Problem 14.

Cellular Materials

The problem

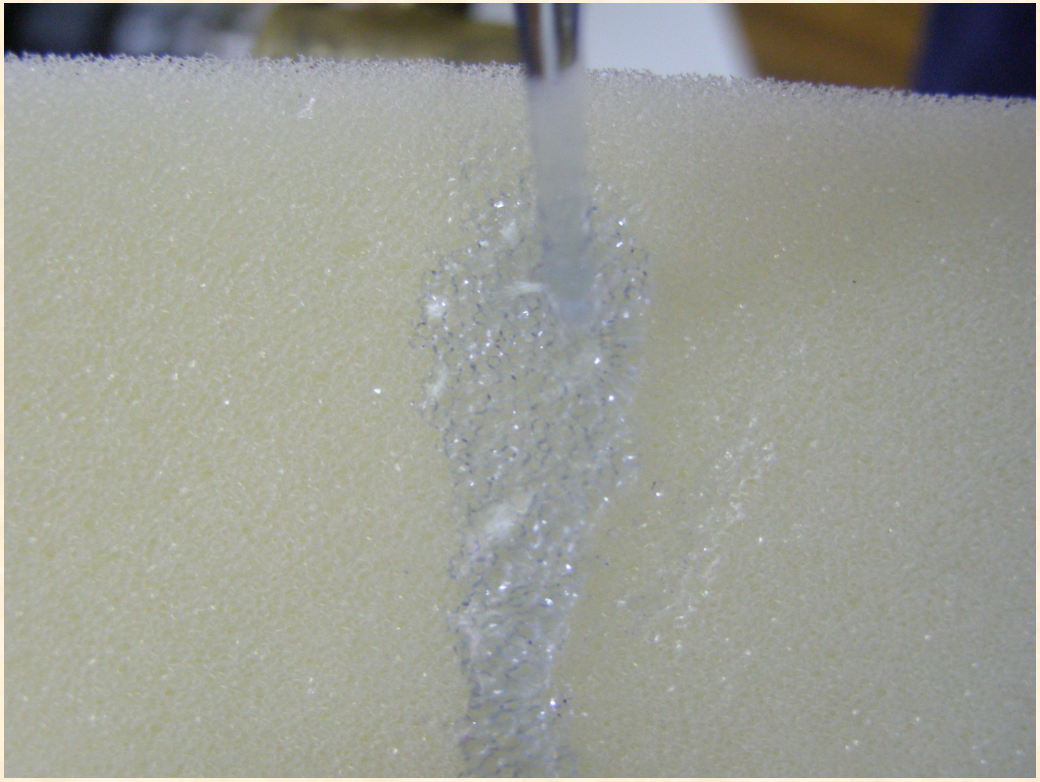
Investigate the behaviour of a stream of fluid when it strikes the surface of a sponge-like material.

Introduction

- Two investigation phases:
  - Liquid behaviour on surface – sponge penetration conditions
  - Behaviour inside sponge – life history
- Main parameters:
  - Liquid flow rate
  - Sponge angle
  - Intersurface tension
  - Sponge cell sizes

Surface behaviour

- **For some parameter values – liquid stays on sponge surface everywhere!**



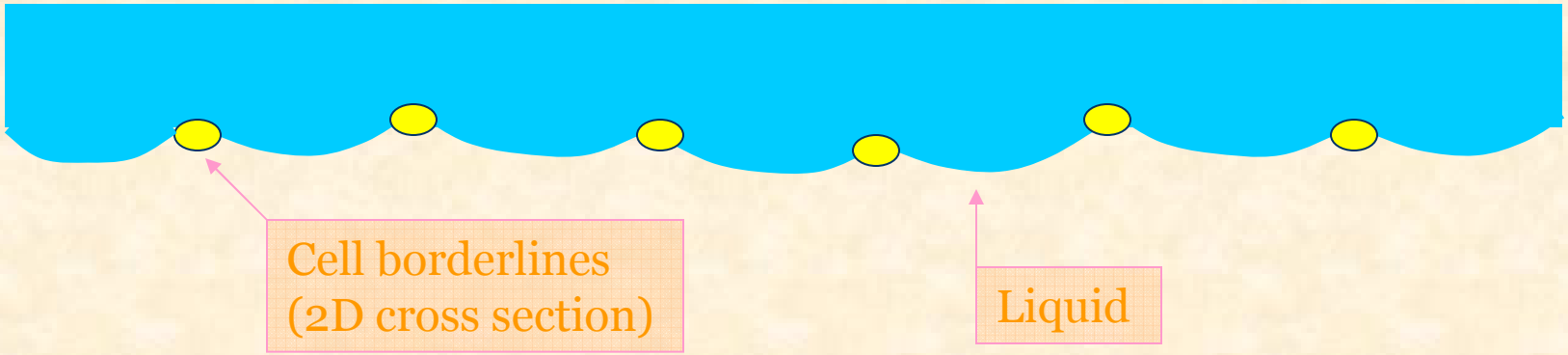
Surface behaviour cont.

- **For smaller surface tension/larger flow rate – penetration:**



Surface behaviour cont.

- **On cellular surface – surface tension membranes form:**



- **Membranes support liquid**
- **Penetration – membrane indention/separation from cell structure**

Surface behaviour cont.

