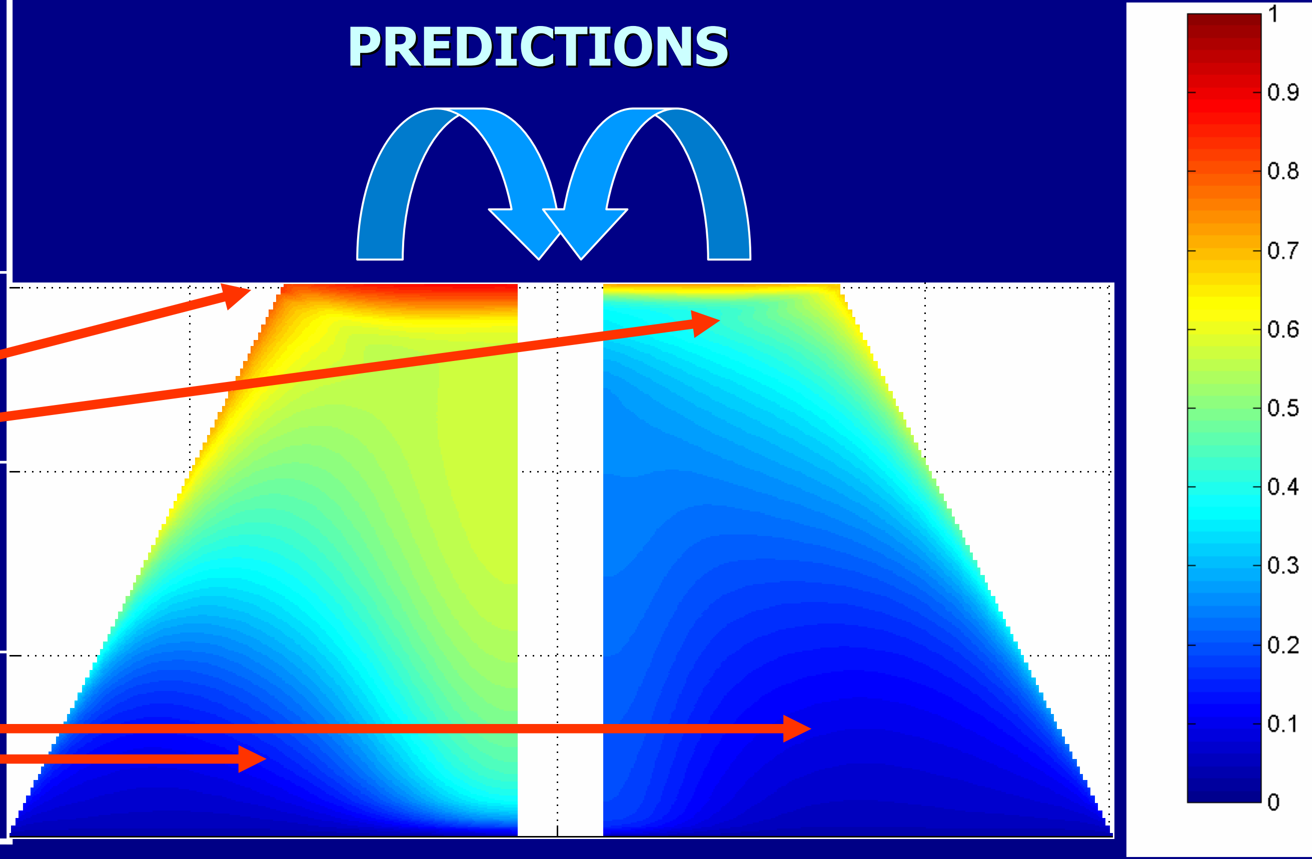
Crowder & Launder Design:

Industrial Data Comparison

MEASUREMENTS

Froth depth cm	Inner froth quality %	Outer froth quality %
5	90	70
25	25	22
75	10	6

PREDICTIONS



Inner froth   Outer froth

Case Study 3: Operation

Froth washing to improve performance

Water is added to the froth to rinse out unwanted waste particles

<u>a. Horizontal distribution</u>

Even or uneven?

<u>b. Vertical distribution</u>

Inside or on top?

… back to Red Dog Mine

Wash water header (raised)

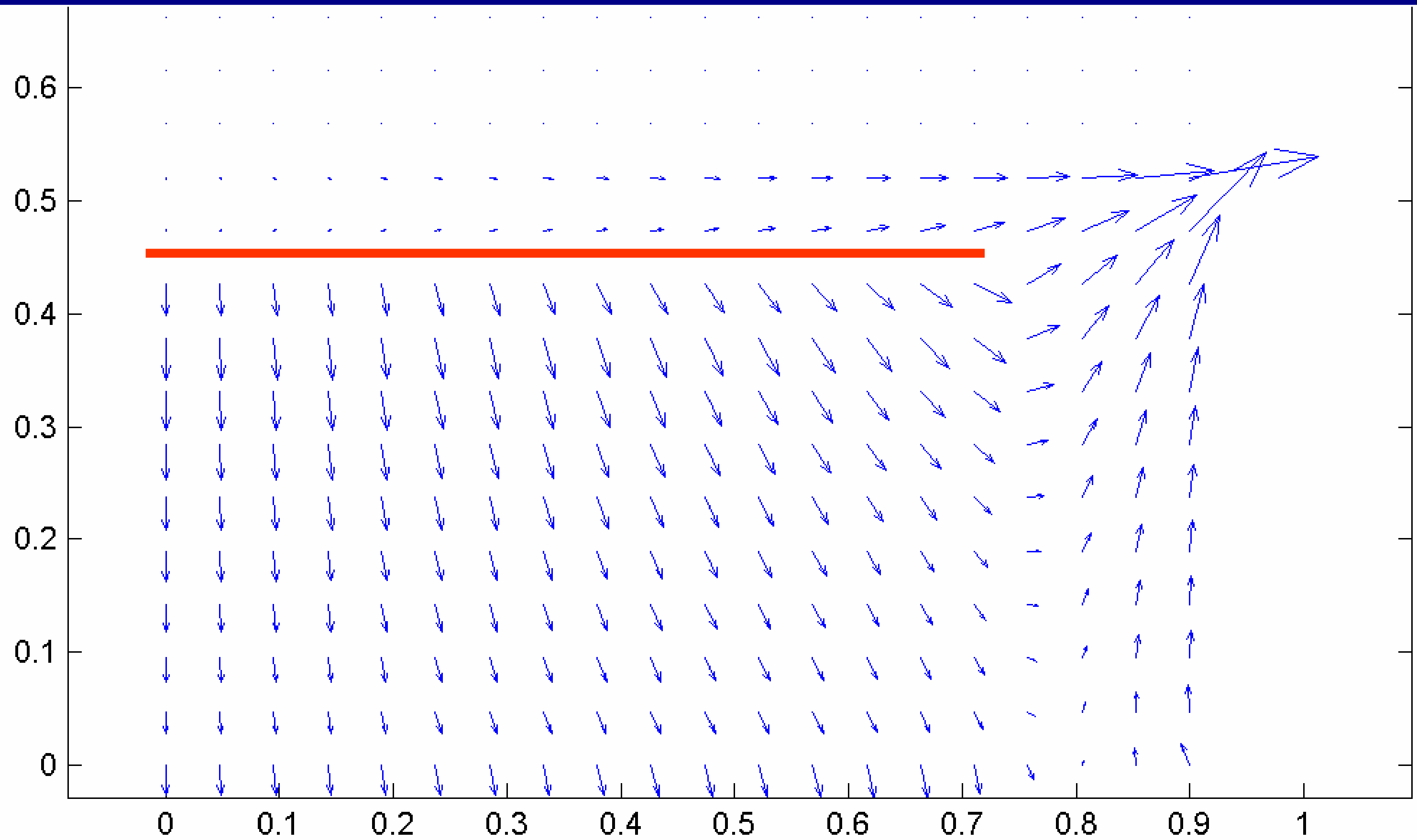
Red Dog Simulations:

- Used plant operating conditions and data
- Predict mineral recoveries very well, but only when:

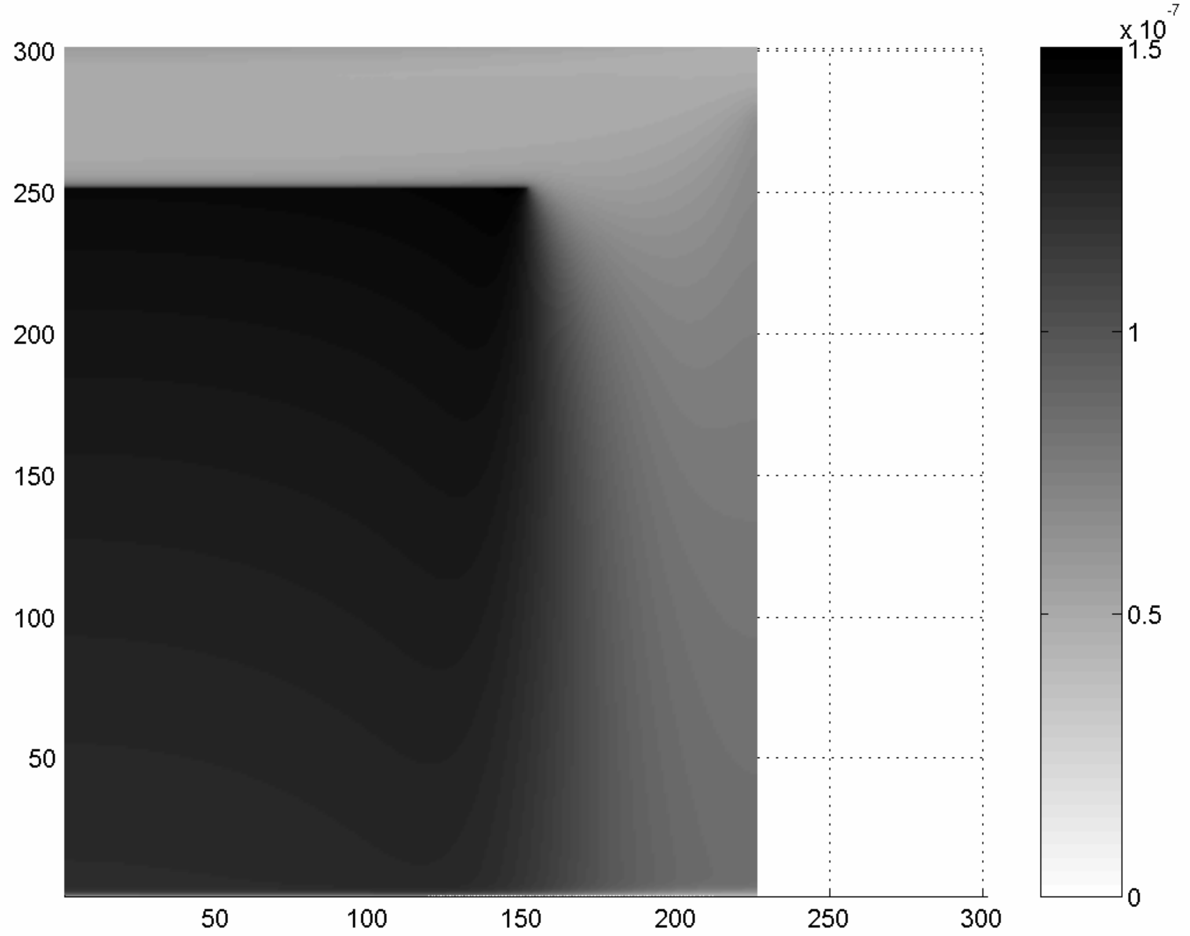
  wash water rate is 50% lower…

  … or unevenly distributed across the froth

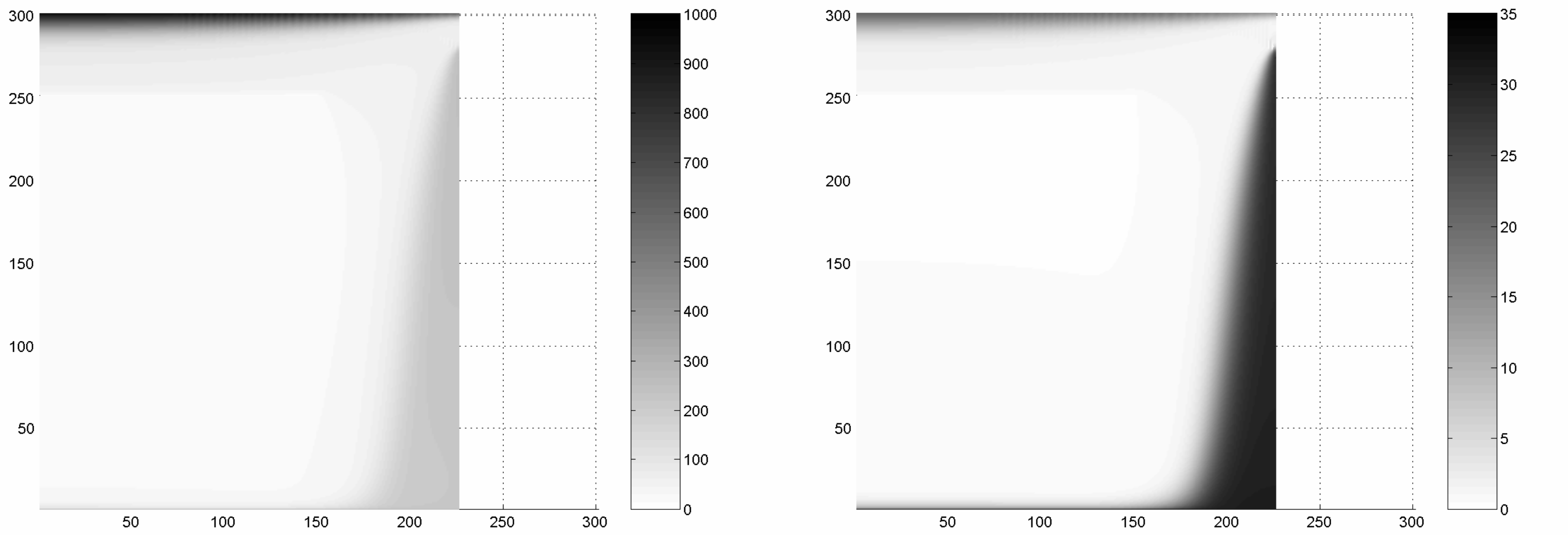
Red Dog Column Simulations:
Water motion for UNEVEN wash water



Uneven Wash Water Distribution: Froth liquid content



Concentration of different particle types in Plateau borders

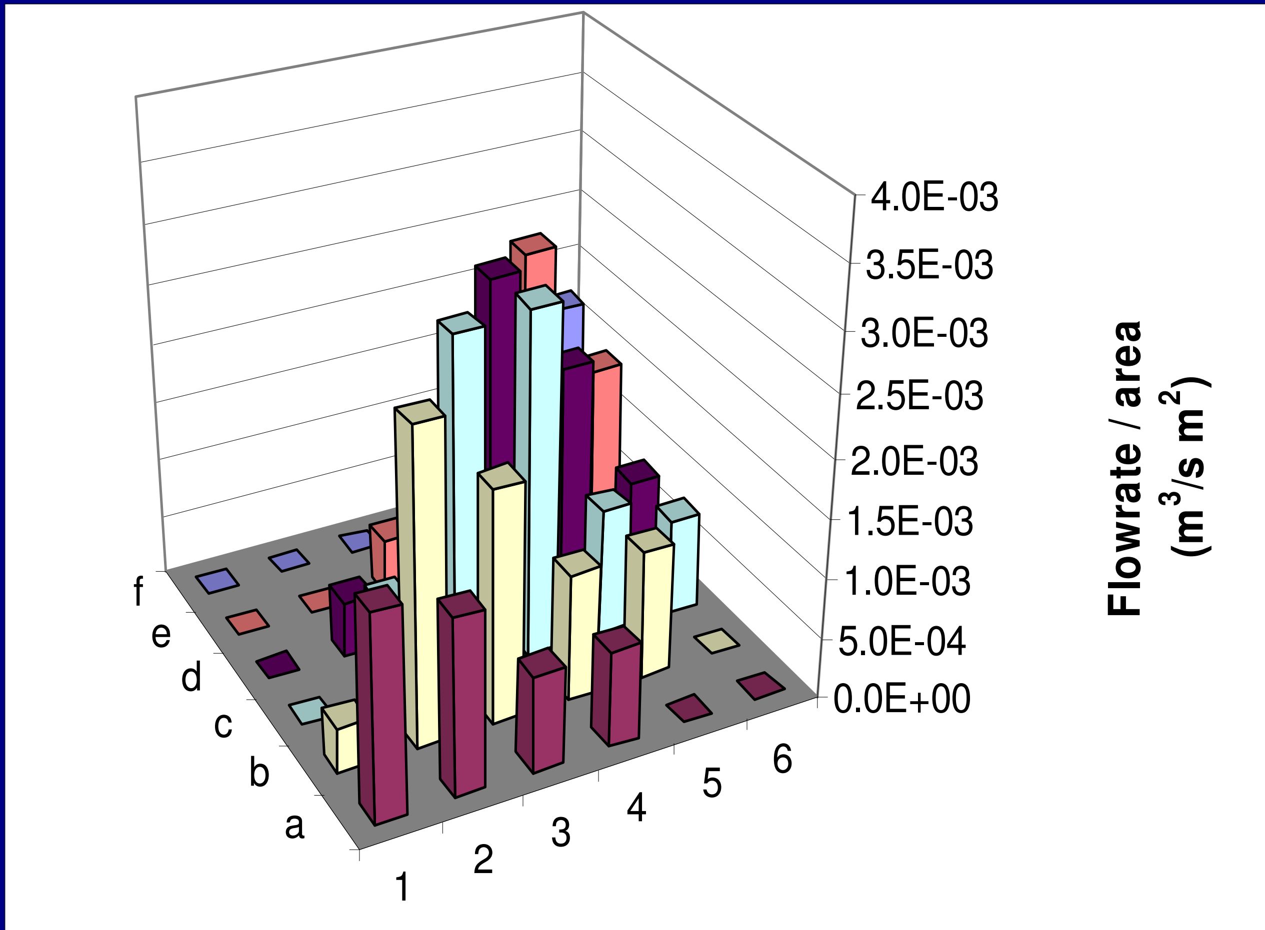


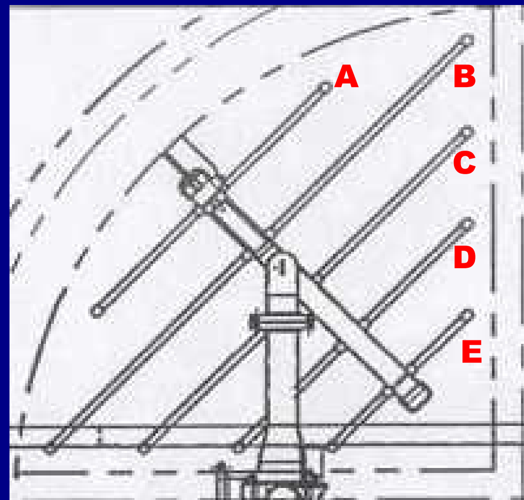
Valuable Mineral **Waste**

Simulation outcome:

- Wash water distribution critical
  - Even distribution will give the required performance and use less water
- Confirmed distribution predictions with a water distributor model
- Redesigned the spray system
- Installed and test

Distribution of flow with existing spray system (All holes d=6.25mm)





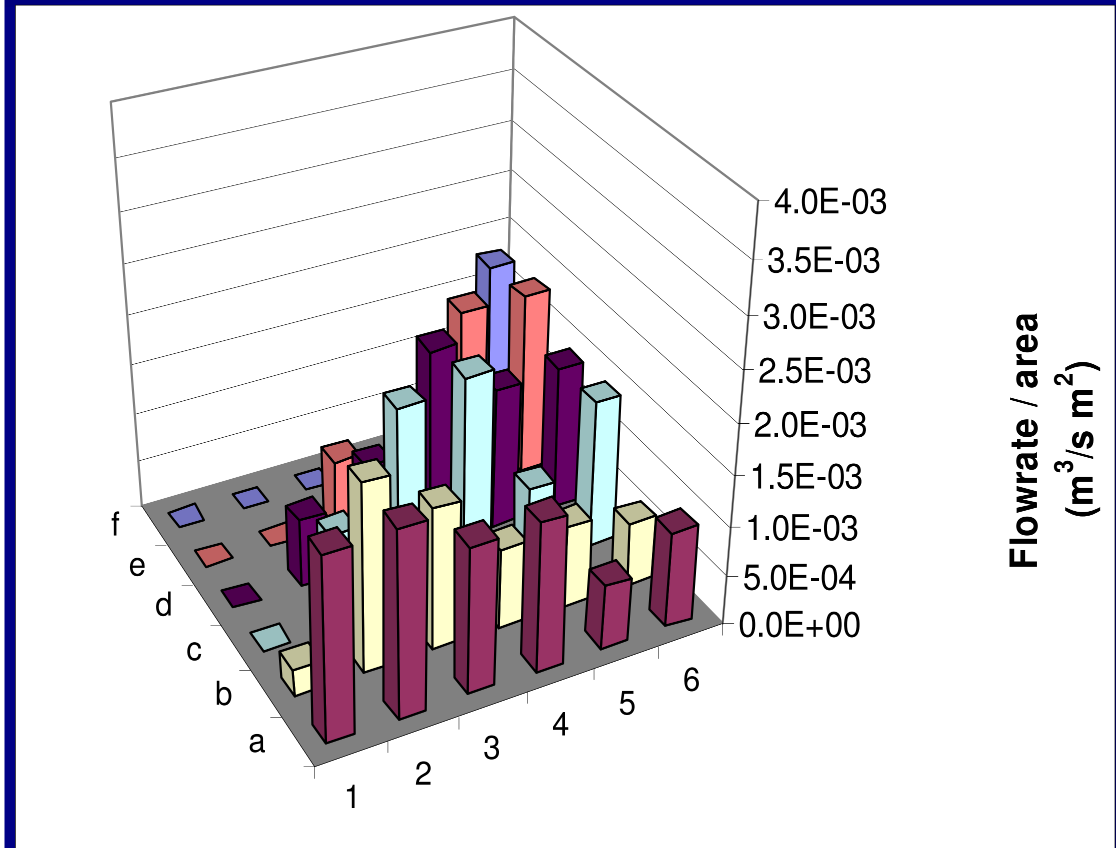
Model matches FrothSim predictions of uneven distribution

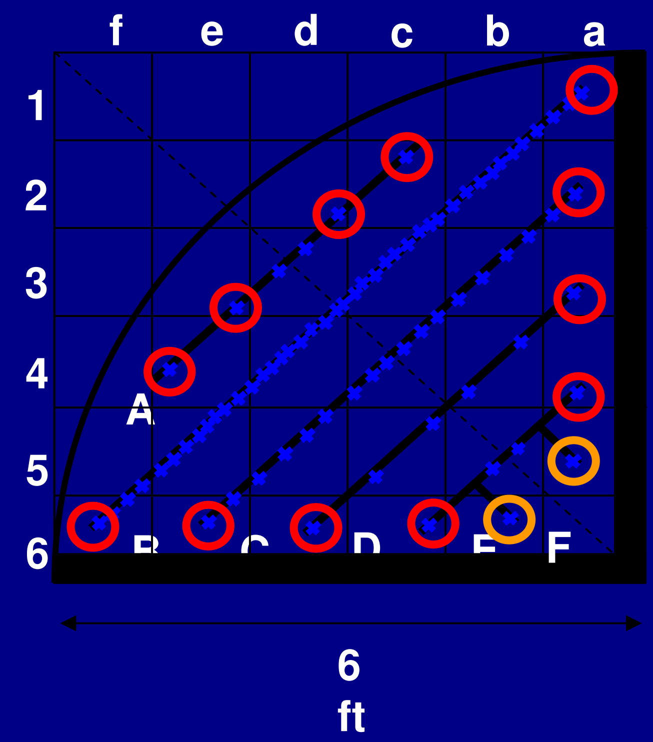
Red Dog Mine

Wash water header (raised)

