Multiphase Research toward the Development of Novel Fluid Management Systems aboard Spacecraft

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…

- **ISS Fluids Experiments…**
  - Handheld: CFE
  - Automated: CCF
- **Applications…**
  - Coffee cups to micro-fluidics

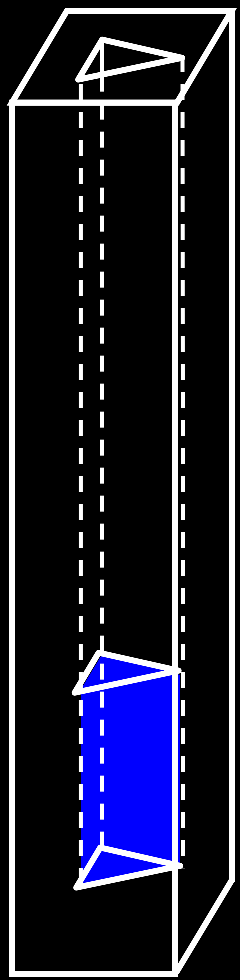
Portland State UNIVERSITY

Spacecraft Capillary Fluid Systems

- **Liquid propellants**
- **Life Support systems, primarily water processing:** plants, animals, crew
- **Phase-change thermal systems and power cycles**
- **Routine fluids management:** medical, experiments, food…

Challenges…

Capillary-Driven Corner Flow



Review of Theory

N.S. equation: $$Su\frac{D\mathbf{U}}{Dt} = -\nabla P + \nabla^2\mathbf{U} + Bo\,\mathbf{g}$$

Assumptions:

- Wetting fluid satisfying Concus-Finn condition, i.e. $\theta < \pi / 2 - \alpha$
- Locally parallel flow—slender fluid column

<u>***z*-comp. N.S.:**</u>

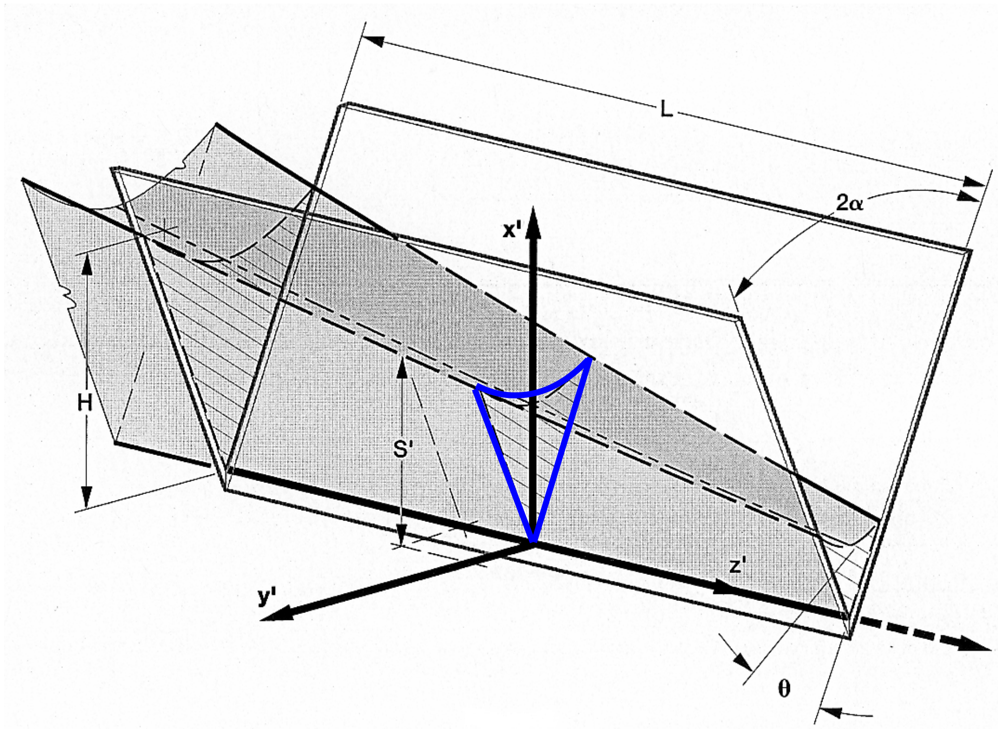
$$\frac{1}{\mu}\frac{\partial P}{\partial z} = \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}$$

<u>**Global mass balance:**</u>

$$\frac{\partial A}{\partial t} = -\frac{\partial \dot{Q}}{\partial z} = -\frac{\partial}{\partial z}\left(A\langle w\rangle\right)$$

<u>**Sample Gov. PDE:**</u>

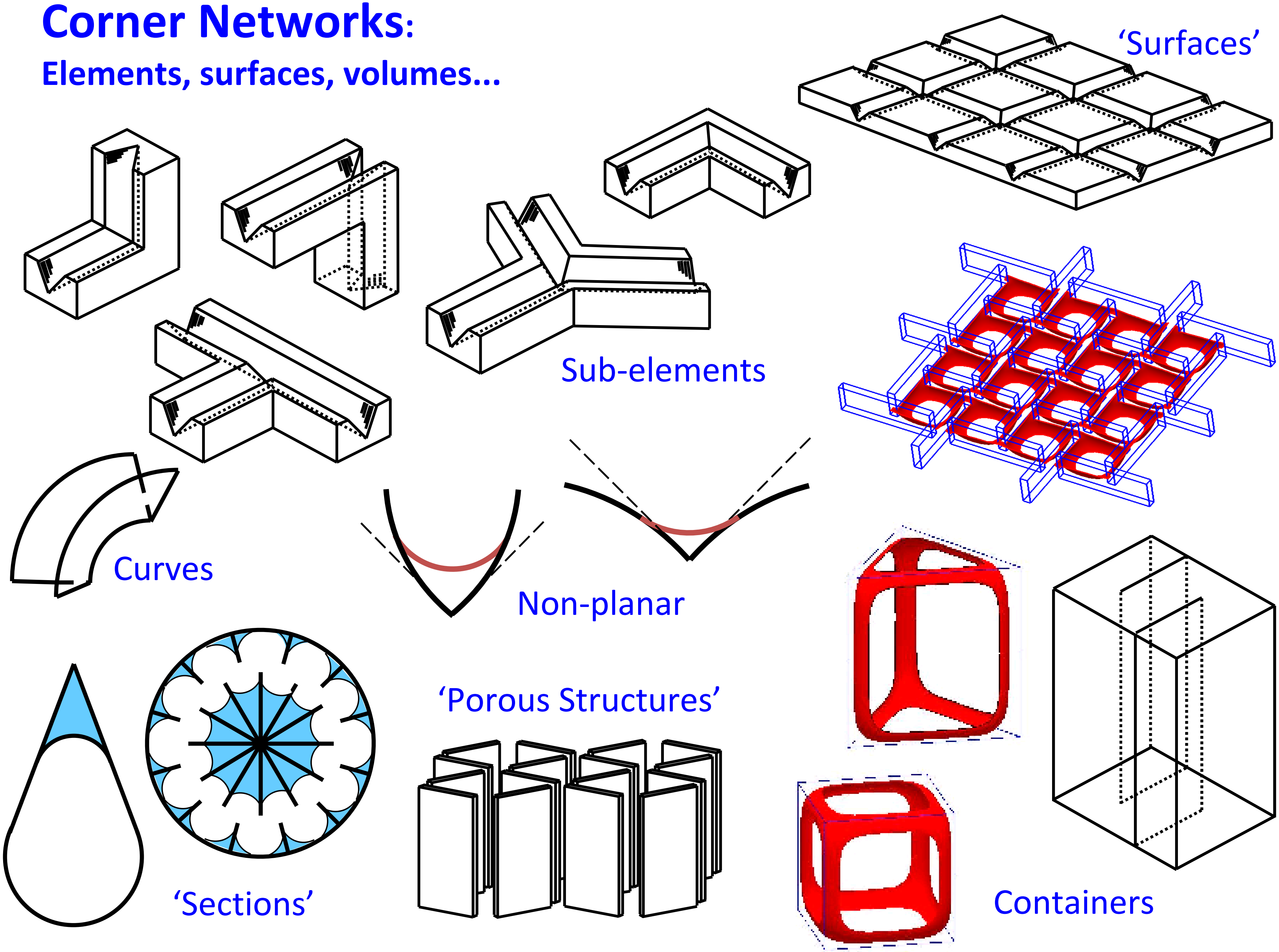
$$\frac{\partial h}{\partial t} = 2\left(\frac{\partial h}{\partial z}\right)^2 + h\frac{\partial^2 h}{\partial z^2}$$



…leads to analytic solutions…needs B.C.s…

Corner Networks:

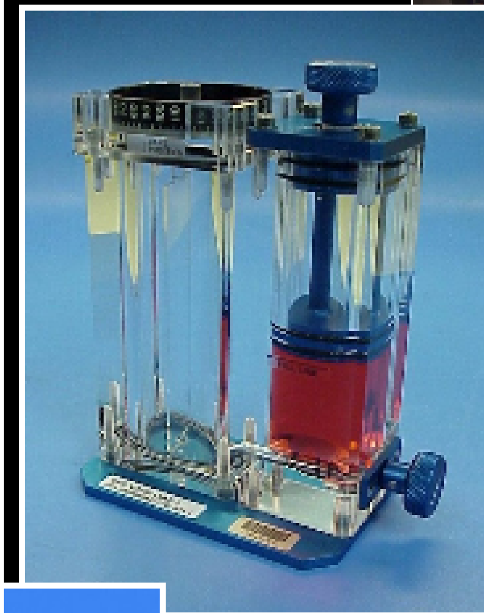
Elements, surfaces, volumes...