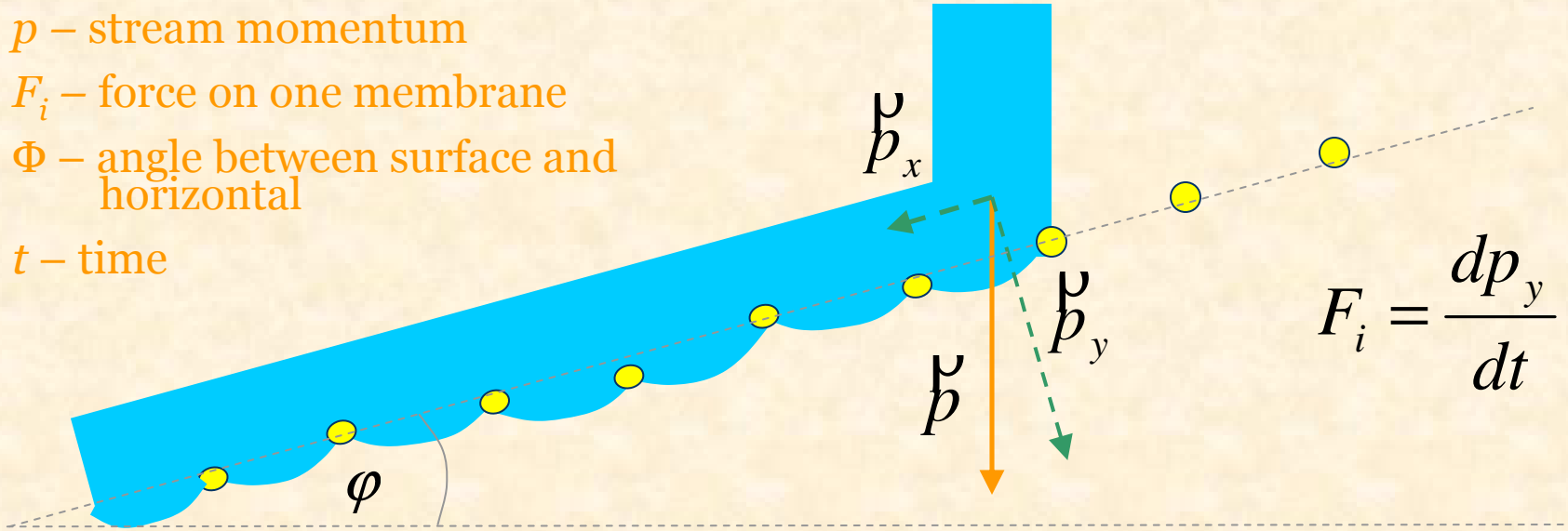
- **Largest force on membranes – stream hitting point**
- **Membranes annihilate fluid velocity component normal to surface:**

p – stream momentum

F_i – force on one membrane

Φ – angle between surface and horizontal

t – time



$$F_i = \frac{dp_y}{dt}$$

Surface behaviour cont.

- **Penetration condition:**

  Force on membranes at stream impact point larger than critical membrane value

$$\sum_i F_i \leq F_c$$

F_c – critical force

F_i – force on one membrane

Summation over membranes at impact site only

- **Force on membranes:**

$$\sum_i F_i = \frac{\rho}{S} Q^2 \cos^2 \varphi$$

ρ – liquid density

S – impact surface area

Q – volume flow rate

Surface behaviour cont.

- **Critical force:**
  - **Proportional to surface tension**
  - **Inversely proportional to mean cell area**

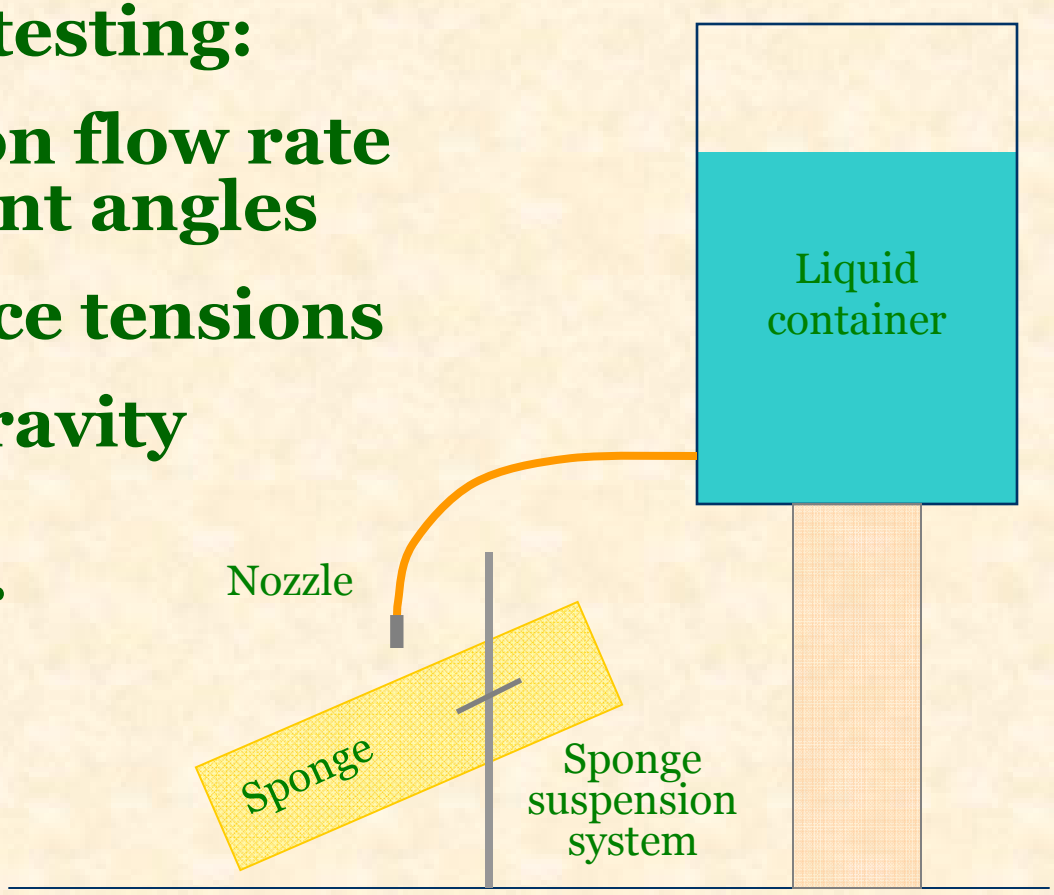
⇒ **Penetration condition:**

$$\frac{\rho}{S} Q^2 \cos^2 \varphi \geq \Gamma \frac{\sigma}{\langle S_i \rangle}$$