Distribution of flow with modifications

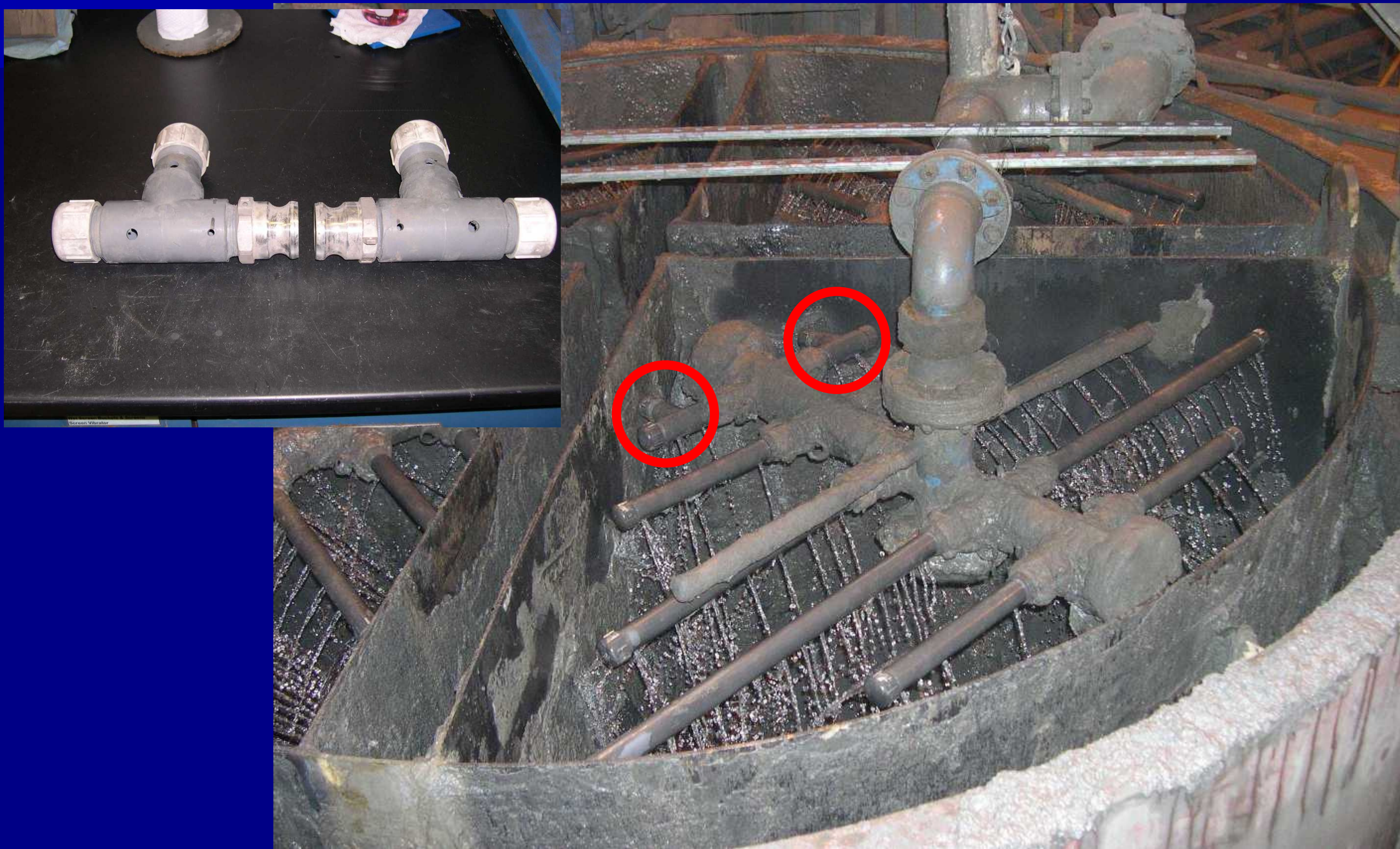
(Modified holes increased to d=0.01m)





- **Distribution significantly improved**
- **Corner flow**

Header modification

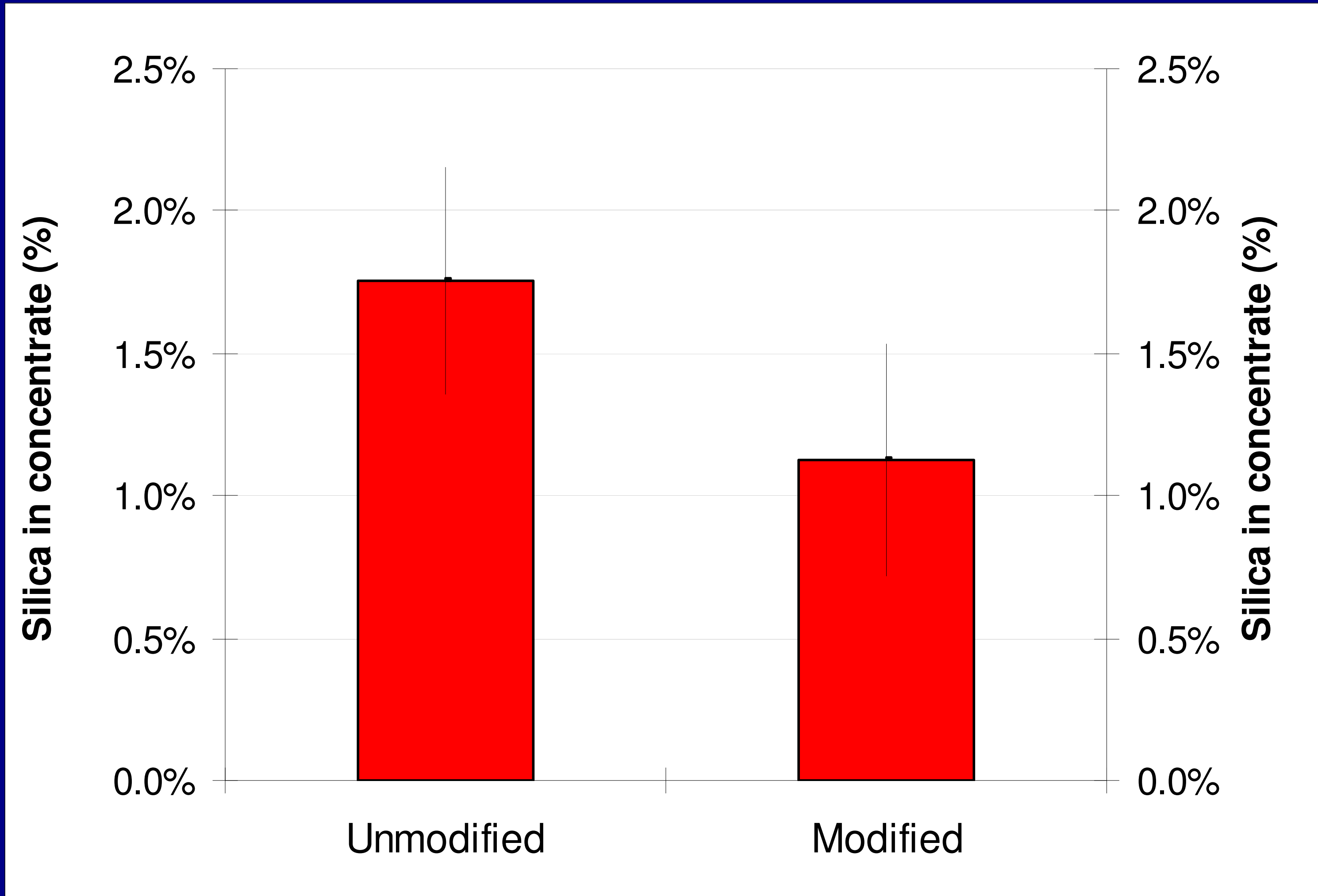


Wash water header modifications

Waste particles in product

36% decrease after modification

Economic benefit $1.5m annually



Case Study 3: Operation

Froth washing to improve performance

Water is added to the froth to rinse out unwanted waste particles

a. <u>Horizontal distribution</u>

Even or uneven?