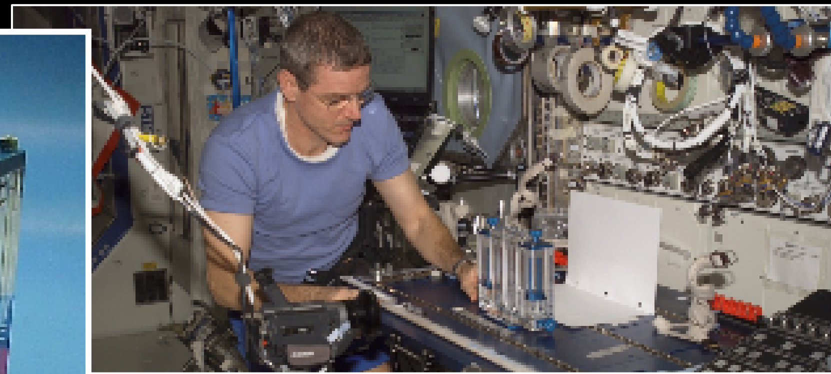
CFE on ISS

ICF-1

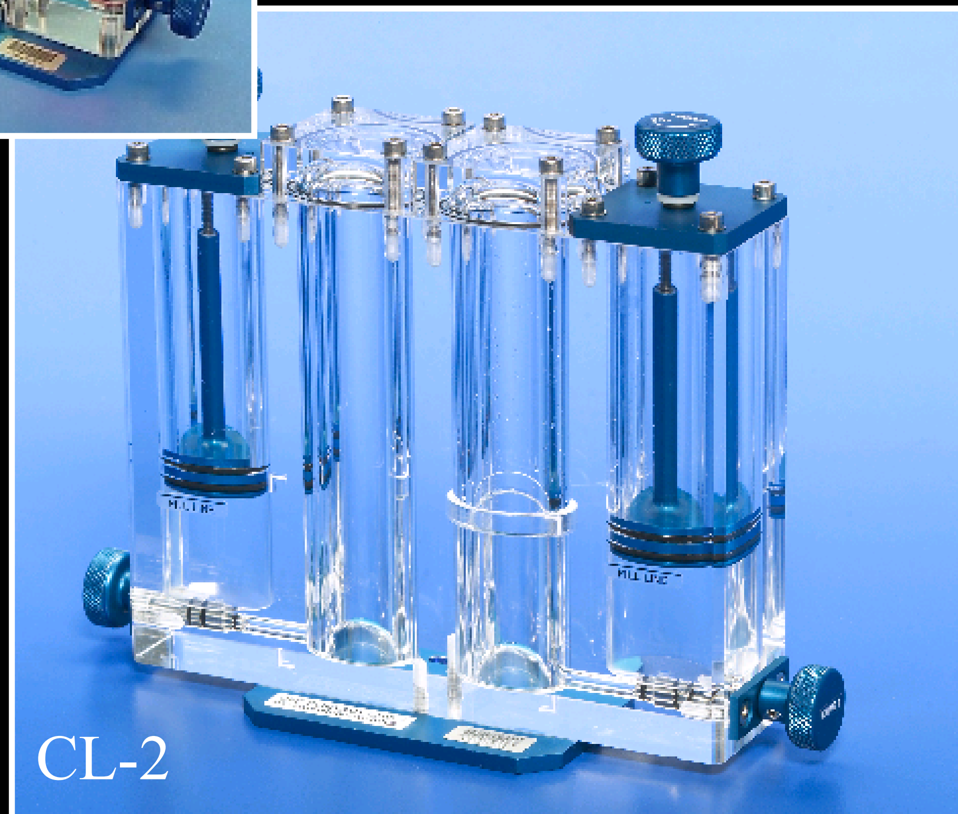
VG-1



W.McArthur

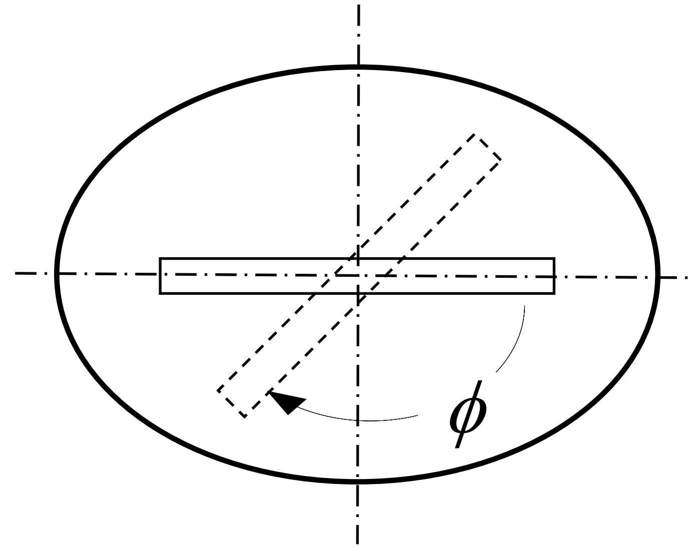


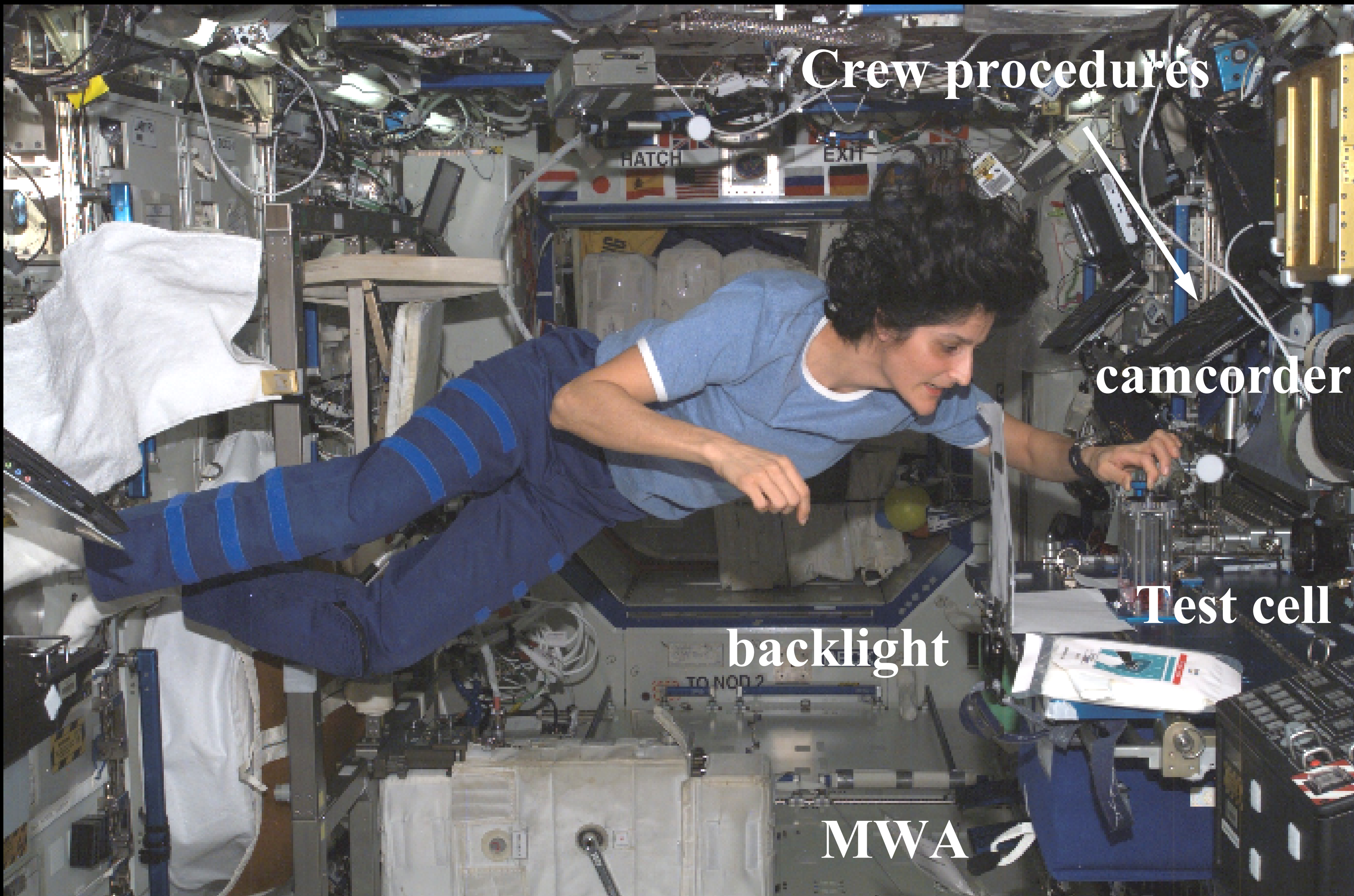
ICF-2



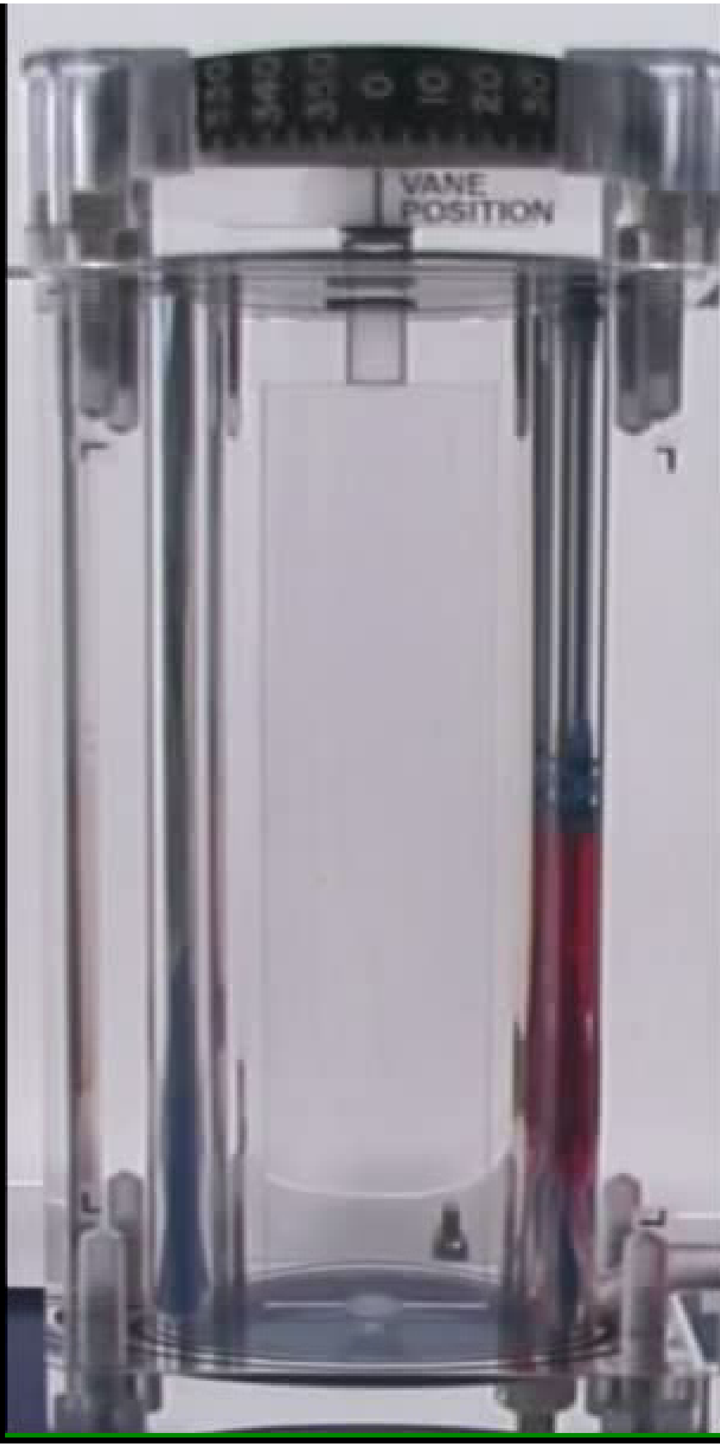
CL-2


VANE
POSITION
FILL LINE


ϕ



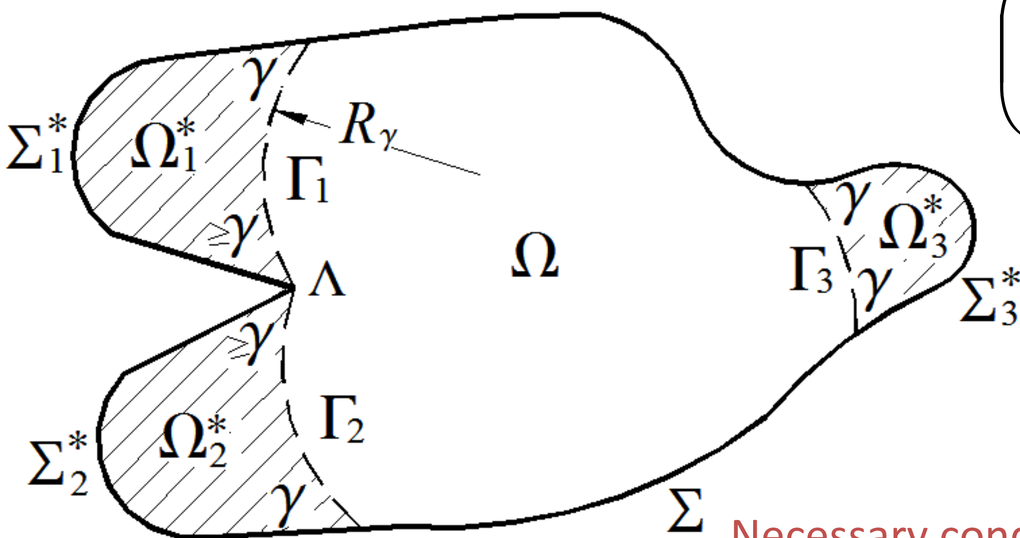
Sunita Williams, CFE-VG-2


VANE
POSITION


VANE POSITION
VANE POSITION
VANE POSITION
VANE POSITION

Existence - A Necessary Condition

$$R_\gamma = \frac{\Omega}{\Sigma \cos\gamma}$$



Integrating YLG over □*

$$\left(\frac{\Sigma}{\Omega}\Omega^* - \Sigma^*\right)\cos\gamma = \int_\Gamma \upsilon \cdot \mathbf{T}u \, ds$$

$$\left|\mathbf{T}u\right| = \frac{\left|\nabla u\right|}{\sqrt{1+\left|\nabla u\right|^2}} < 1$$

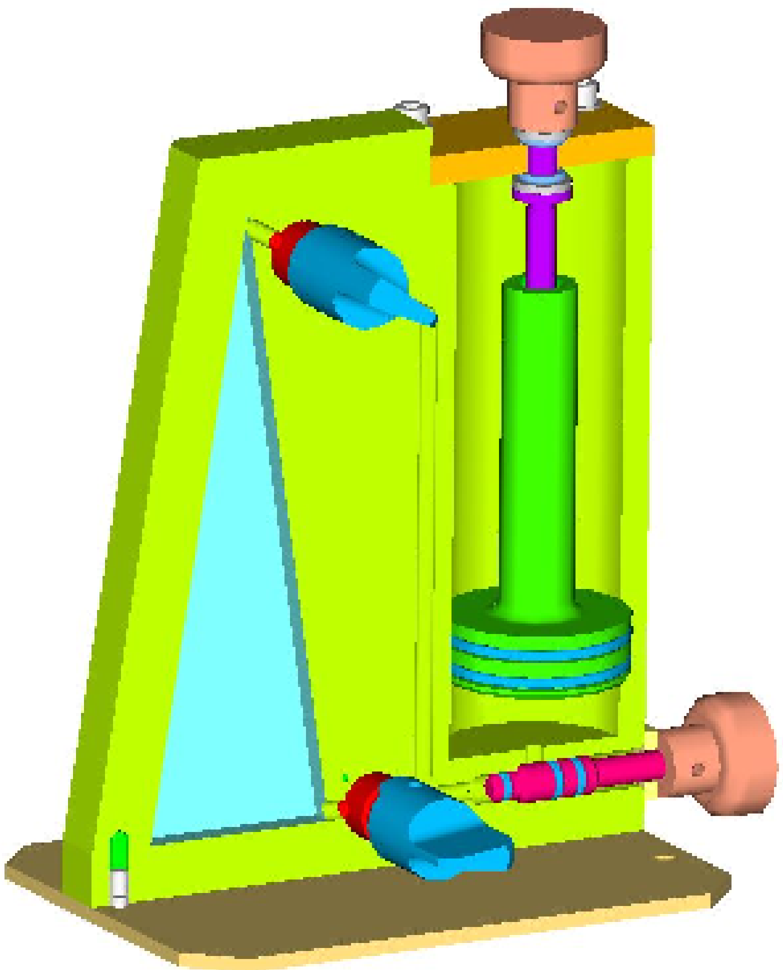
Necessary condition:

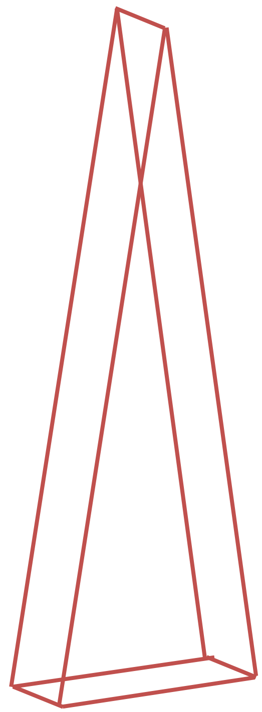
$$\Phi\left(\Omega^*\right) \equiv \Gamma - (\cos\gamma)\Sigma^* + \left(\frac{\Sigma\cos\gamma}{\Omega}\right)\Omega^* > 0$$

Remark: Existence if no arc □ admitted;
at □=0, existence depends.