Γ – constant
S_i – mean cell area
σ – liquid surface tension

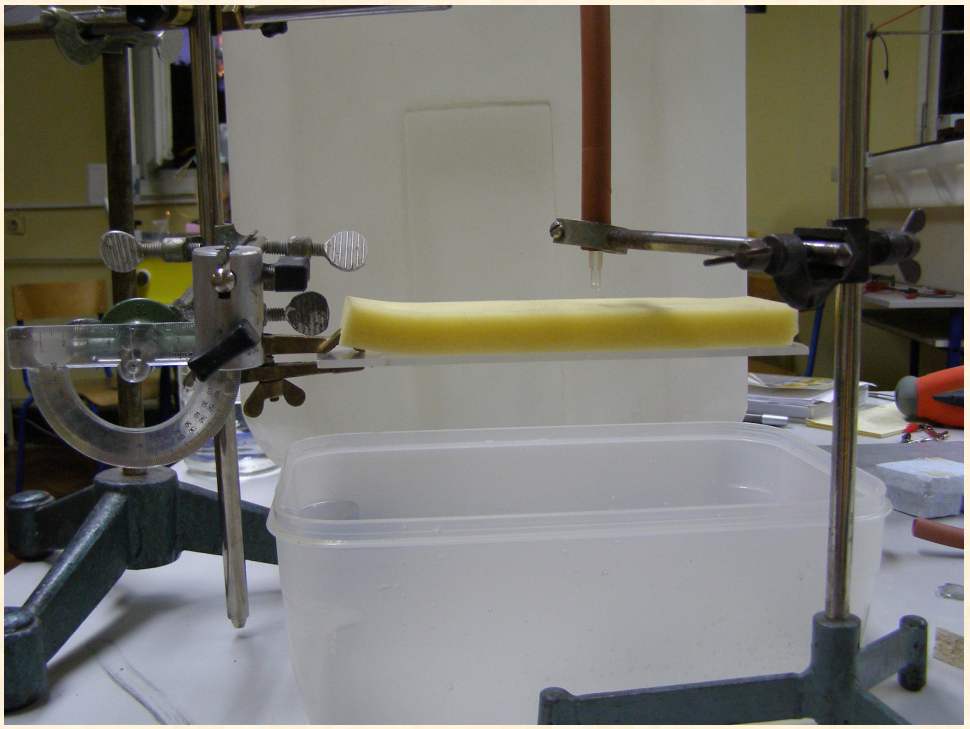
Surface behaviour cont.

- Experimental testing:
  - Penetration flow rate for different angles
  - Two surface tensions
- Apparatus – gravity driven flow
- Liquid – water
- Detergent

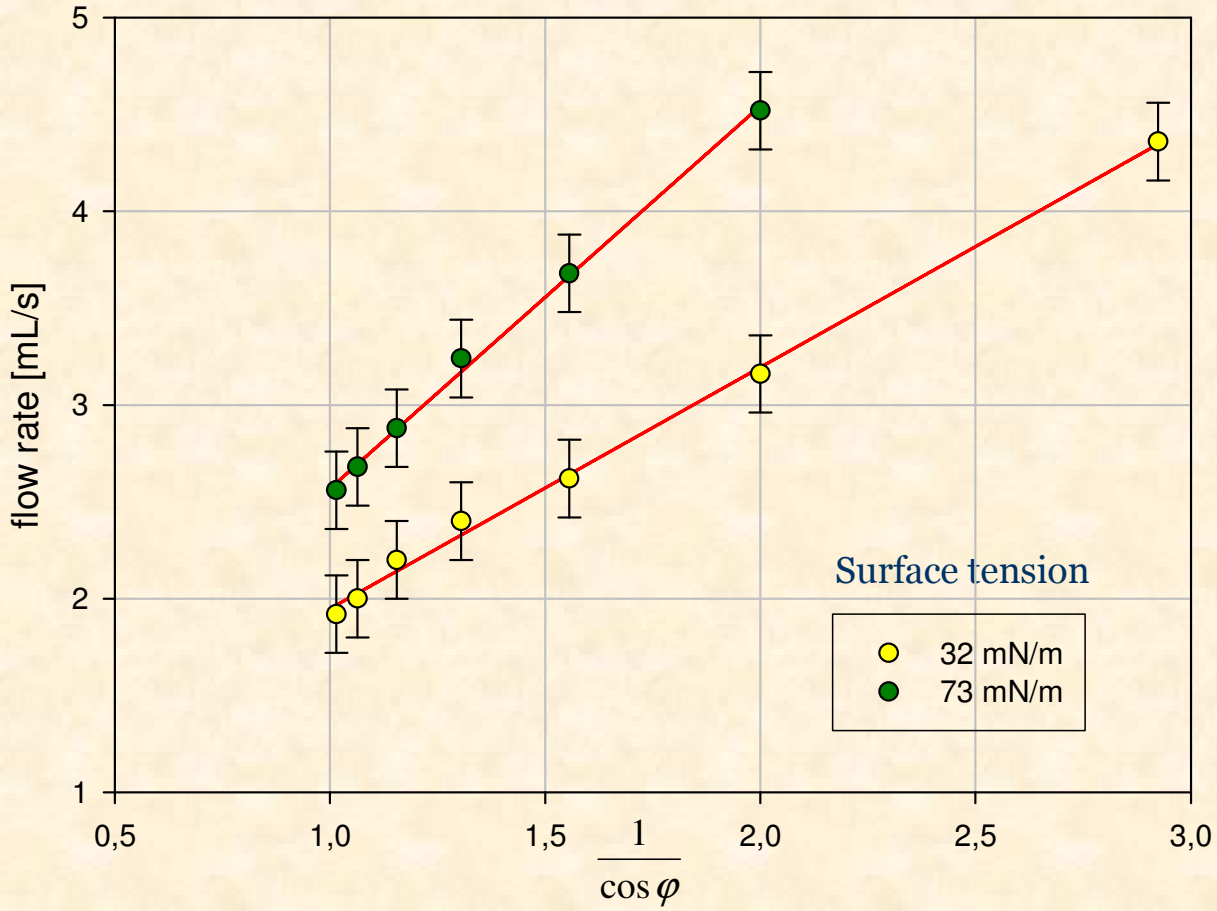


Surface behaviour cont.





Surface behaviour cont.