b. <u>Vertical distribution</u>

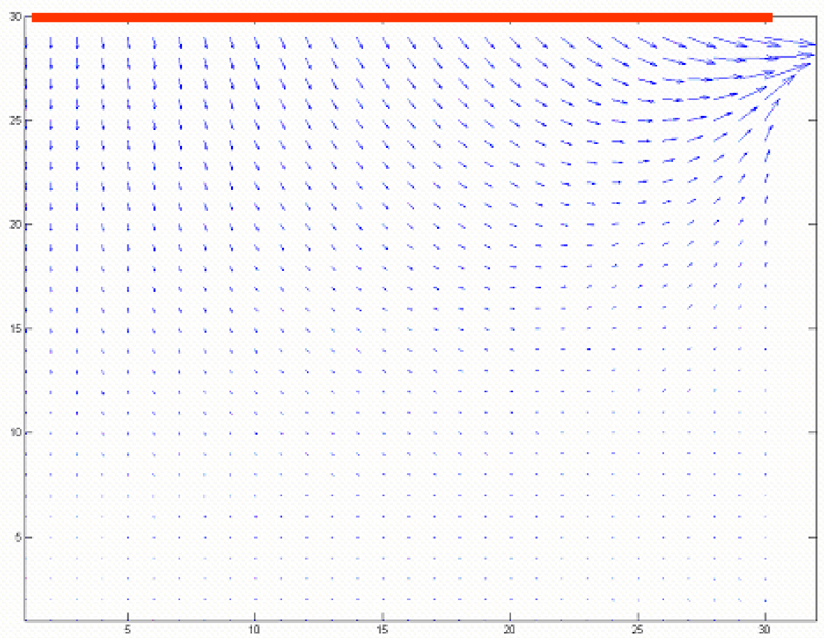
Inside or on top?