P. Concus and R. Finn, 1974

CFE: Interior Corner Flow…





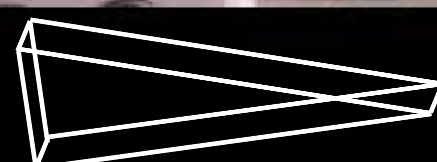
2-D taper

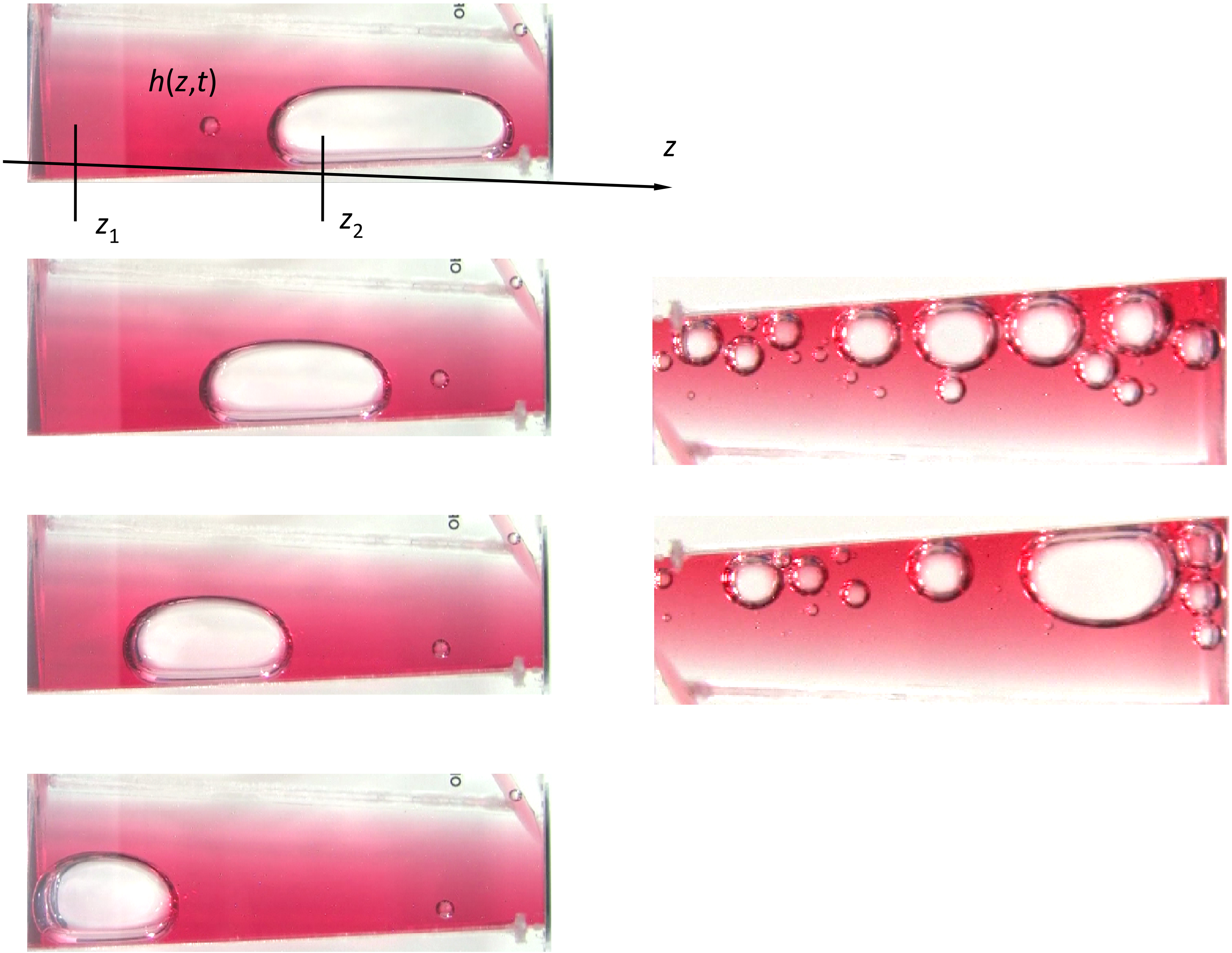
Phase Separation

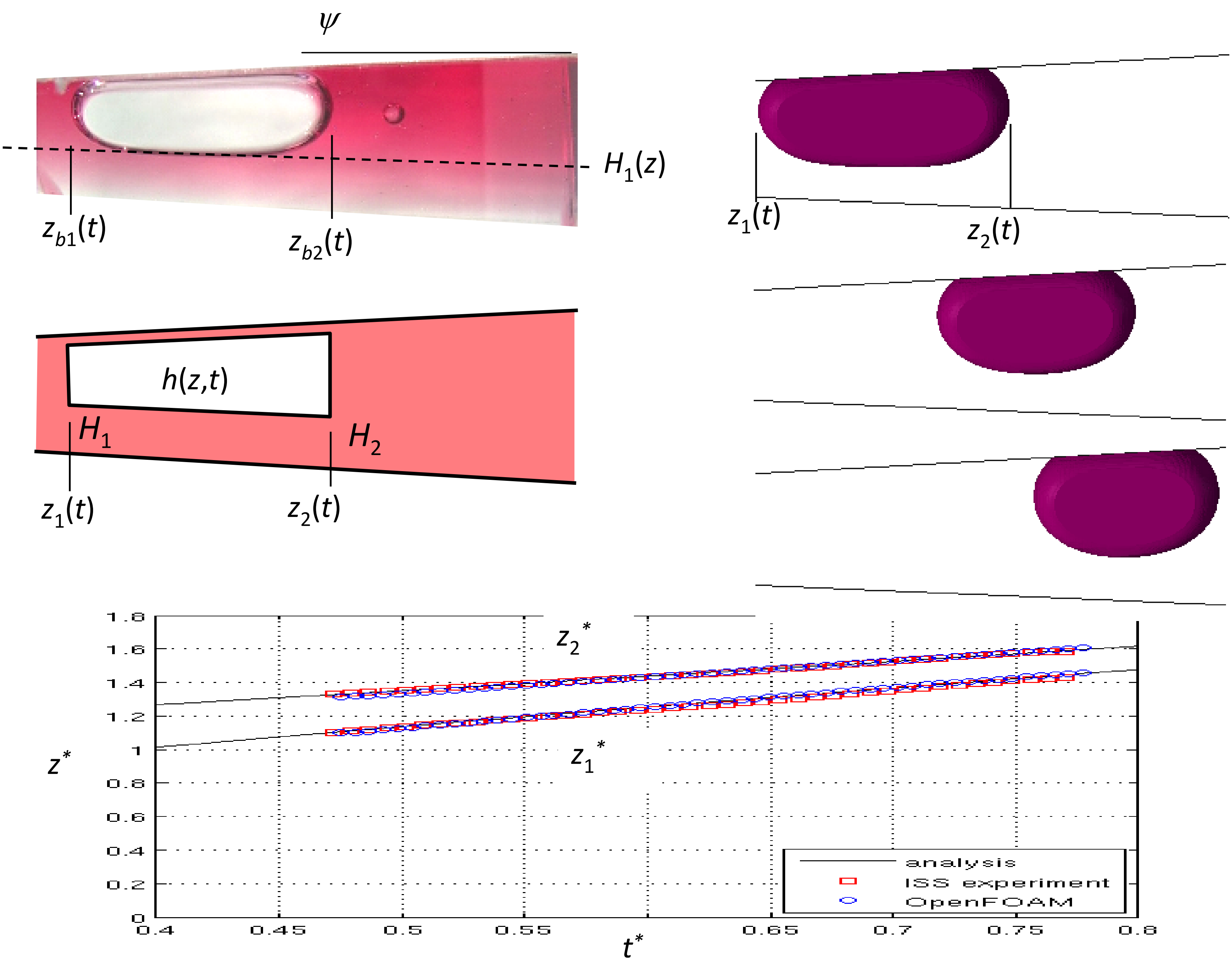
64x

24x

CFE-2; ICF-2, linear taper

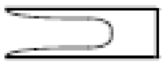
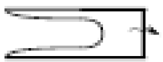
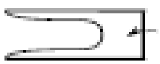
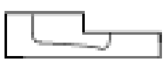
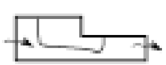