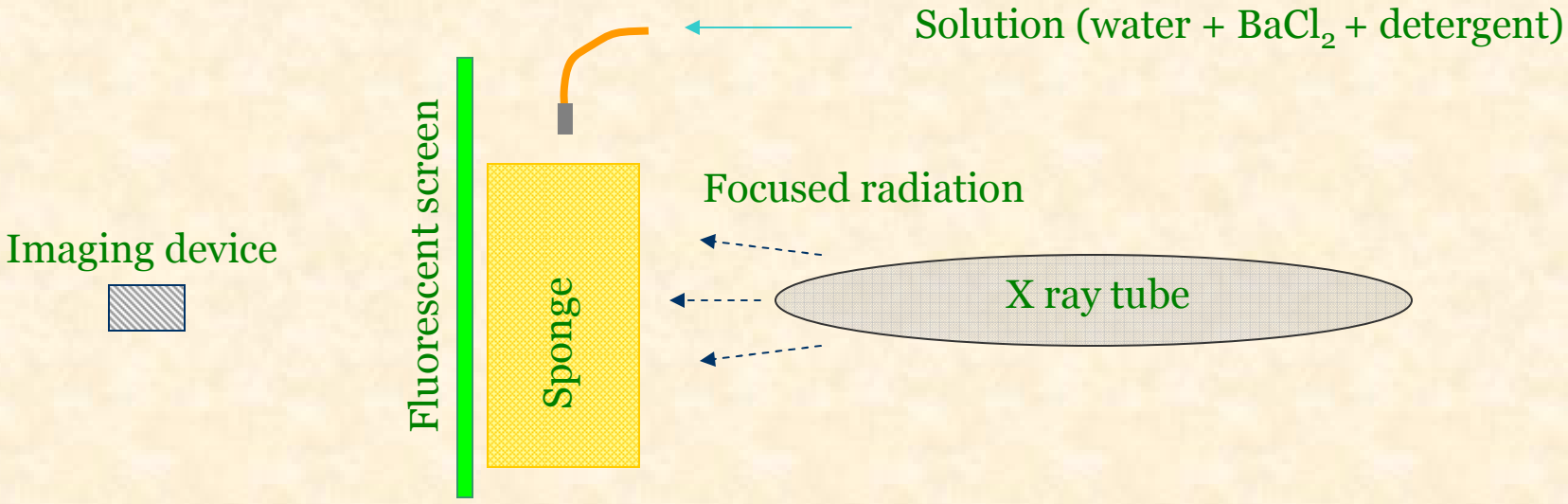


$$\Gamma_1 = 21\,\mathrm{m}^3$$

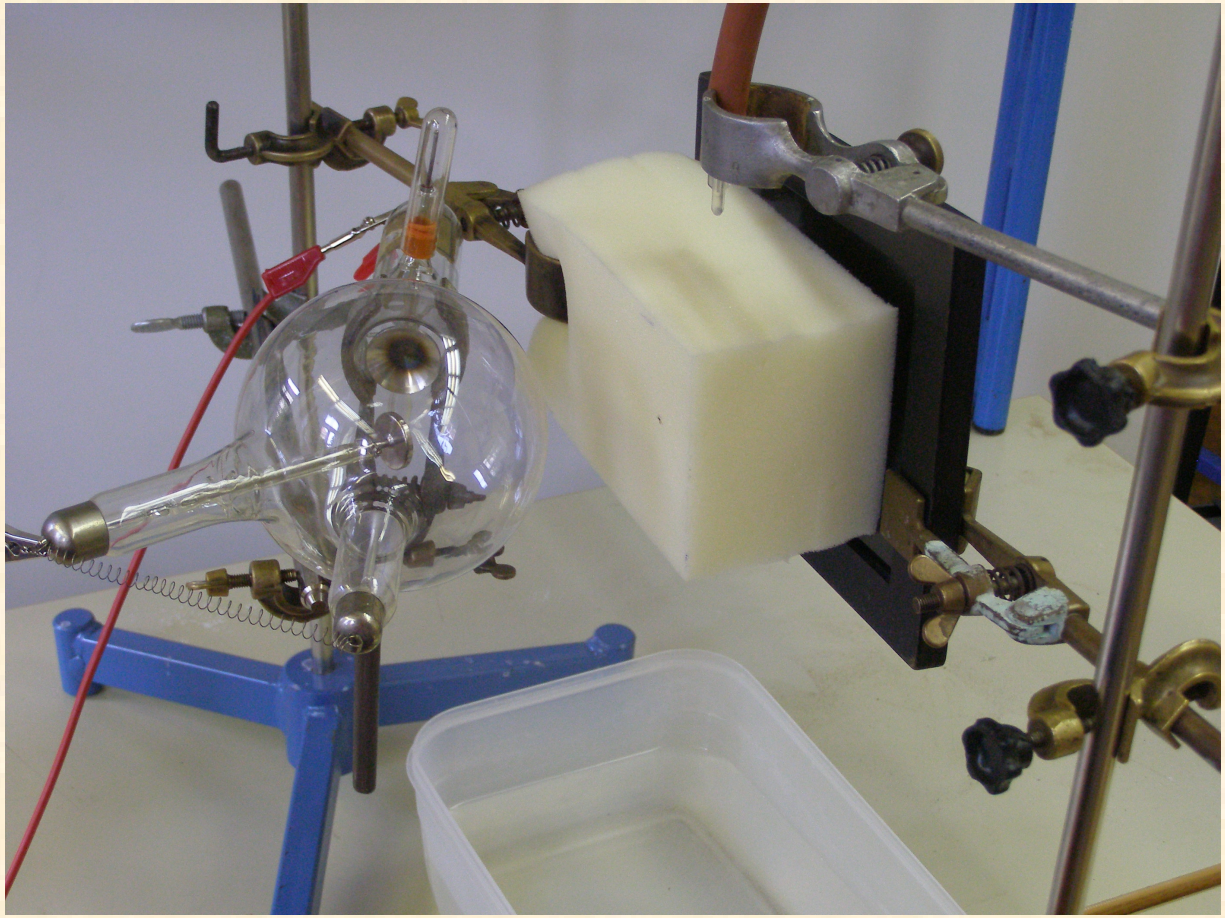
$$\frac{\Gamma_1}{\Gamma_2} = 0.9$$

Penetration and life history

- **If penetration occurs – distinct ″life history″ of stream behaviour**
- **Several general flow development phases**
- **Sponge imaging – x ray:**



Penetration and life history cont.