Overhead Pan Design

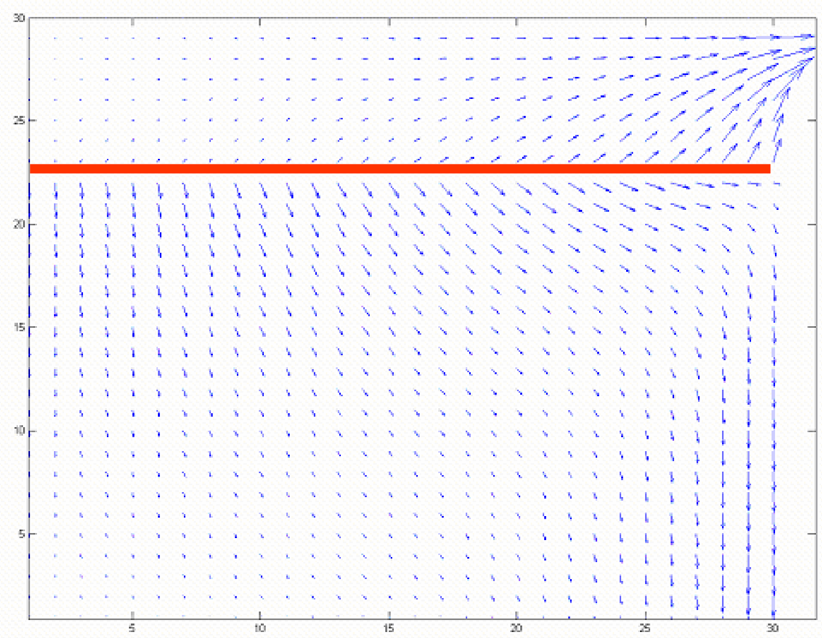
Submerged Header Design

Overhead and Internal washing

Surface water addition

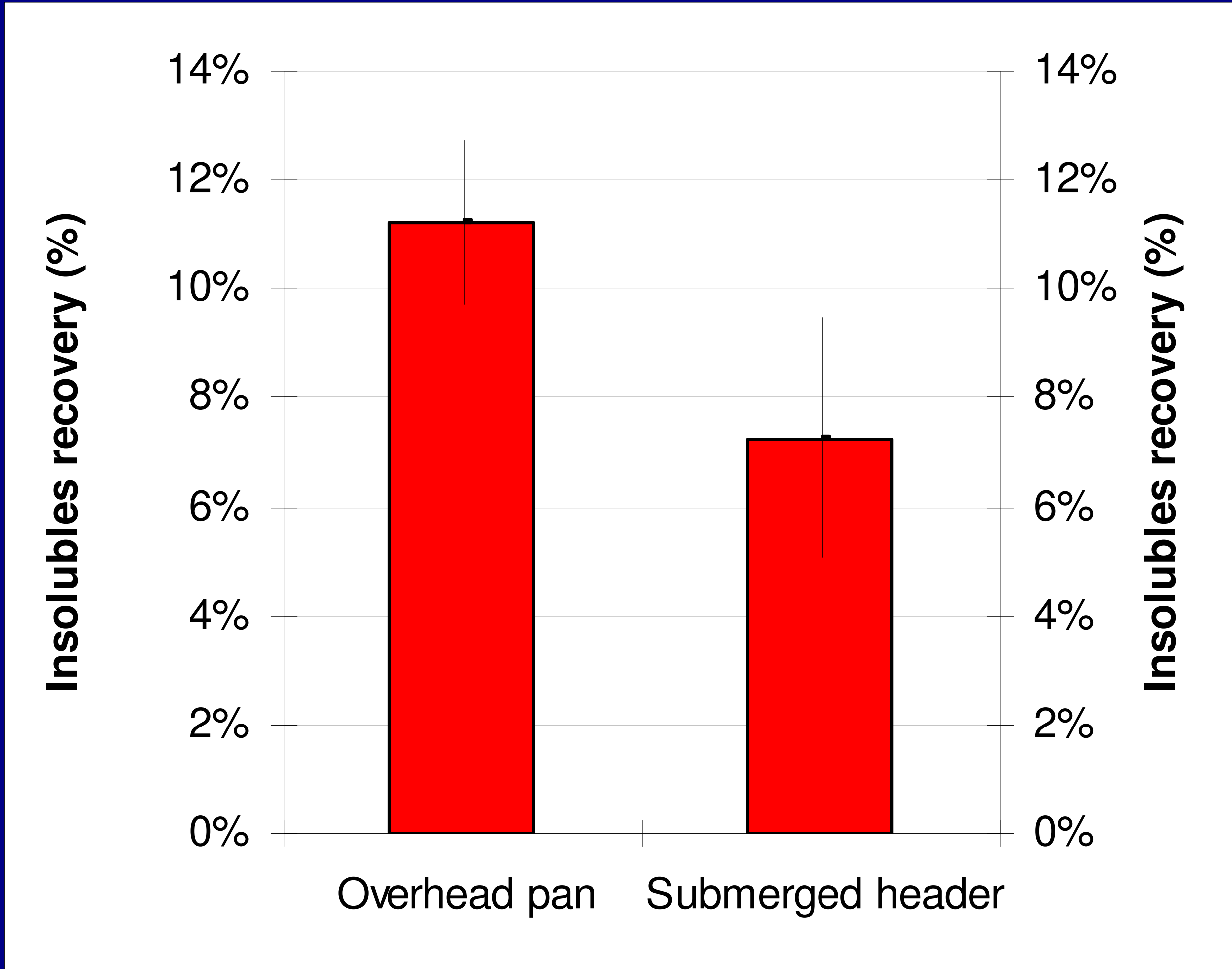


Internal water addition



Results: Gangue Recovery

35% decrease in waste with submerged header



3 Froth Case Studies

We understand more, design smarter, operate better

What's left to do?

What is left to do?