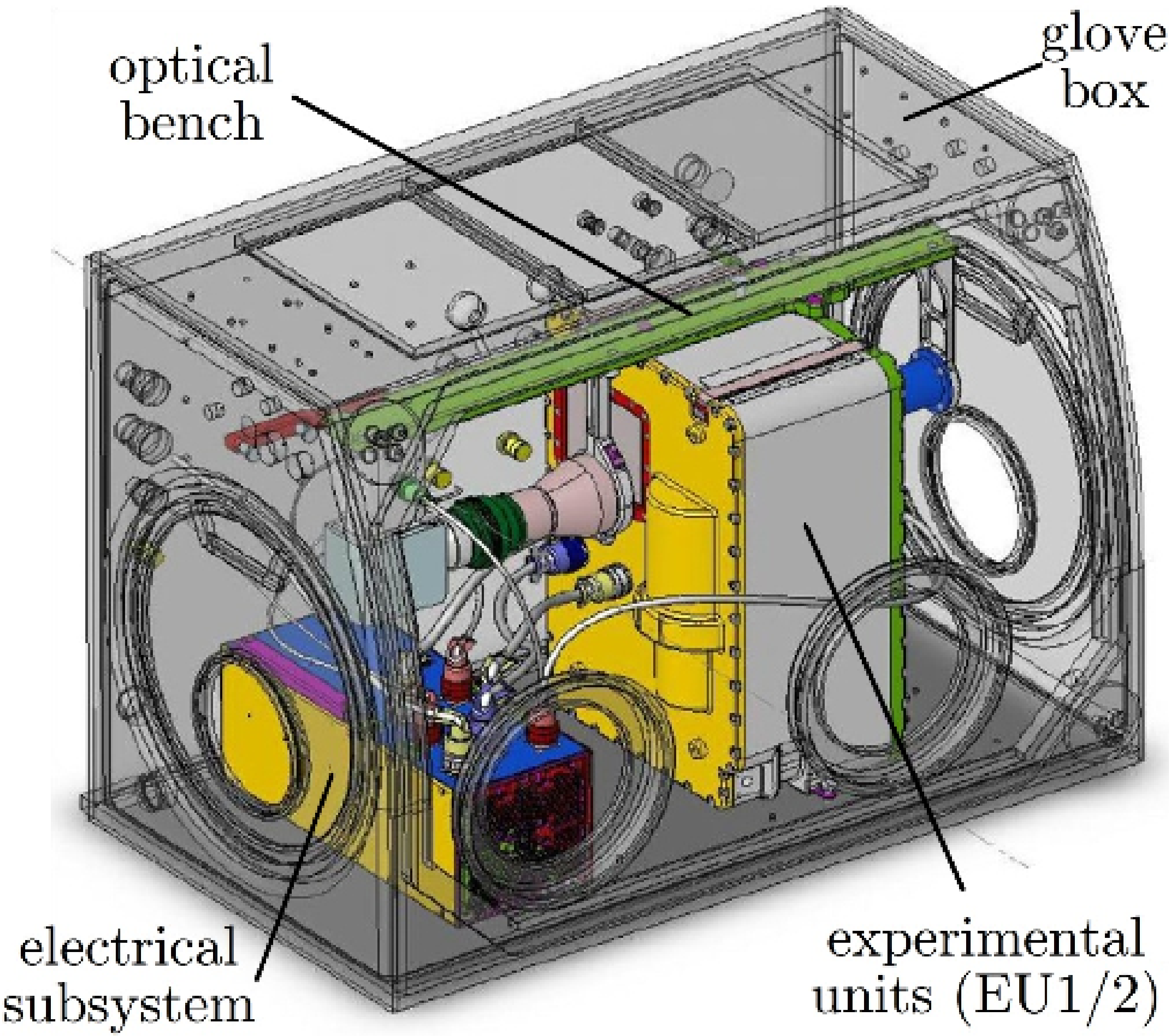

$h(z,t)$
z
z_1
z_2

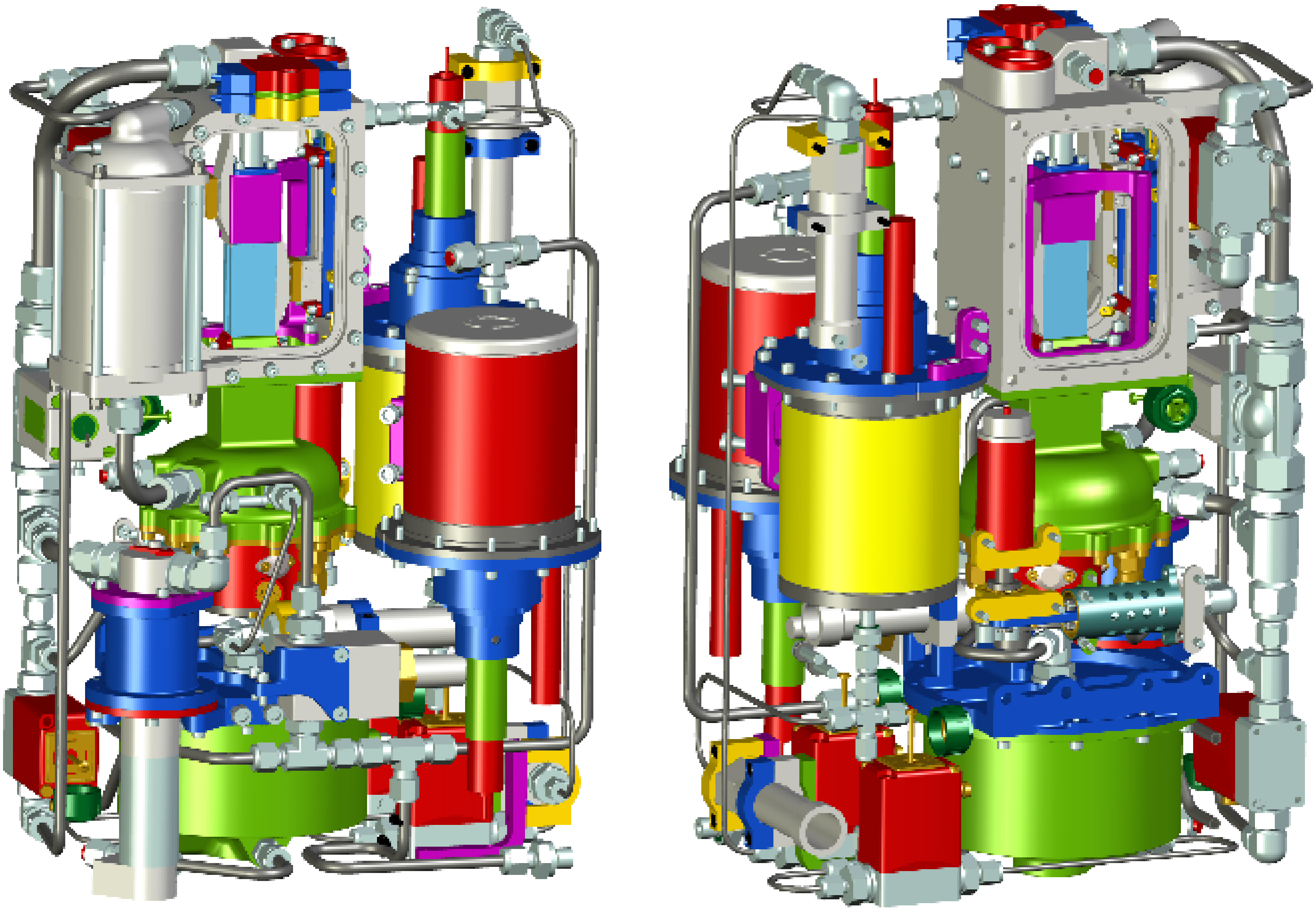


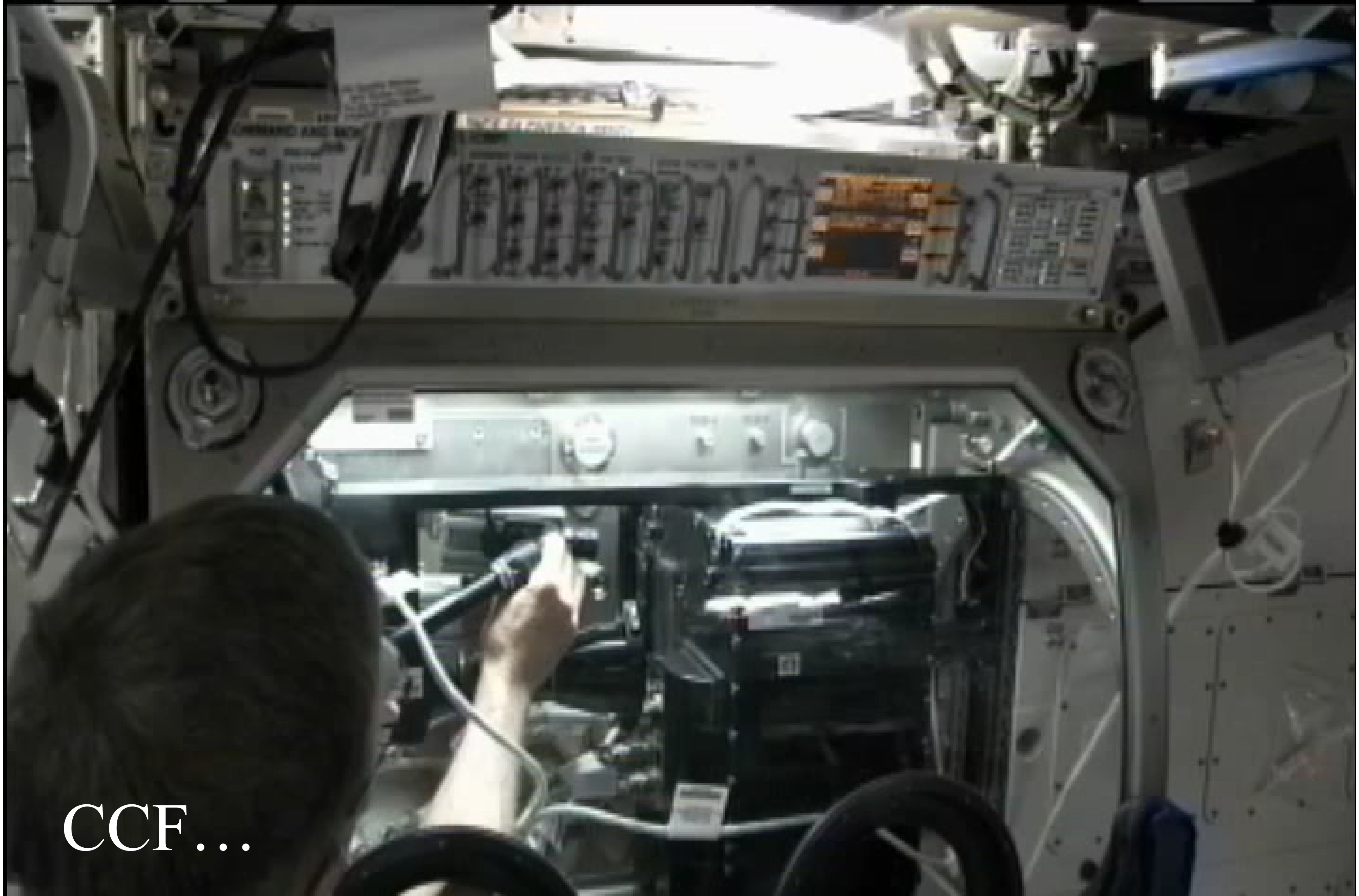
ψ
H1(z)
zb1(t)
zb2(t)
z1(t)
z2(t)
h(z,t)
H1
H2
z1(t)
z2(t)
z2*
z1*
z*
t*
analysis
ISS experiment
OpenFOAM

Table 5.1: Dimensional Solutions

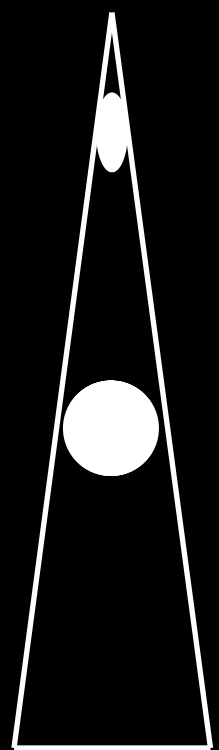
Flow Type	**A$_s$**	**Q$_{cap}$**	**Solution**
	A_s	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_s\big\rvert_{z_2}^{3/2}\frac{1}{z_2}$	$t = \int \frac{3z_2}{A_s\big\rvert_{z_2}^{1/2}\frac{\sigma}{\mu}F_Q}dz_2$
	A_0	$m\mathcal{W}F_A H^2\frac{1}{3z_2}$	$z_2 = \left(\frac{V(0)}{A_0}^2 + \frac{2}{3}\frac{\sigma}{\mu}A_0^{1/2}F_Q t\right)^{1/2}$
	$A_0(1+z/z_s)^{2/3}$	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_0^{3/2}\frac{1+z_2/z_s}{z_2}$	$t = \frac{z_s^2}{F_Q A_0^{1/2}\frac{\sigma}{\mu}}\left[\frac{9}{10}\left(1+\frac{z_2}{z_s}\right)^{2/3}\left(2\frac{z_2}{z_s}-3\right)+\frac{27}{10}\right]$
	$A_0(1+z/z_s)^{2/3}$	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_0^{3/2}\frac{1}{z_s}$	$z_2 = \left(\frac{5}{9}\frac{A_0^{1/2}}{z_s^{1/3}}\frac{\sigma}{\mu}F_Q t\right)^{3/5}, z_2 \gg z_s$
	A_0	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_0^{3/2}\frac{1}{z_2}$	$t = F_Q A_0^{1/2}\frac{\sigma}{\mu}\left(\frac{A_0}{Q_{imp}}\right)^2\left[\frac{z_2 Q_{imp}}{F_Q\frac{\sigma}{\mu}A_0^{3/2}} + \mathrm{Ln}(1+\frac{z_2 Q_{imp}}{F_Q\frac{\sigma}{\mu}A_0^{3/2}})\right]$
	A_0	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_0^{3/2}\frac{1}{z_2}$	$t = F_Q A_0^{1/2}\frac{\sigma}{\mu}\left(\frac{A_0}{Q_{imp}}\right)^2\left[-\frac{z_2 Q_{imp}}{F_Q\frac{\sigma}{\mu}A_0^{3/2}} - \mathrm{Ln}(1+\frac{z_2 Q_{imp}}{F_Q\frac{\sigma}{\mu}A_0^{3/2}})\right]$
	–	$\frac{F_Q}{3}\frac{\sigma}{\mu}\frac{A_s\rvert_{z_2}^{3/2} - A_s\rvert_{z_1}^{3/2}}{z_2-z_1}$	$Q_{cap}\big\rvert_{z_1} = A_s\big\rvert_{z_1}\frac{dz_1}{dt}$
	$(z/z_s)^2$	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_0^{3/2}\frac{1}{z_2-z_1}$	$t = \frac{V_u^2}{4\frac{\sigma}{\mu}F_Q A_0^{5/2}}\left[3+\left(\frac{z_1 A_0}{V_u}\right)^3\right]^{4/3} - \left(\frac{z_1 A_0}{V_u}\right)^4 - 3^{4/3}$
	$(z/z_s)^{2/3}$	$\frac{F_Q}{3}\frac{\sigma}{\mu}A_0^{3/2}$	$z_1 = \left(\frac{A_0^{5/2}}{V_U^2}\frac{\sigma}{\mu}F_Q t\right)^{3/5}$
	A_{s1}, A_{s2}	$\frac{m\mathcal{W}F_A(H_2^3-H_1^3)}{3\left[\frac{V_u}{A_1}+z_2(1-\frac{A_2}{A1})\right]}$	$z_2 = \frac{\frac{V_u}{A_2} - \left[\frac{V_u}{A_2}^2 - \frac{2m\mathcal{W}F_A(H_2^3-H_1^3)t}{3A_2}A(1-A)\right]^{1/2}}{1-\Lambda}$
	A_{s1}, A_{s2}	$\frac{m\mathcal{W}F_A(H_2^3-H_1^3)}{3\left[\frac{V_u}{A_0}\right]}$	$z_2 = \frac{m\mathcal{W}F_A(H_2^3-H_1^3)}{3V_u}t$
	A_{s1}, A_{s2}	$\frac{m\mathcal{W}F_A(H_2^3-H_1^3)}{3\left[\frac{V_u}{A_1}+z_2(1-\Lambda)\right]}$	$z_1(1-\Lambda) = F_A\mathcal{W}\frac{H_2^3-H_1^3}{3Q_{imp}} - \frac{V_u}{A_2}$

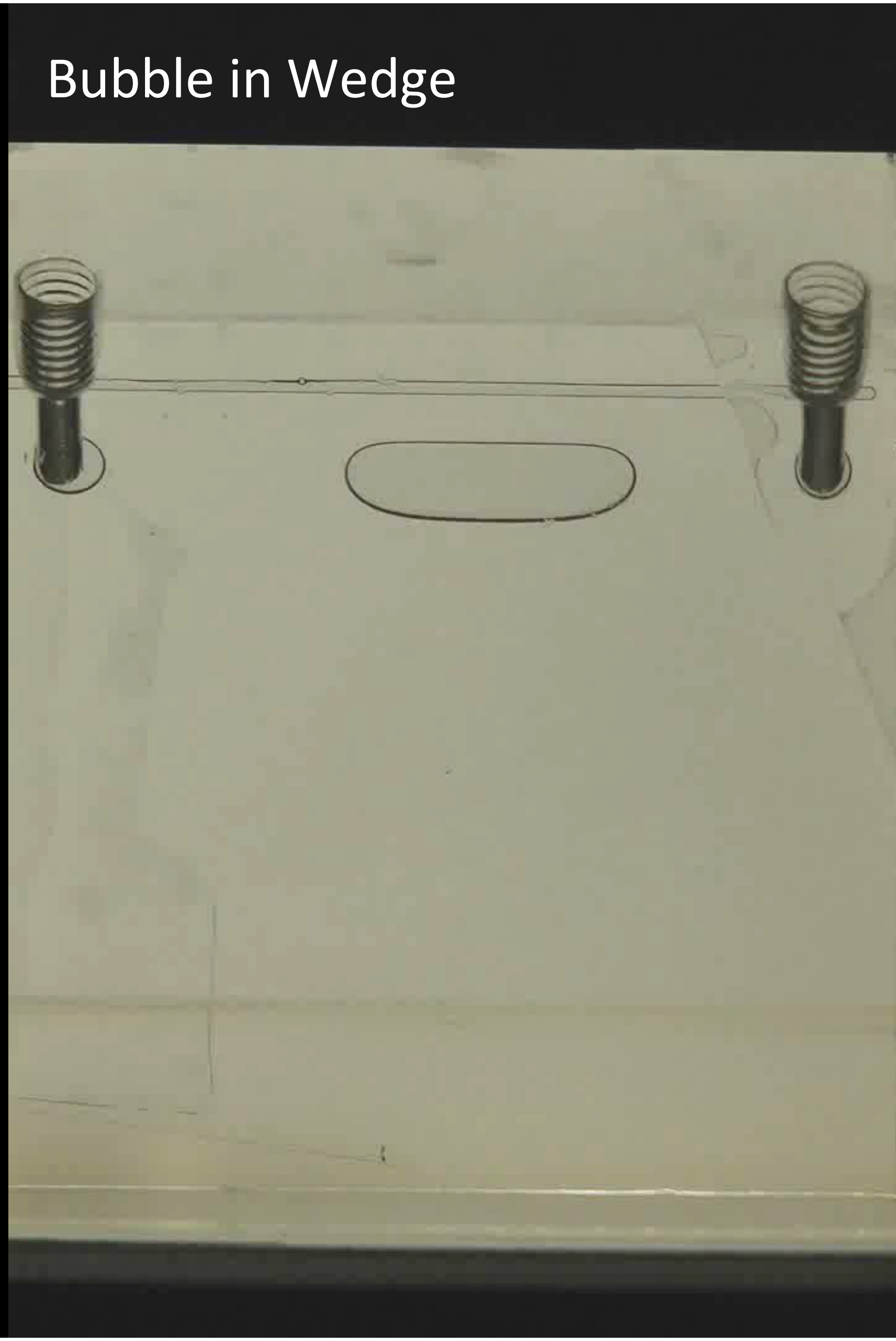

optical
bench
glove
box
electrical
subsystem
experimental
units (EU1/2)