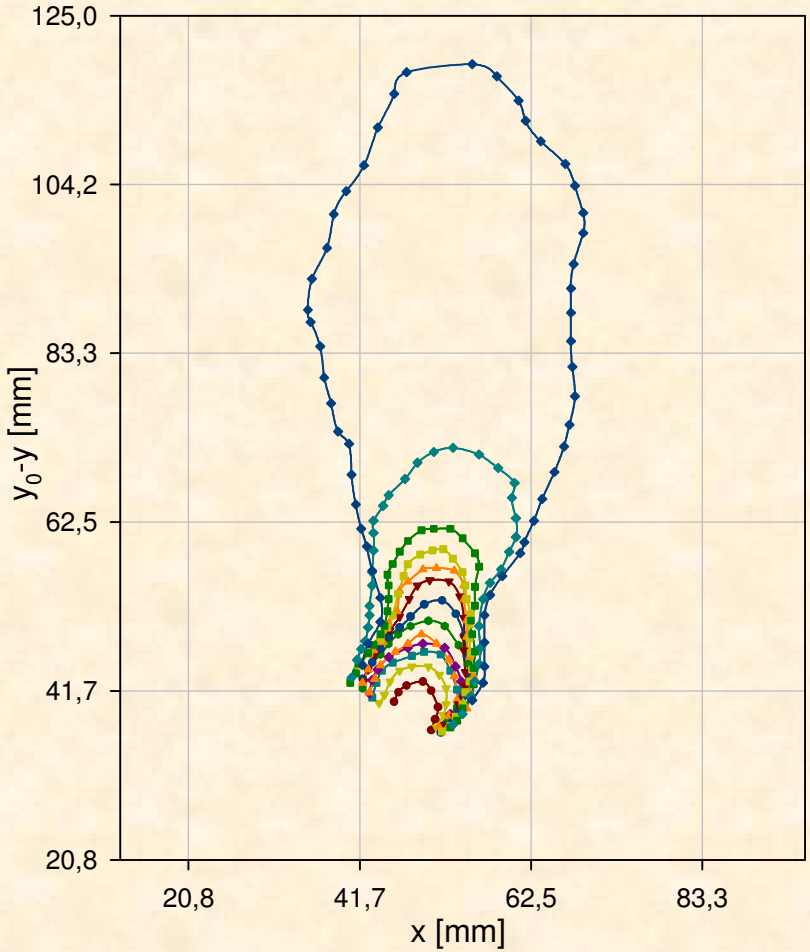
Penetration and life history cont.

- Flow structure – chaotical!
- Influences:
  - Hydrostatic pressure
  - Capillary effects
- For small-celled sponges – two distinct phases:
  - Liquid front penetration phase
  - Uniform flow through sponge

Penetration and life history cont.

- **Front propagation while penetrating:**

Take interval 8 s
Sponge mean cell size ~0.5 mm
Surface tension 26 mN/m
Volume flow rate 3.5 mL/s
Solution:
distilled water
$BaCl_2$ 0.1 M
surfactant



Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

surface flow reduced

front velocity growth

front size increase

Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

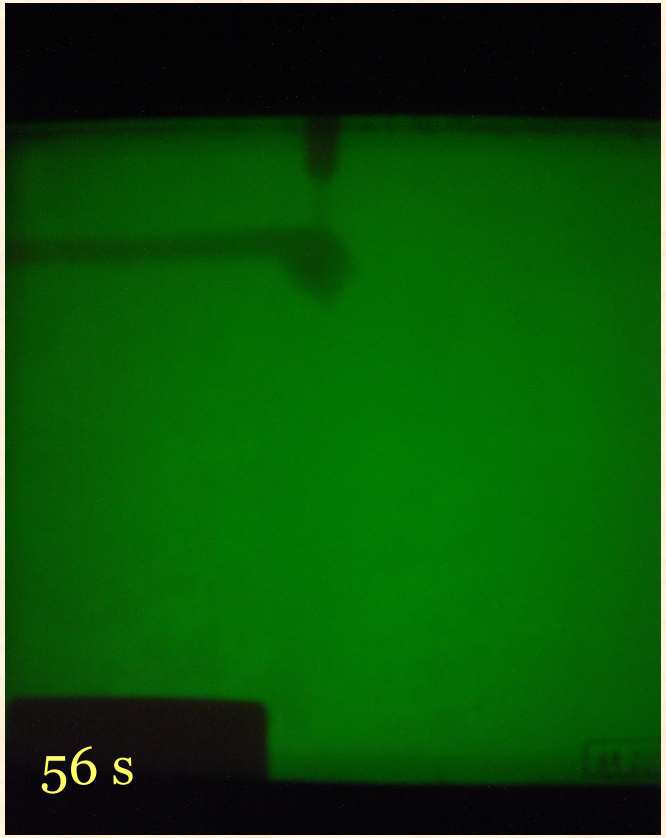
surface flow reduced

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front size increase

Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

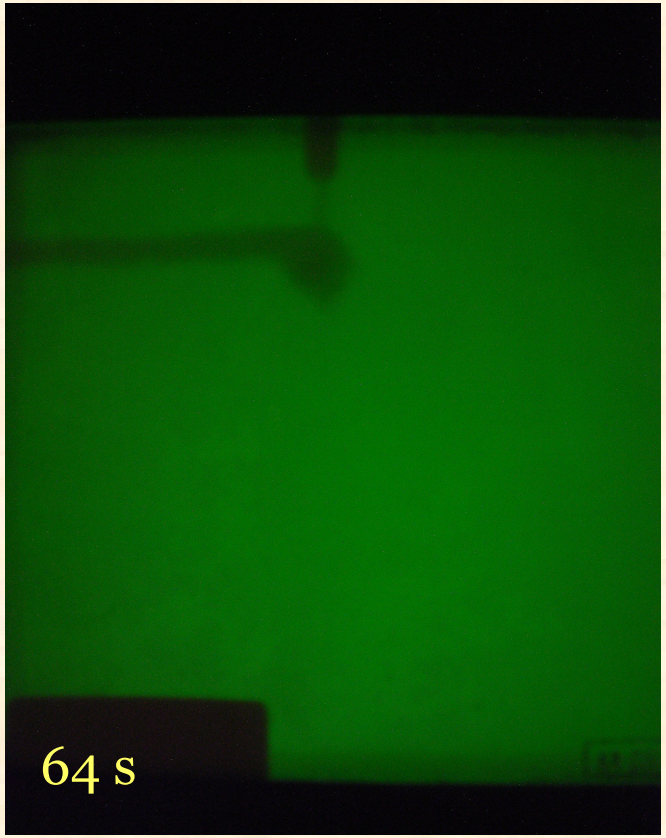
surface flow reduced

front velocity growth

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Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