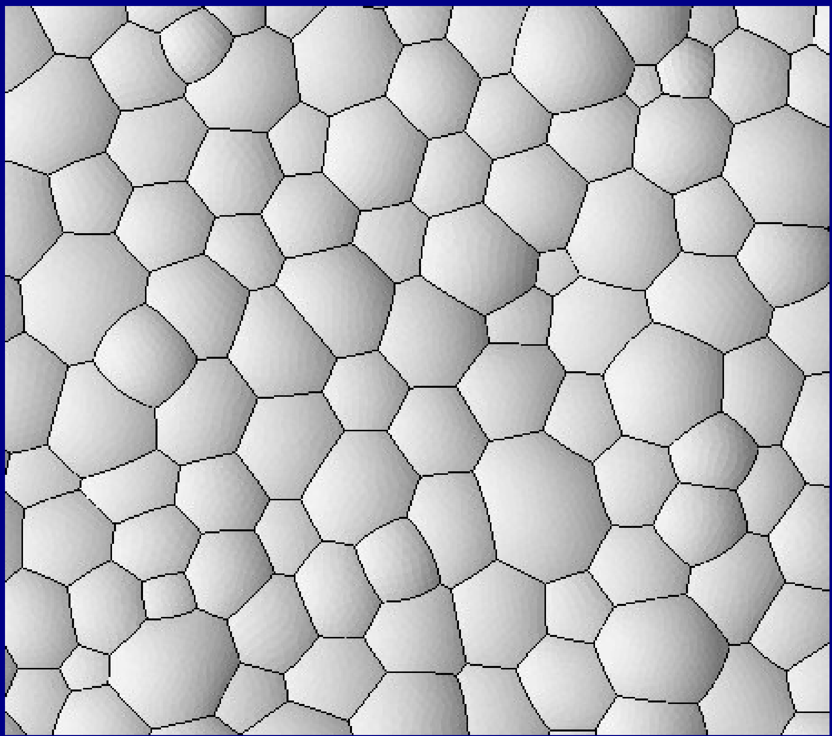
1. **Coalescence and bursting**

2. **Combined models**

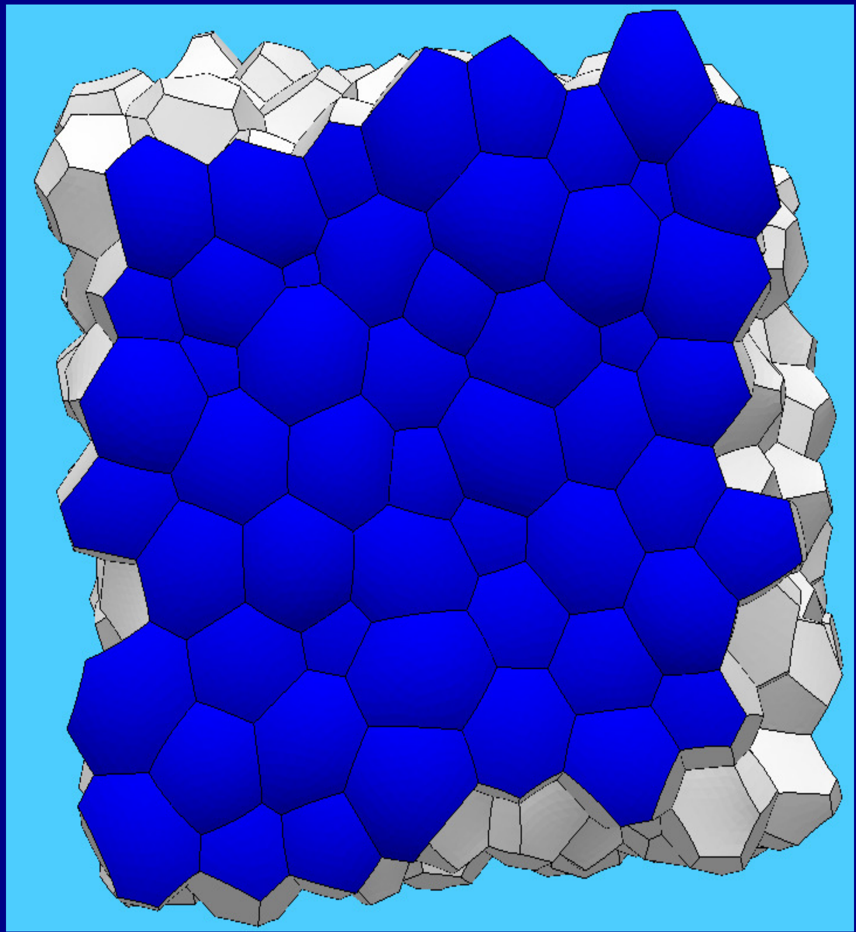
3. **Particle effects & properties**

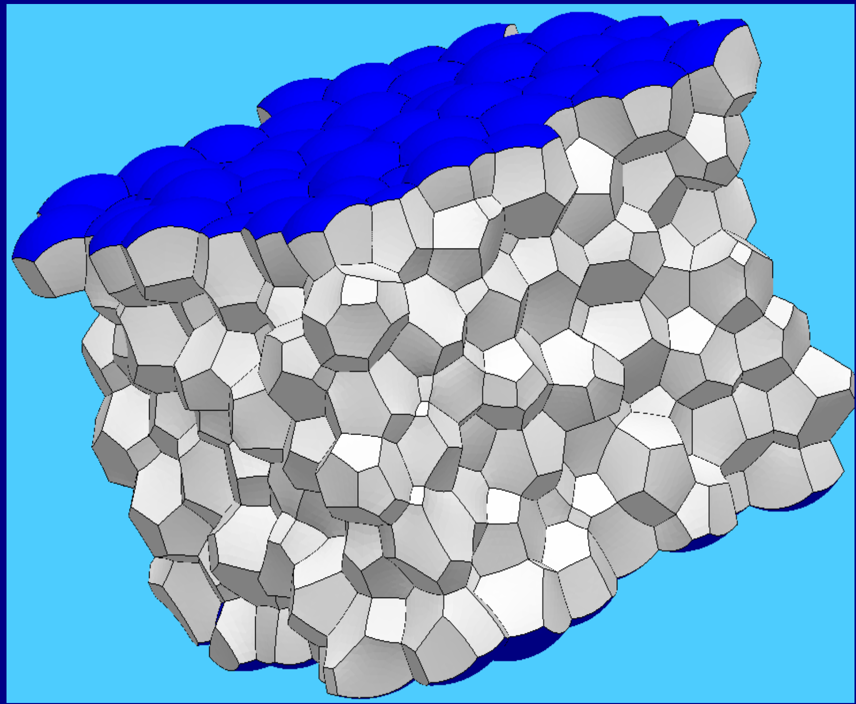
Froth Structure & Surface

Use simulated foam structures to investigate the relationship between foam surface and interior



Foams with Free Surfaces



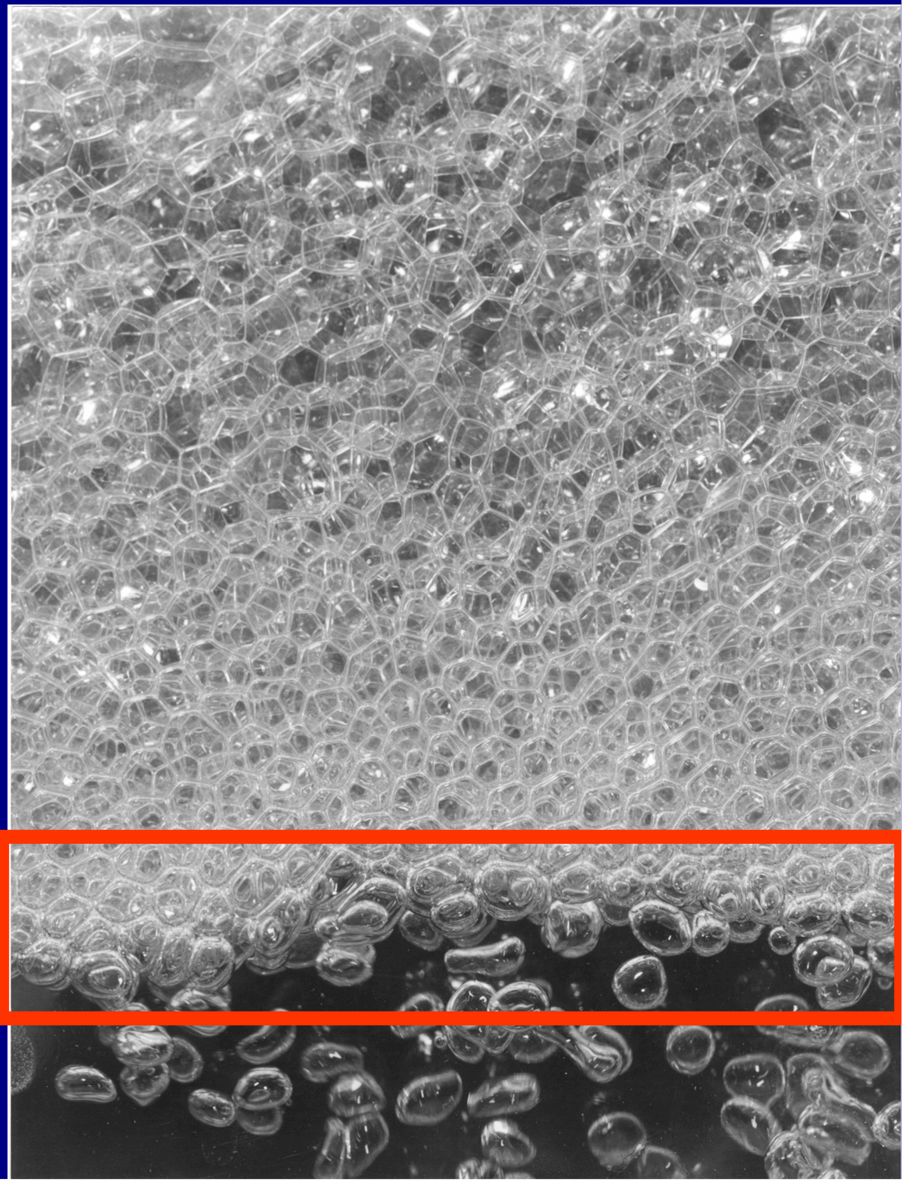


What is left to do?

1. Coalescence and bursting
2. Combined (CFD) models
3. Particle effects & properties

2. Combined (CFD) models
… linking the liquid and the froth

- Matching boundary conditions
- Flux of air, bubble size & distribution
- Particle size and concentration distribution
- Particle and liquid return from froth to pulp



3. Particle effects & properties

Describing continuous and multi-dimensional particle properties in CFD

Particle size, density, hydrophobicity...

Understanding Froths:
Summary

- Combined models to describe a complex multi-phase and dynamic system
- Successful application in understanding, design and operation
- Cannot yet predict coalescence and bursting, model the interface, and more
- Still lots to be done…

Imperial College London

UNDERSTANDING FROTH BEHAVIOUR WITH CFD

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Rio Tinto Professor

Royal School of Mines
Imperial College London