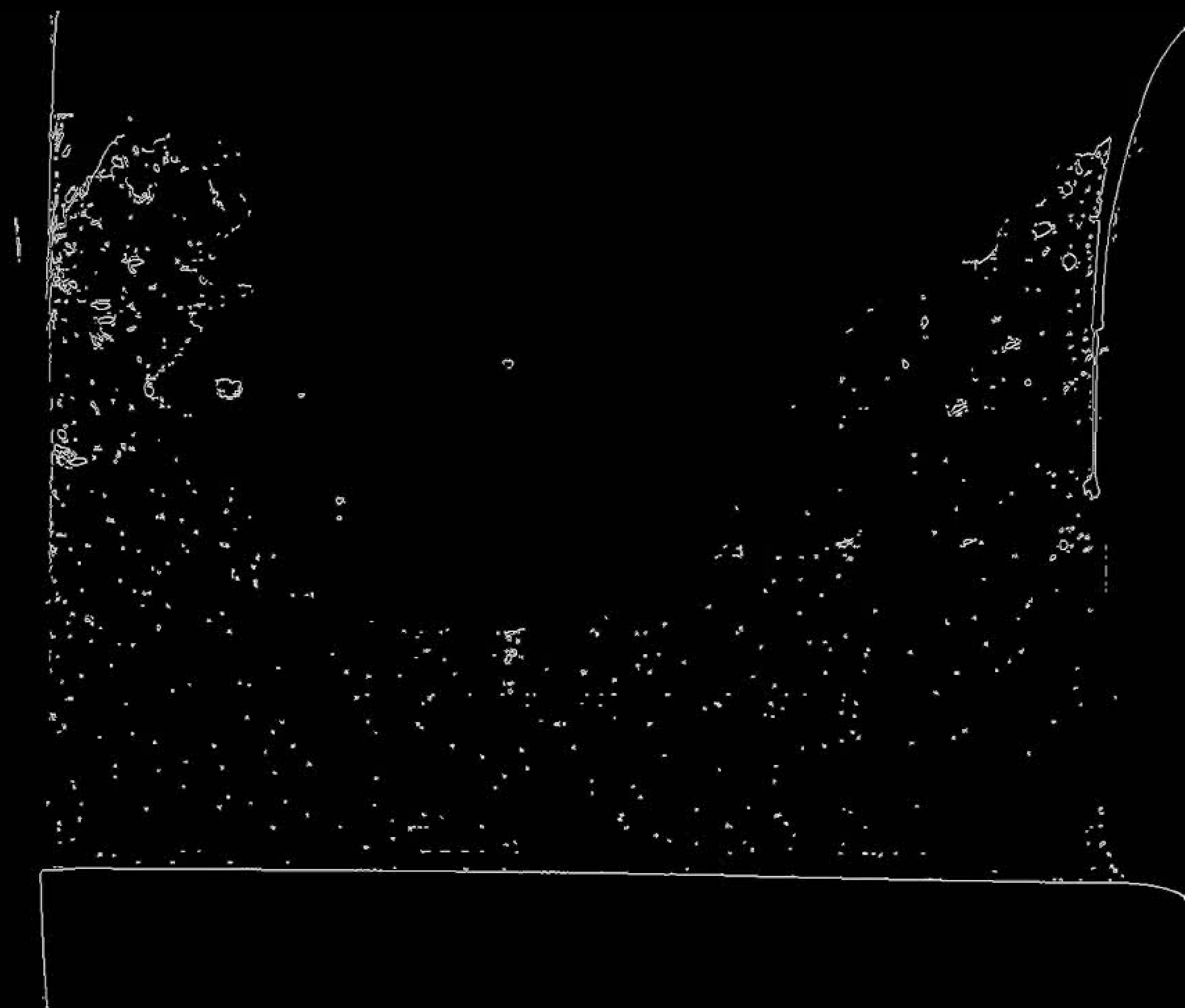
CCF…





Bubble in Wedge

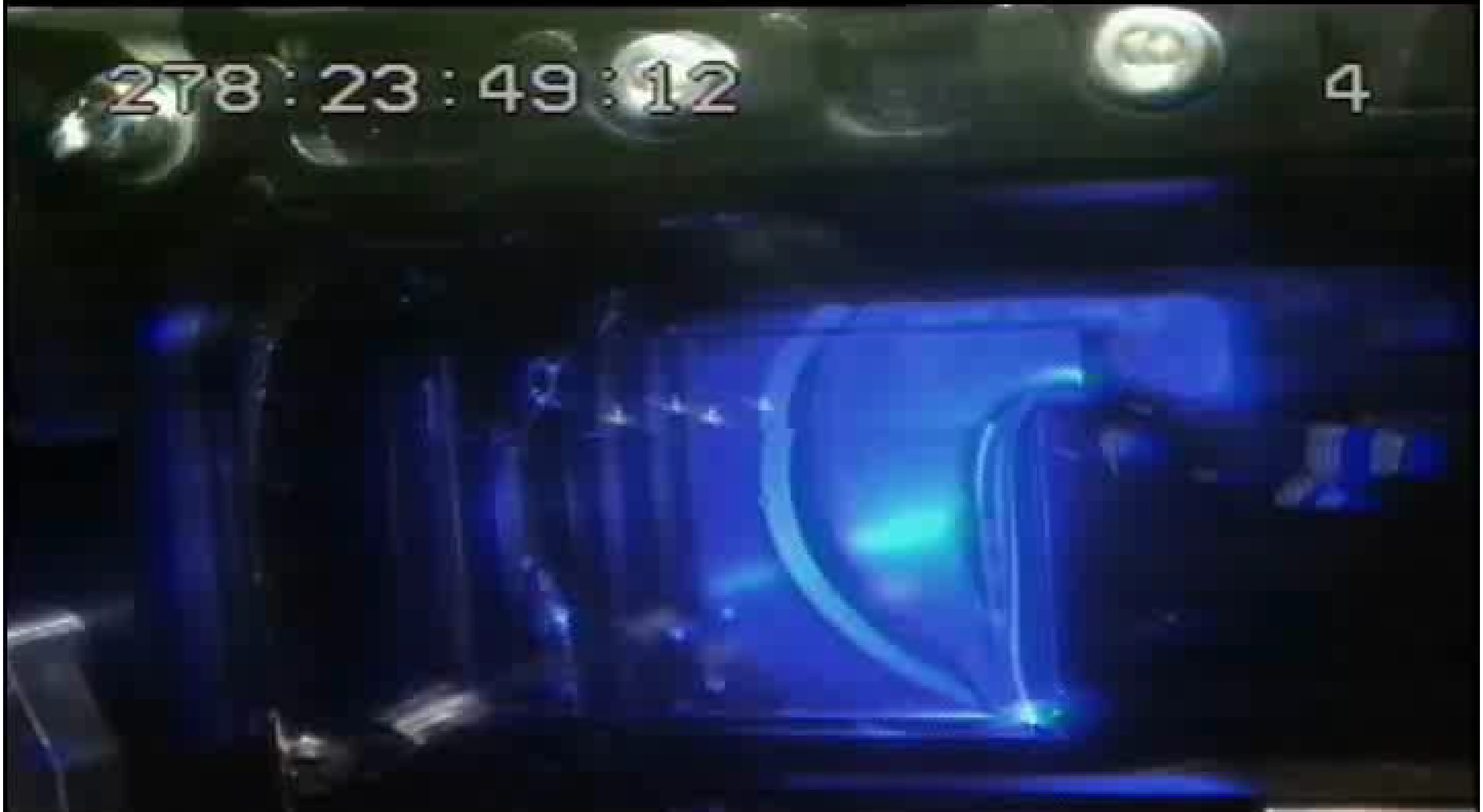
Single …all in

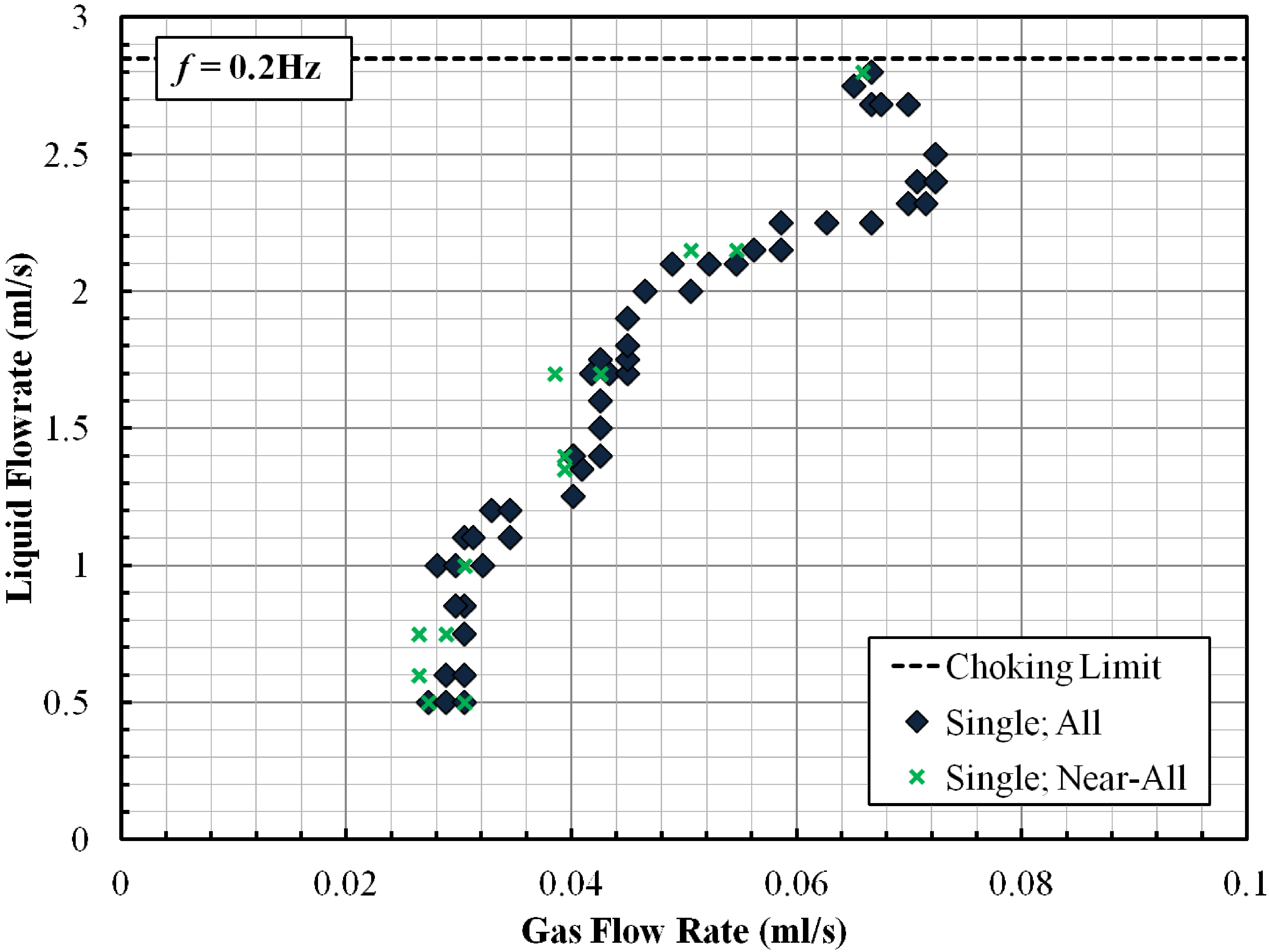


Singles…all in

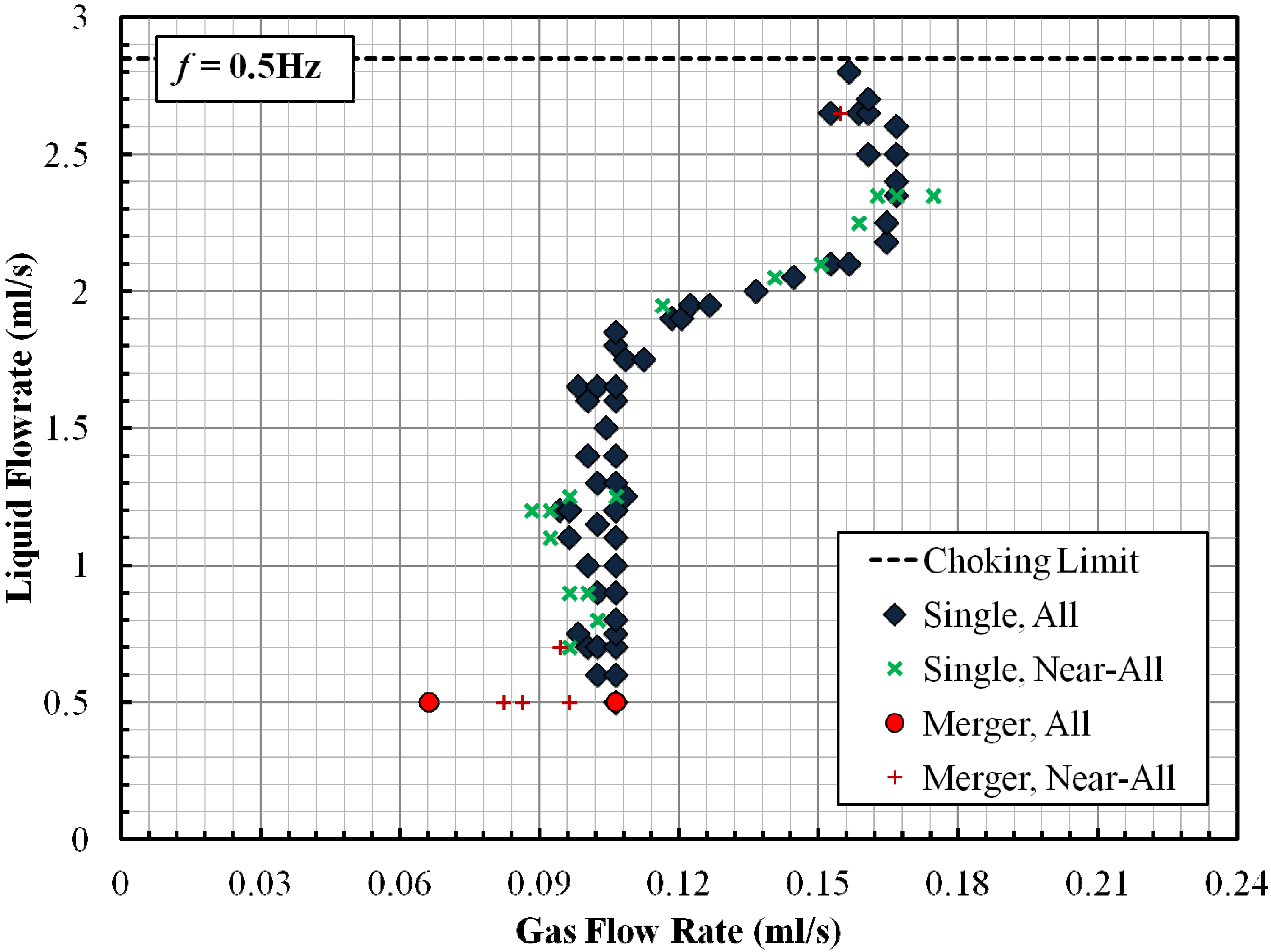
Singles…all out

Single Mergers …and out (MSG camera)