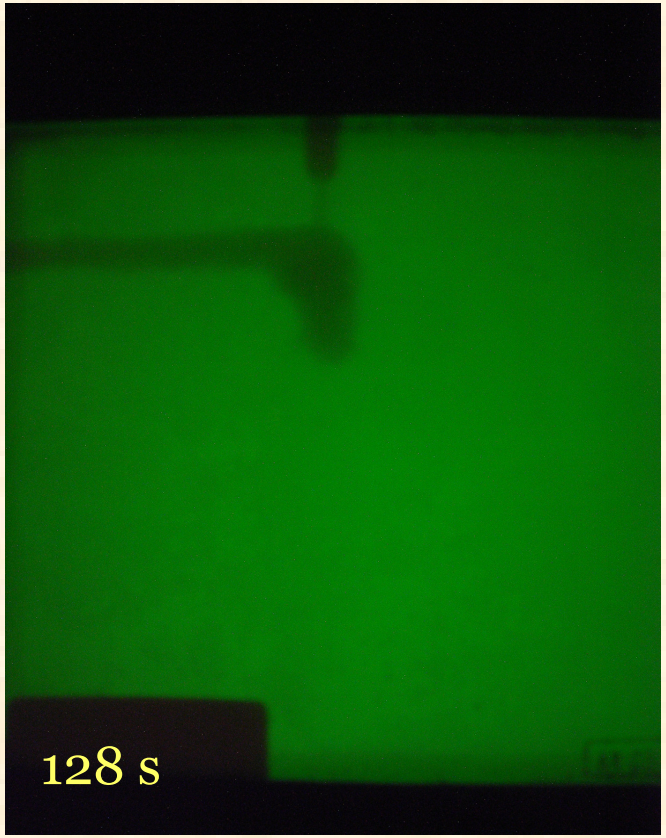
surface flow reduced

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Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

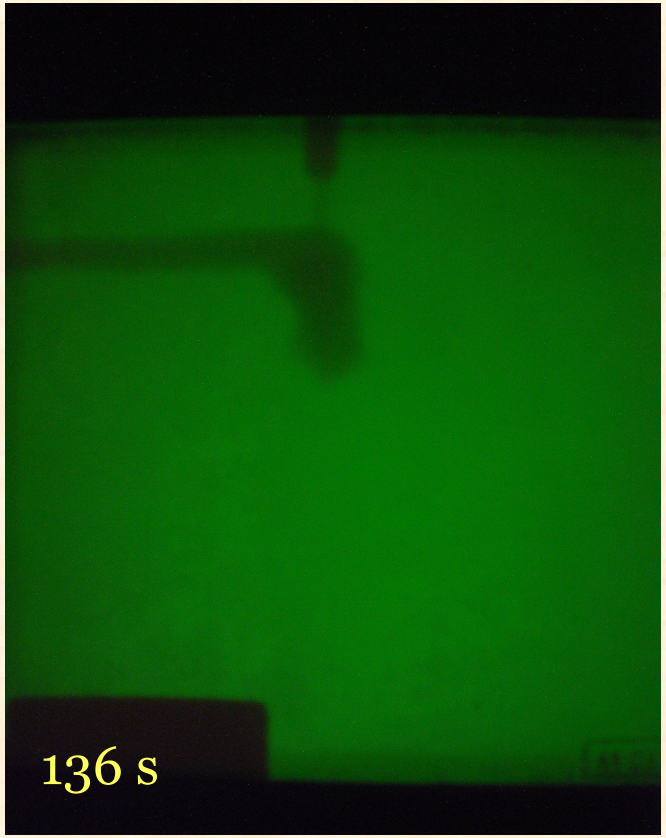
surface flow reduced

front velocity growth

front size increase

Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

surface flow reduced

front velocity growth

front size increase

Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

surface flow reduced

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Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

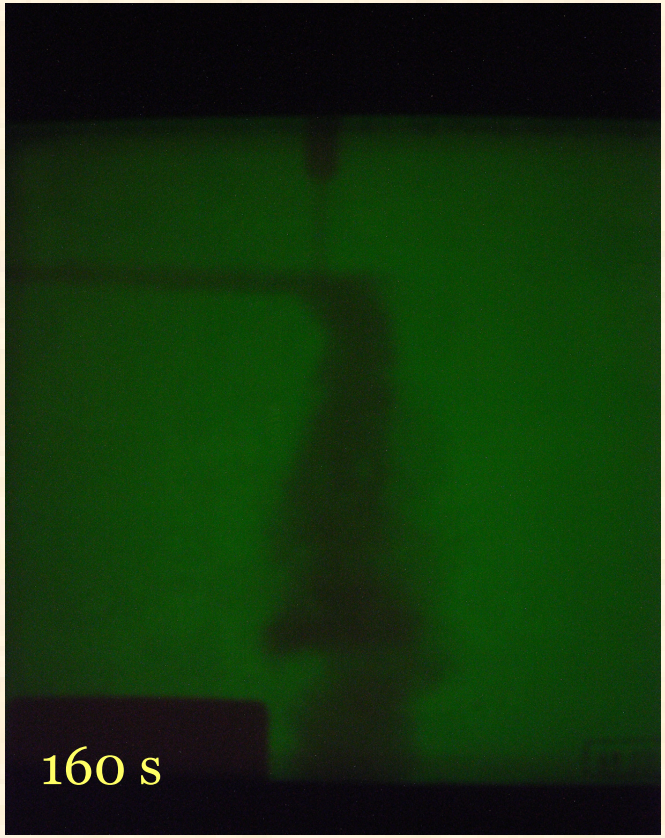
surface flow reduced

front velocity growth

front size increase

Penetration and life history cont.

- **Phase 1: penetration**



Distinct time evolution

While sponge draining accelerates:

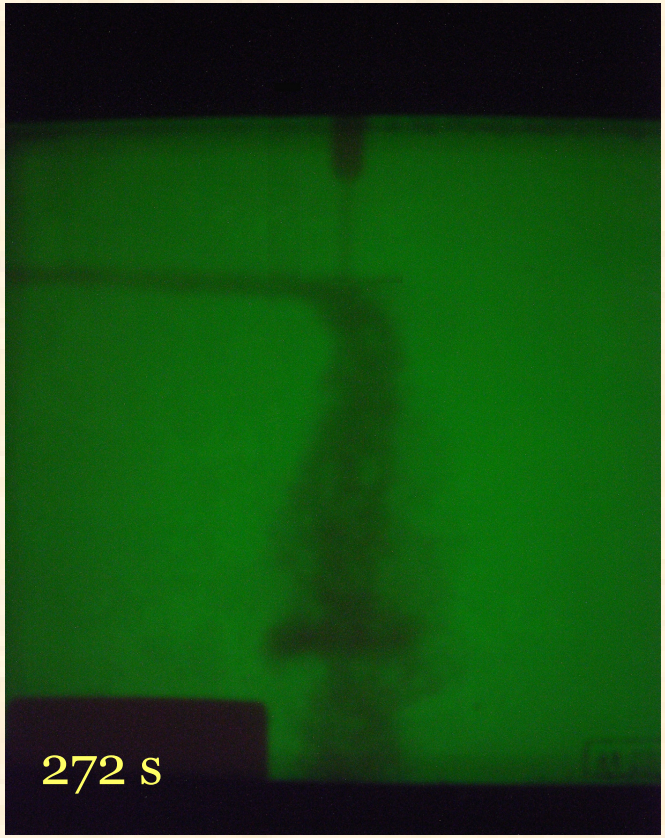
surface flow reduced

front velocity growth

front size increase

Penetration and life history cont.

- **Phase 2: uniform flow**



No evolution

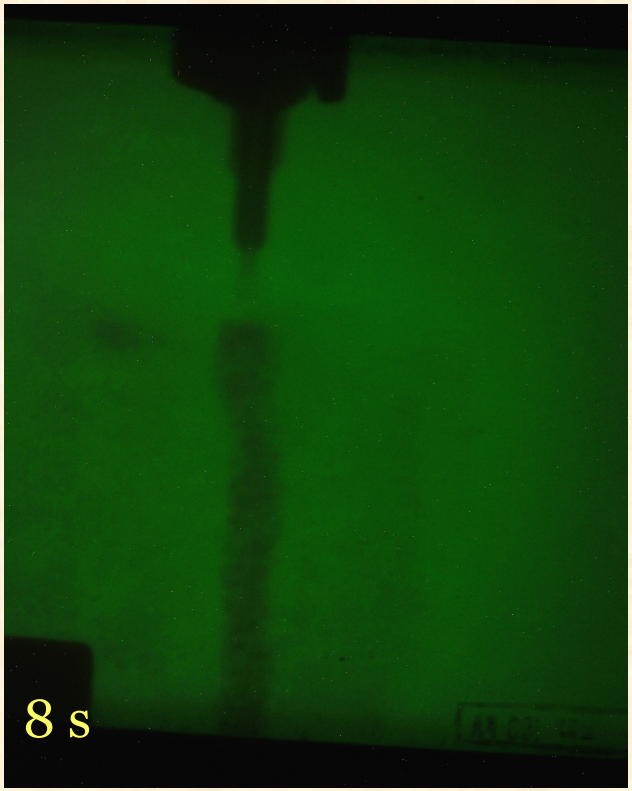
Steady flow

No surface flow – all liquid in sponge

Velocity – viscous drag dependent

Penetration and life history cont.

- **For large-celled/hydrophobic sponges – second phase occurs instantaneously:**



No structure

Narrow liquid line

Small dispersion

Mean cell size 1.0 mm

Penetration and life history cont.

- **Explanation – liquid front propagation mechanism:**
  - **front velocity approximately**

$$v_f \approx \frac{\langle r_i \rangle}{\tau}$$

r_i – mean cell borderline length

τ – mean membrane duration

  - **Membrane duration at lowest position – inversely proportional to force:**

$$\frac{1}{\tau} \sim \rho g z_f + \Delta P_0$$

ρ – liquid density

z_f – penetration depth

ΔP_0 – difference between critical membrane pressure and stream redirection pressure

Penetration and life history cont.