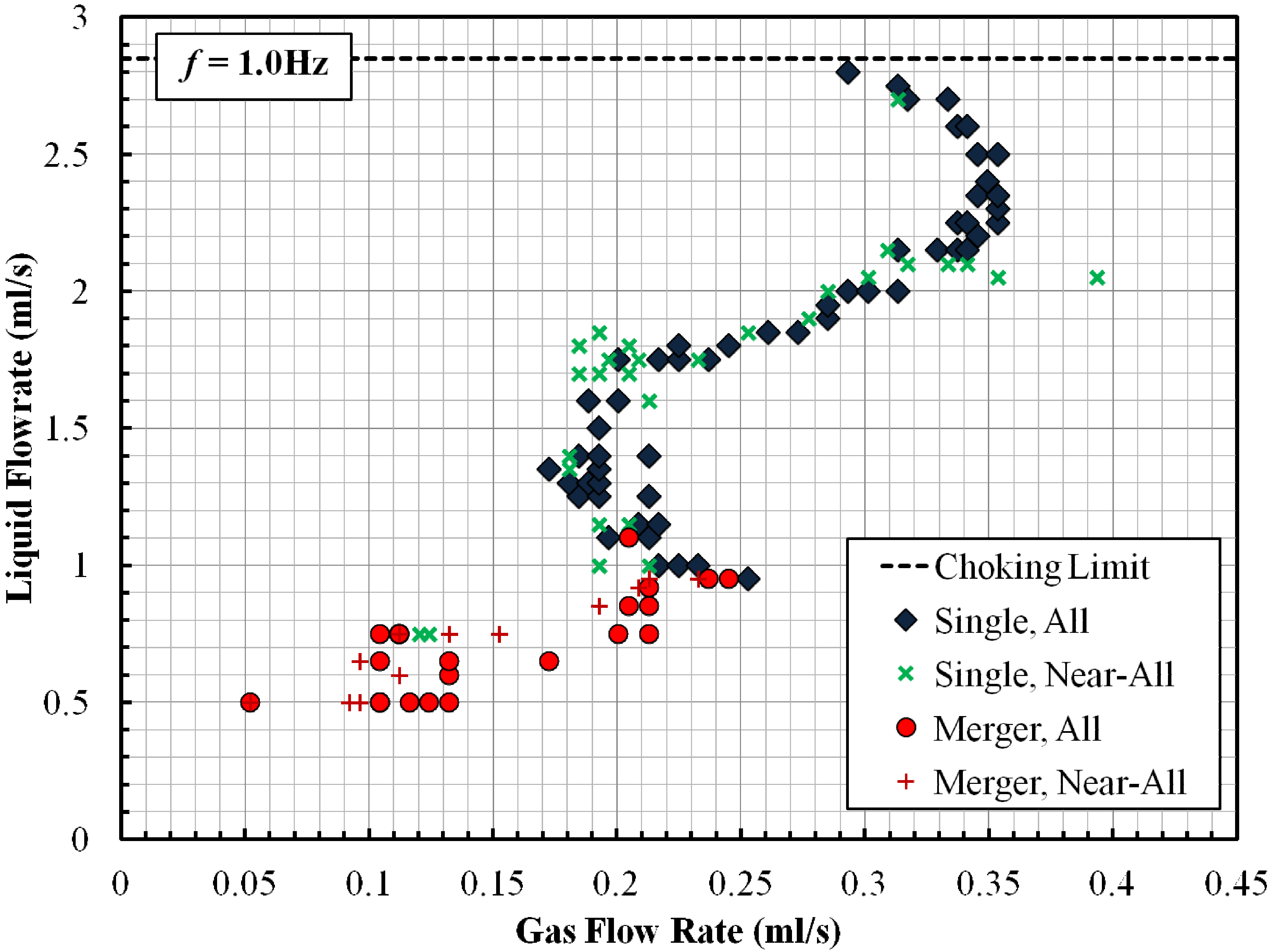




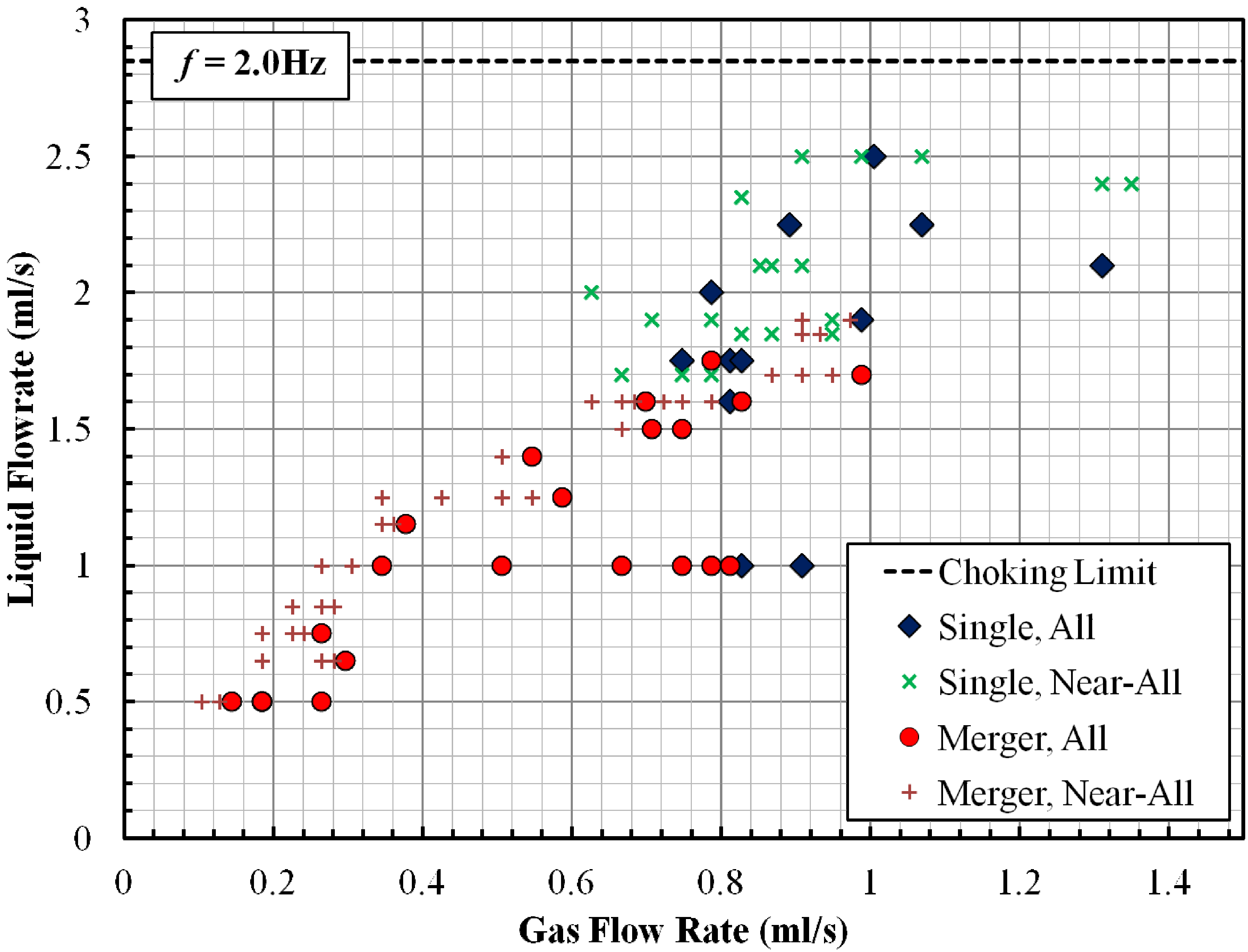
f = 0.2Hz
Liquid Flowrate (ml/s)
Gas Flow Rate (ml/s)
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
Choking Limit
Single; All
Single; Near-All



f = 0.5Hz
Choking Limit
Single, All
Single, Near-All
Merger, All
Merger, Near-All
Liquid Flowrate (ml/s)
Gas Flow Rate (ml/s)
0
0.5
1
1.5
2
2.5
3
0
0.03
0.06
0.09
0.12
0.15
0.18
0.21
0.24



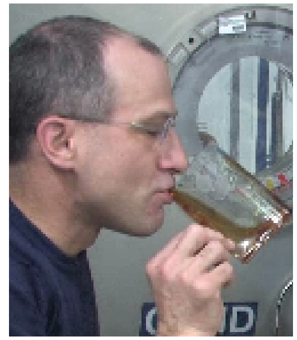
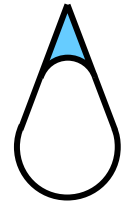
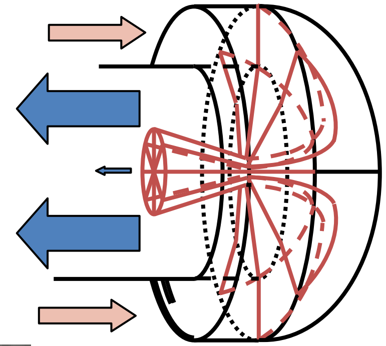
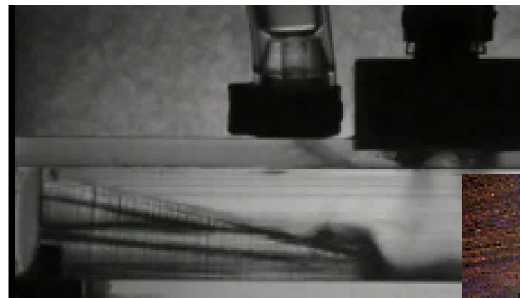
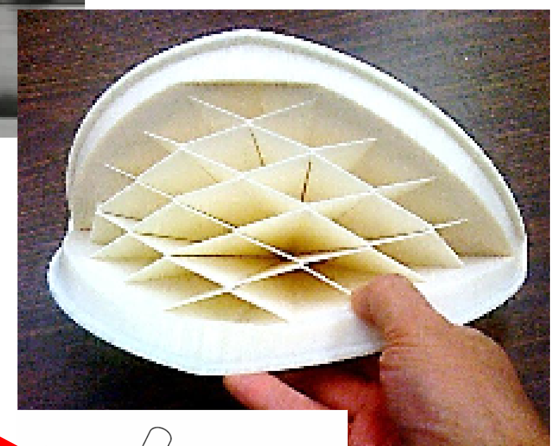
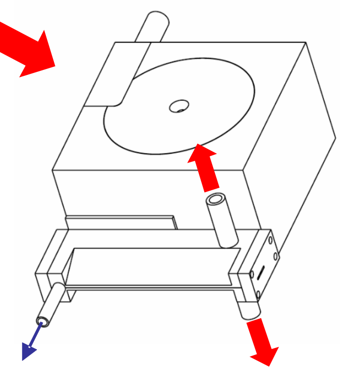
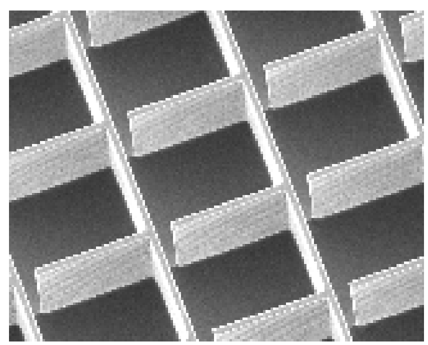
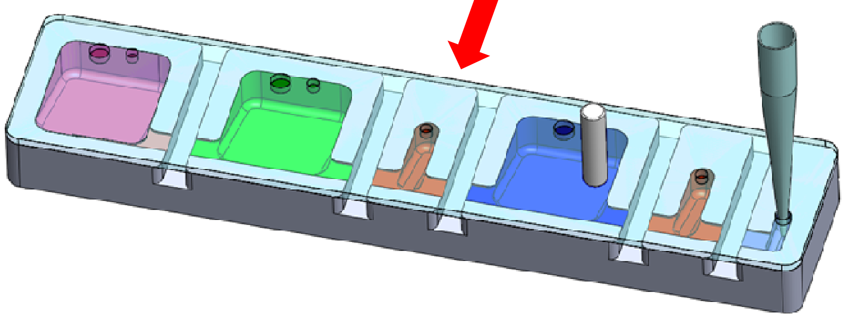
f = 1.0Hz
Choking Limit
Single, All
Single, Near-All
Merger, All
Merger, Near-All
Liquid Flowrate (ml/s)
Gas Flow Rate (ml/s)
0
0.5
1
1.5
2
2.5
3
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45



f = 2.0Hz
Choking Limit
Single, All
Single, Near-All
Merger, All
Merger, Near-All
Liquid Flowrate (ml/s)
Gas Flow Rate (ml/s)
0
0.5
1
1.5
2
2.5
3
0
0.2
0.4
0.6
0.8
1
1.2
1.4

Applications:

Drink…
Condensing HX
Animal and plant habitats
***μ*-g spray cooler**
EMU LHP (freezable)
EMU CO_2 sensor design
3 waste water systems
HP wick structures
AIDS fluidics chip
…

Confidence in Capillary design is increasing quickly…

1. Passive phase separations
2. Ullage positioning
3. Geometry optimizations
4. It is possible to re-assess ALL fluid systems aboard spacecraft in light recent progress stemming from ISS experiments

Some notes…

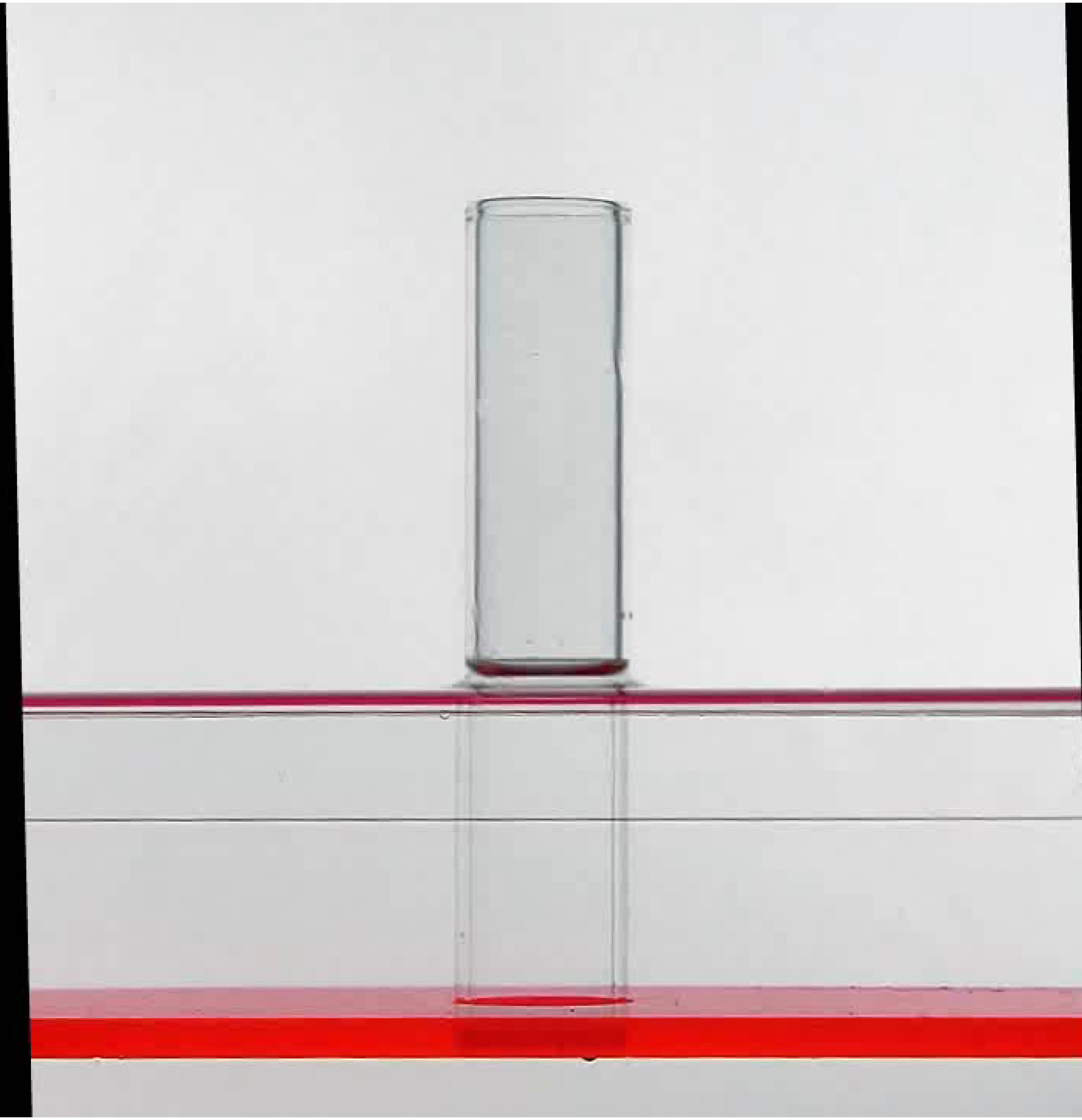
1.Exciting, frightening, exhausting, trying, but you can adapt…

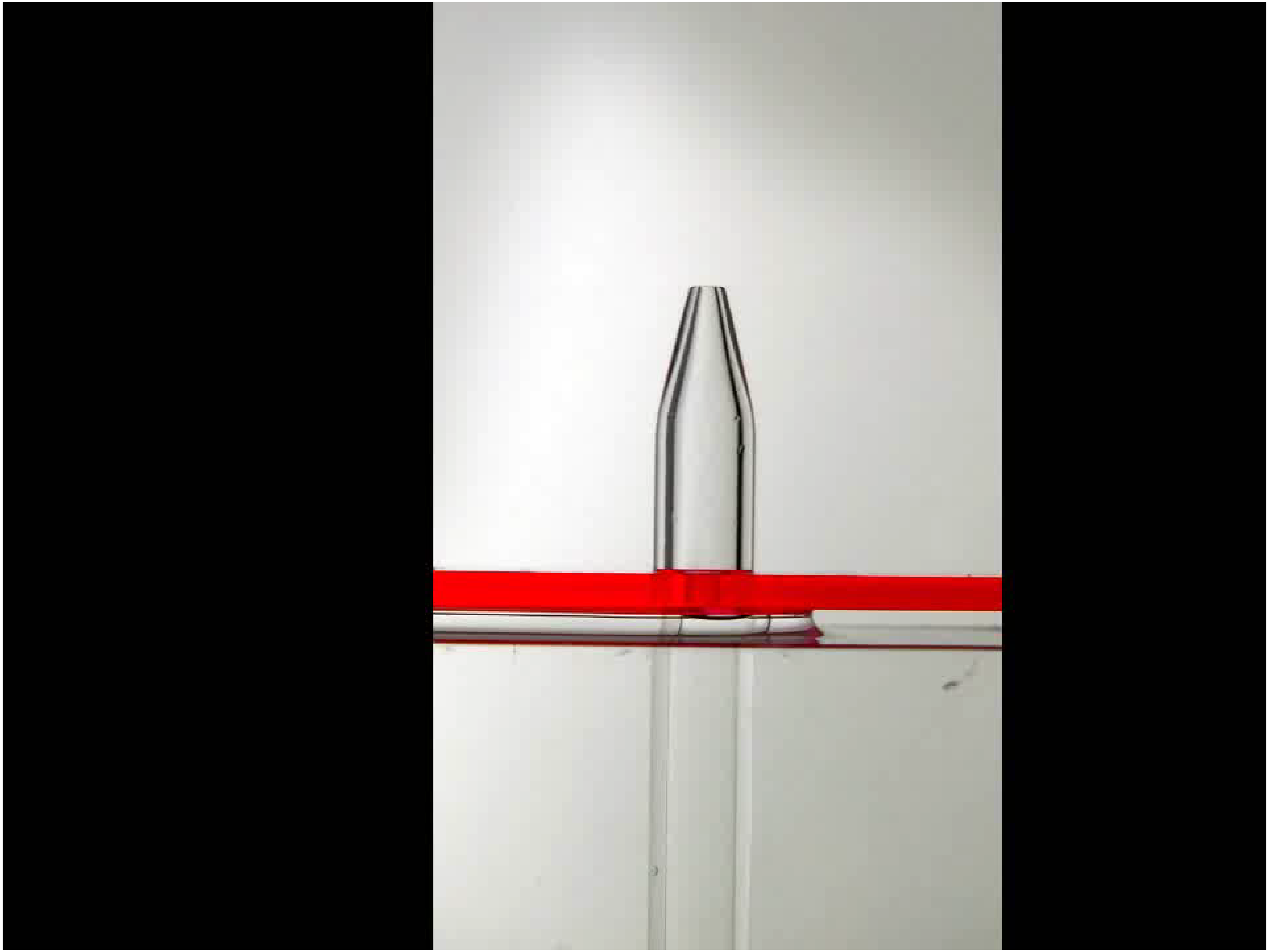
2.You may be surprised to find that ISS experiments are far more successful than you planned. ISS can be quite close to a normal lab—you can adapt.

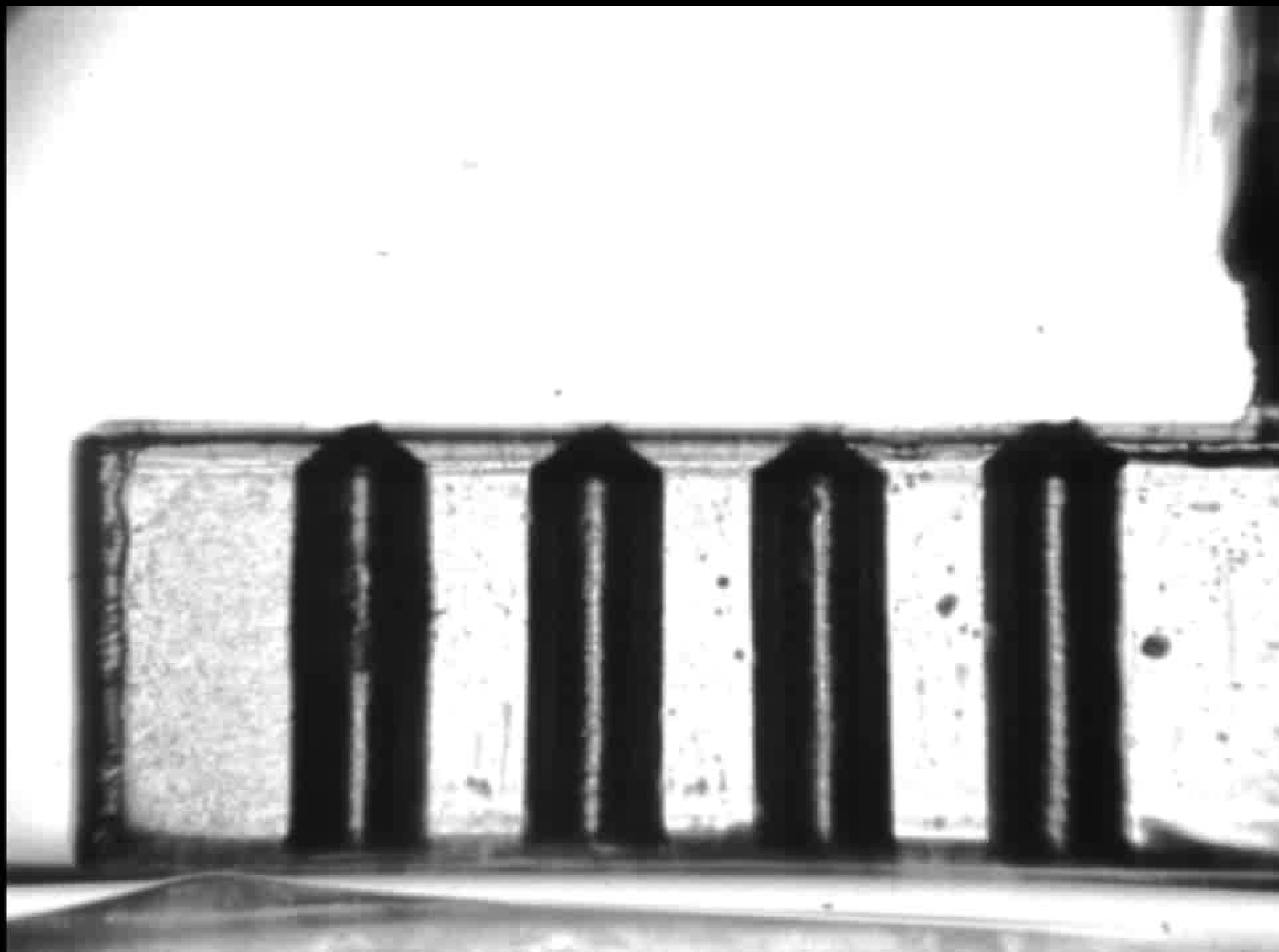
3.Every fluid element must be considered a phase separator or distributor or a bubble/slug generator

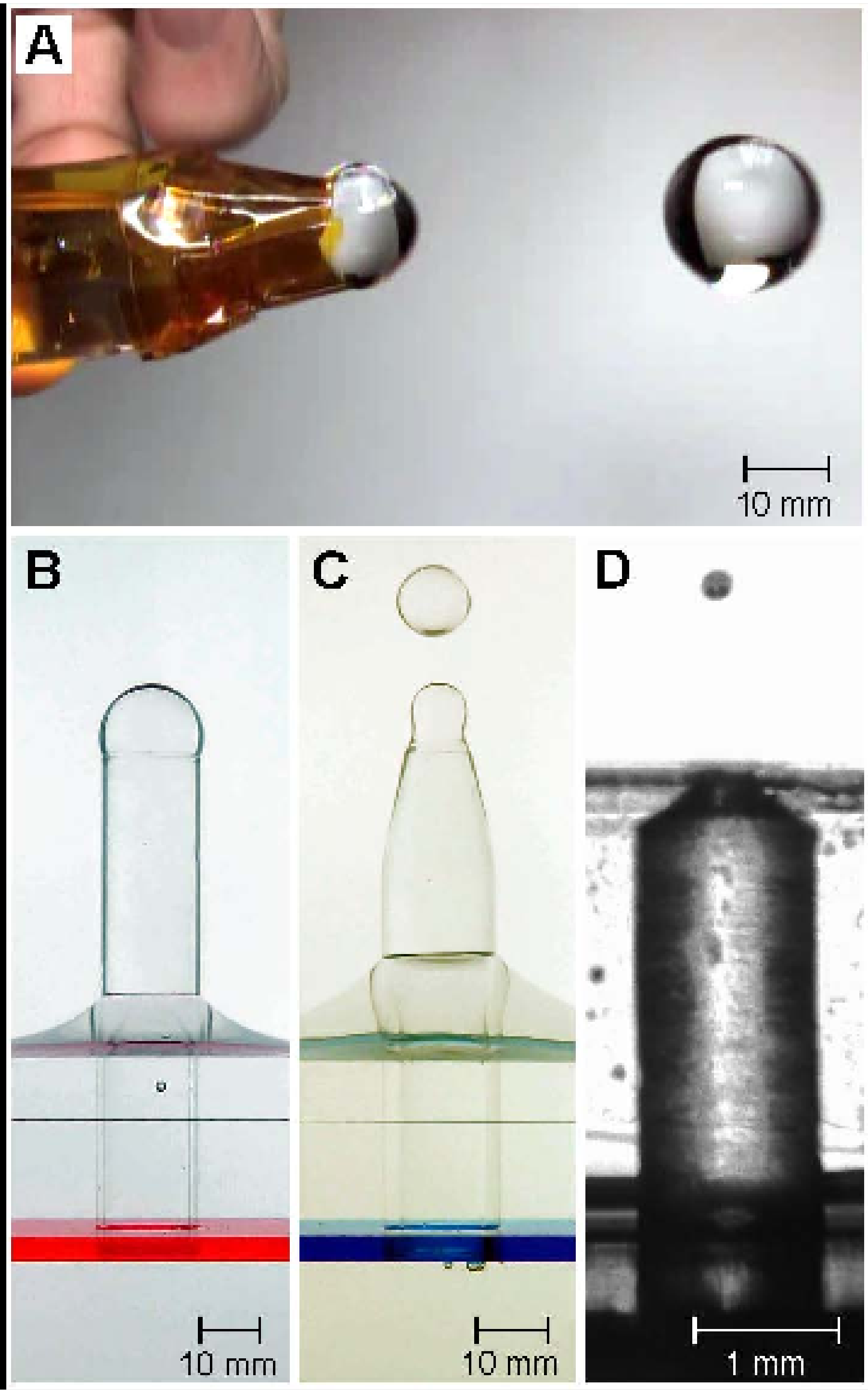
4.Short duration low-g fluids experience do not guarantee long duration low-g outcomes

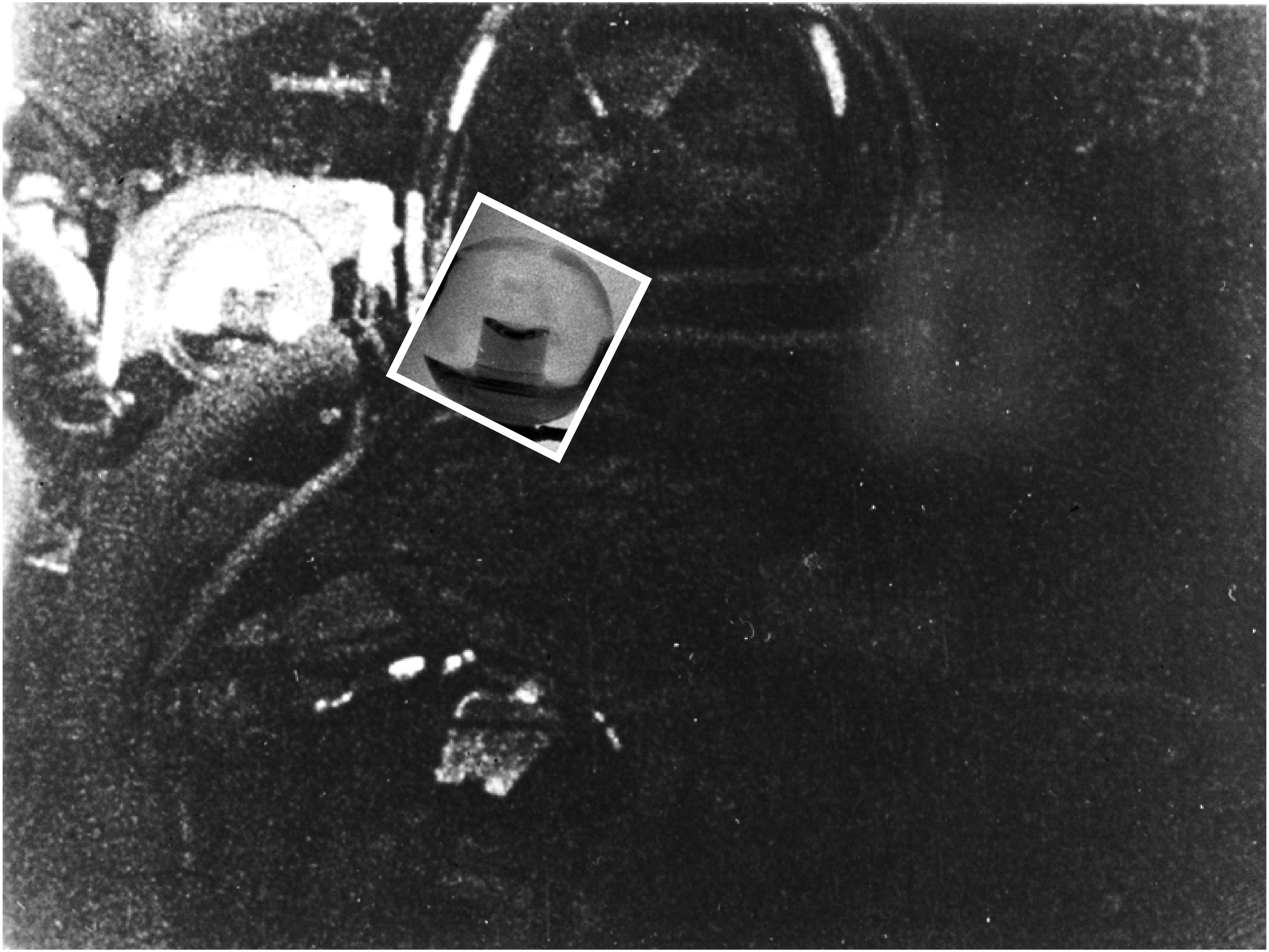
[redacted]