⇒ **Approximate front propagation equation:**

$$\frac{dz_f}{dt} = \beta\left(\rho g z_f + \Delta P_0\right)$$

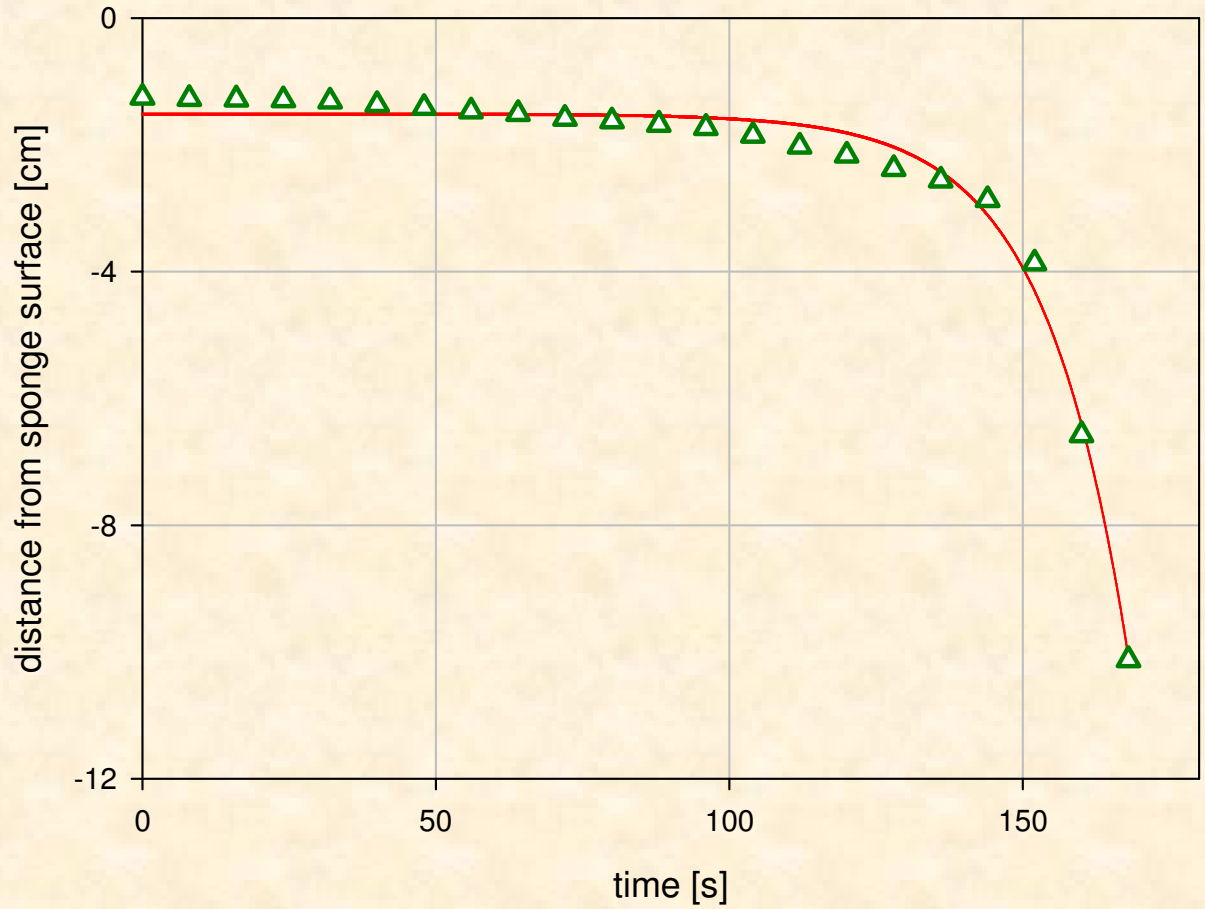
β – proportionality constant

⇒ **Exponential depth increase:**

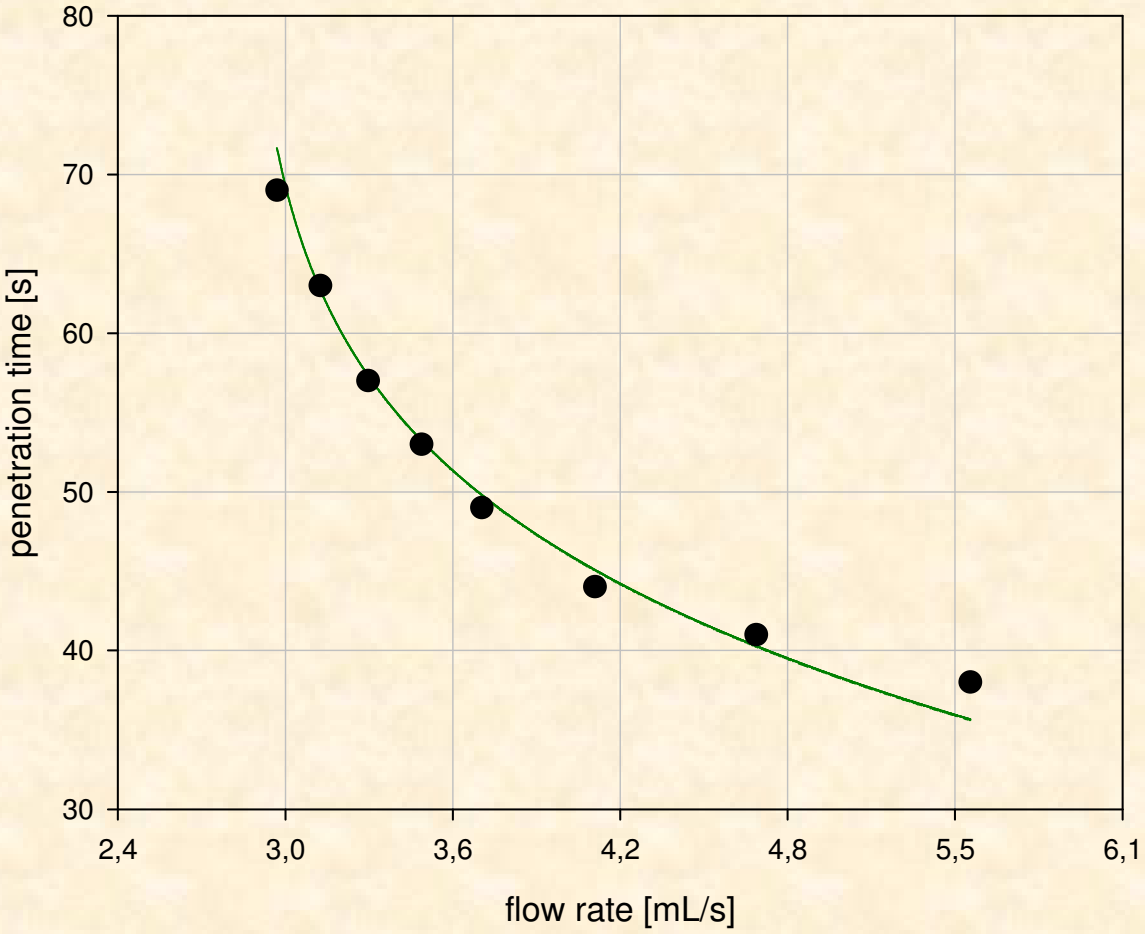
$$z_f(t) = \frac{\Delta P_0}{\rho g}\left(e^{\beta\rho g t} - 1\right)$$

- **Experimentally substantiated:**

Penetration and life history cont.



Penetration and life history cont.



$$\Gamma = 19\ \mathrm{m}^3$$

=> Constants in surface dynamics considerations and penetration model match!

Conclusion