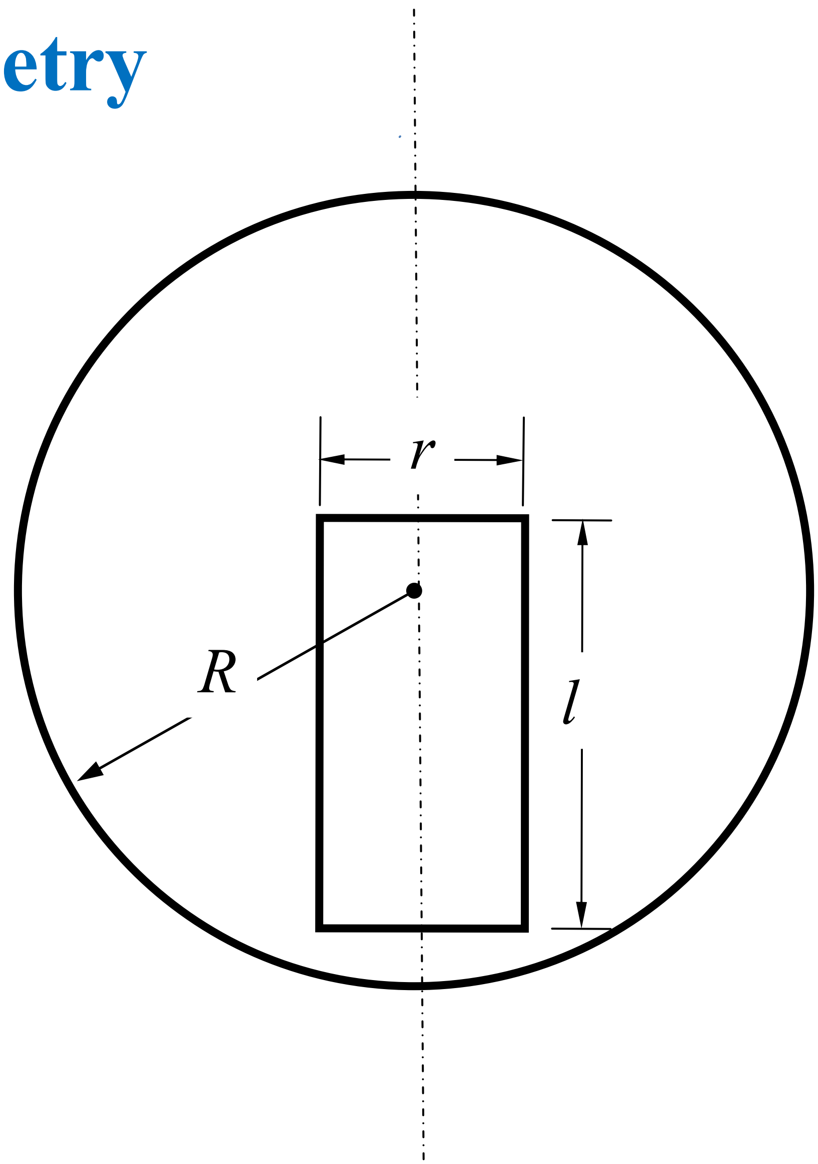





A
10 mm
B
10 mm
C
10 mm
D
1 mm

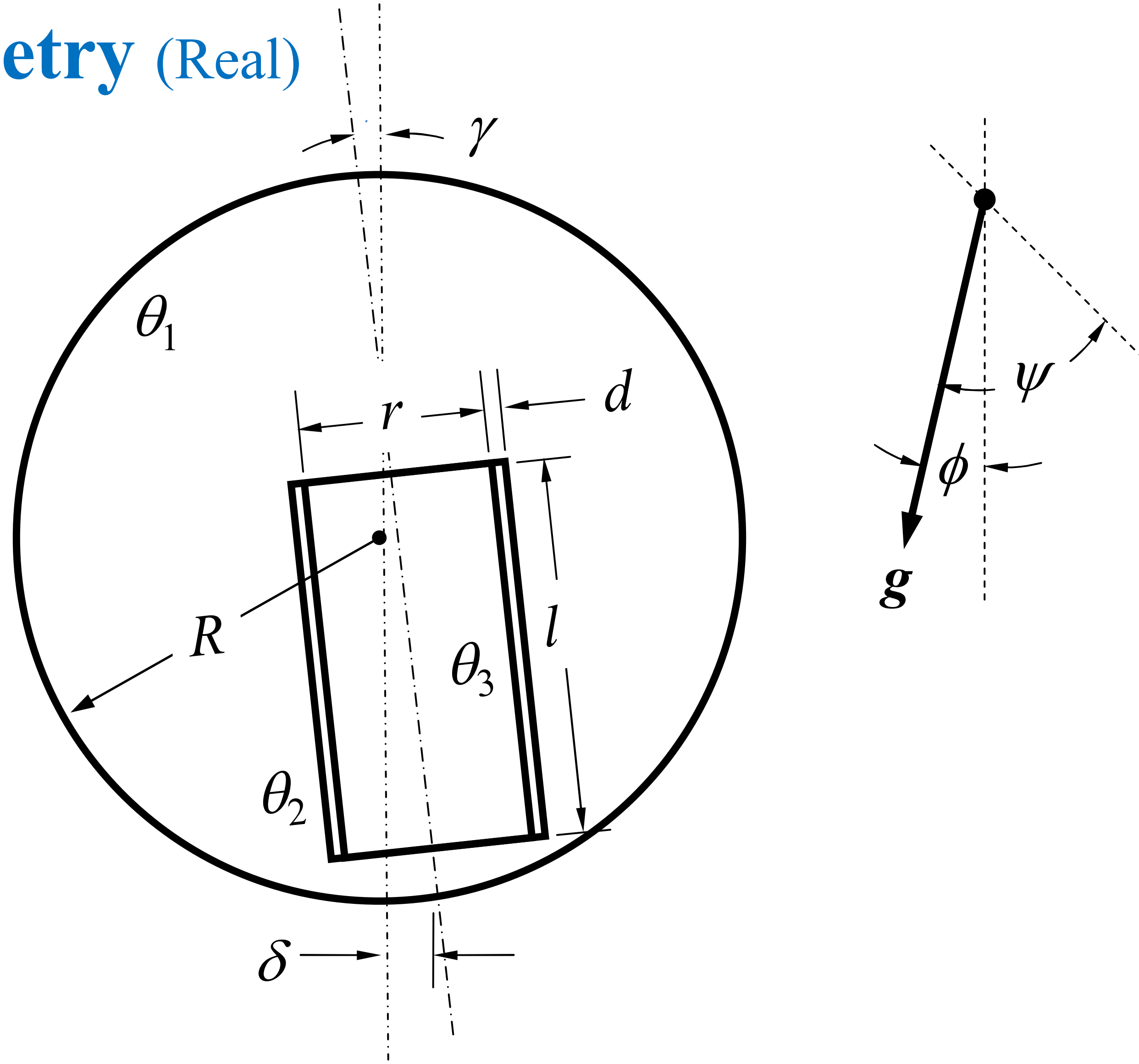


MA-07 Geometry



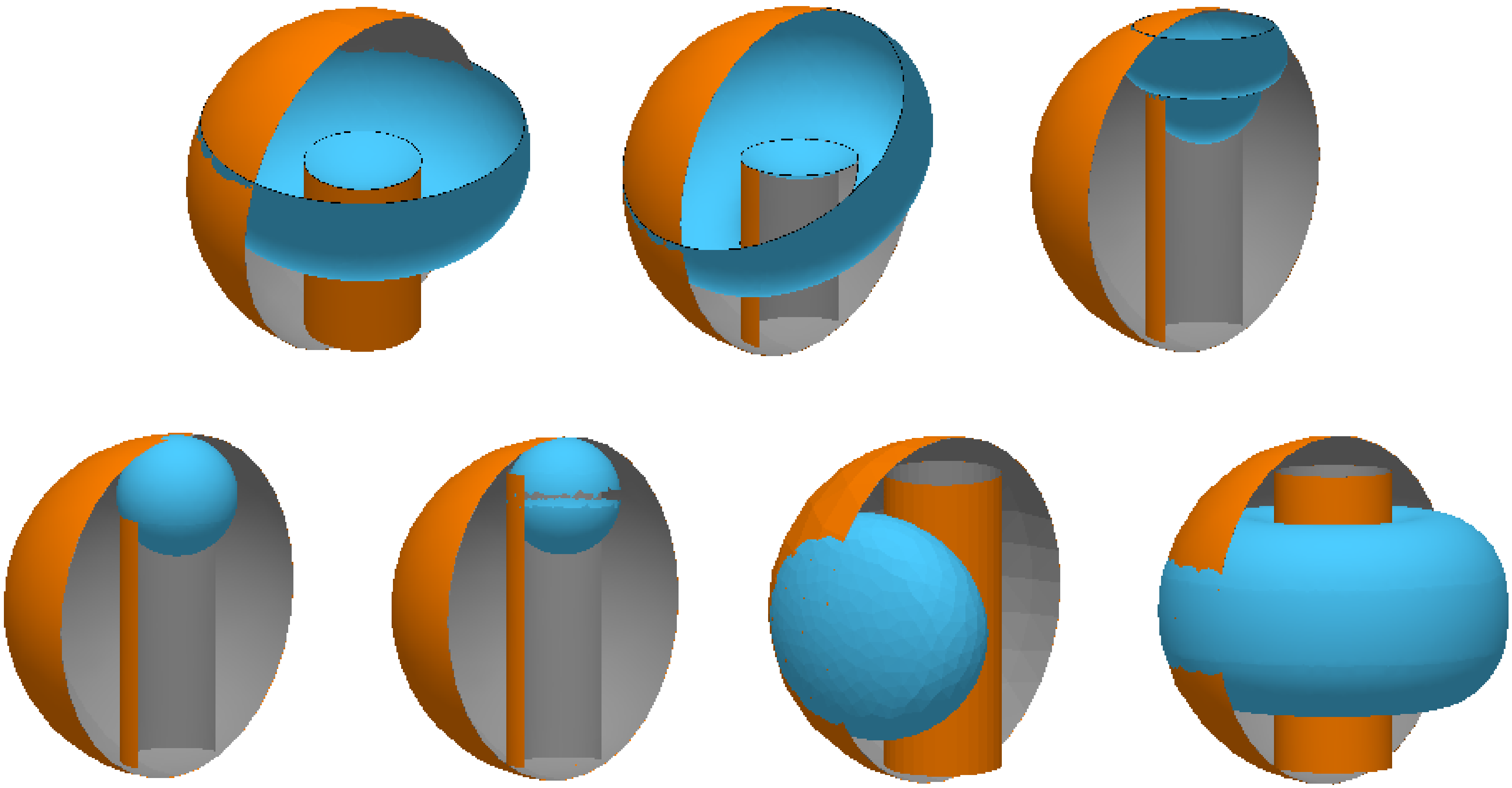
$$S = S(R, r, l, V, \text{ICs})$$

MA-07 Geometry (Real)



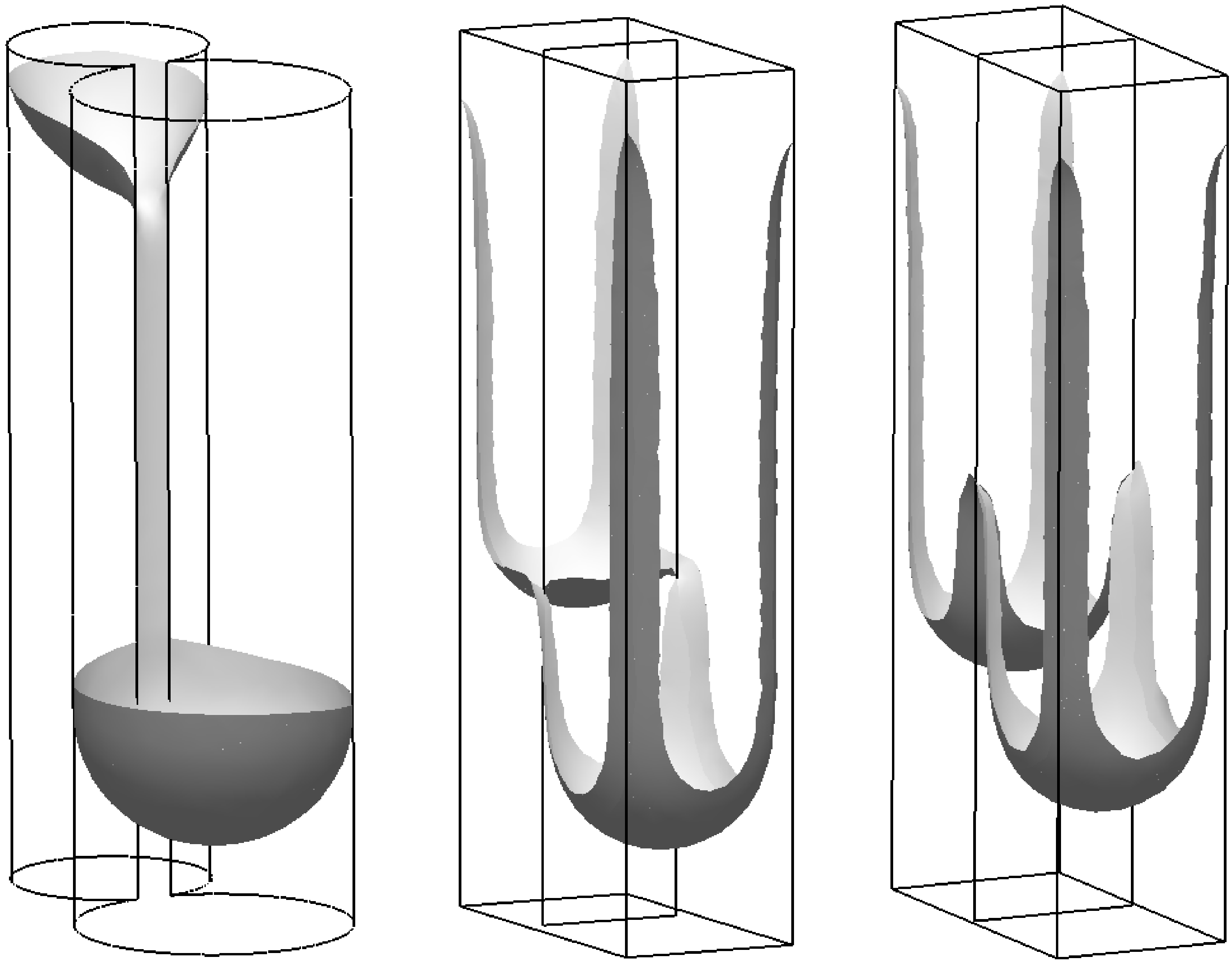
$$S = S(R, r, l, V, \mathrm{ICs}, d, \delta, \gamma, \theta_1, \theta_2, \theta_3, g, \phi, \psi, \sigma, \rho)$$

MA-07 Interface Configuration (SE-FIT)



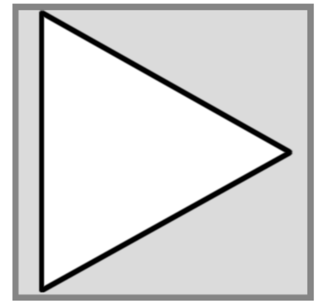
www.se-fit.com

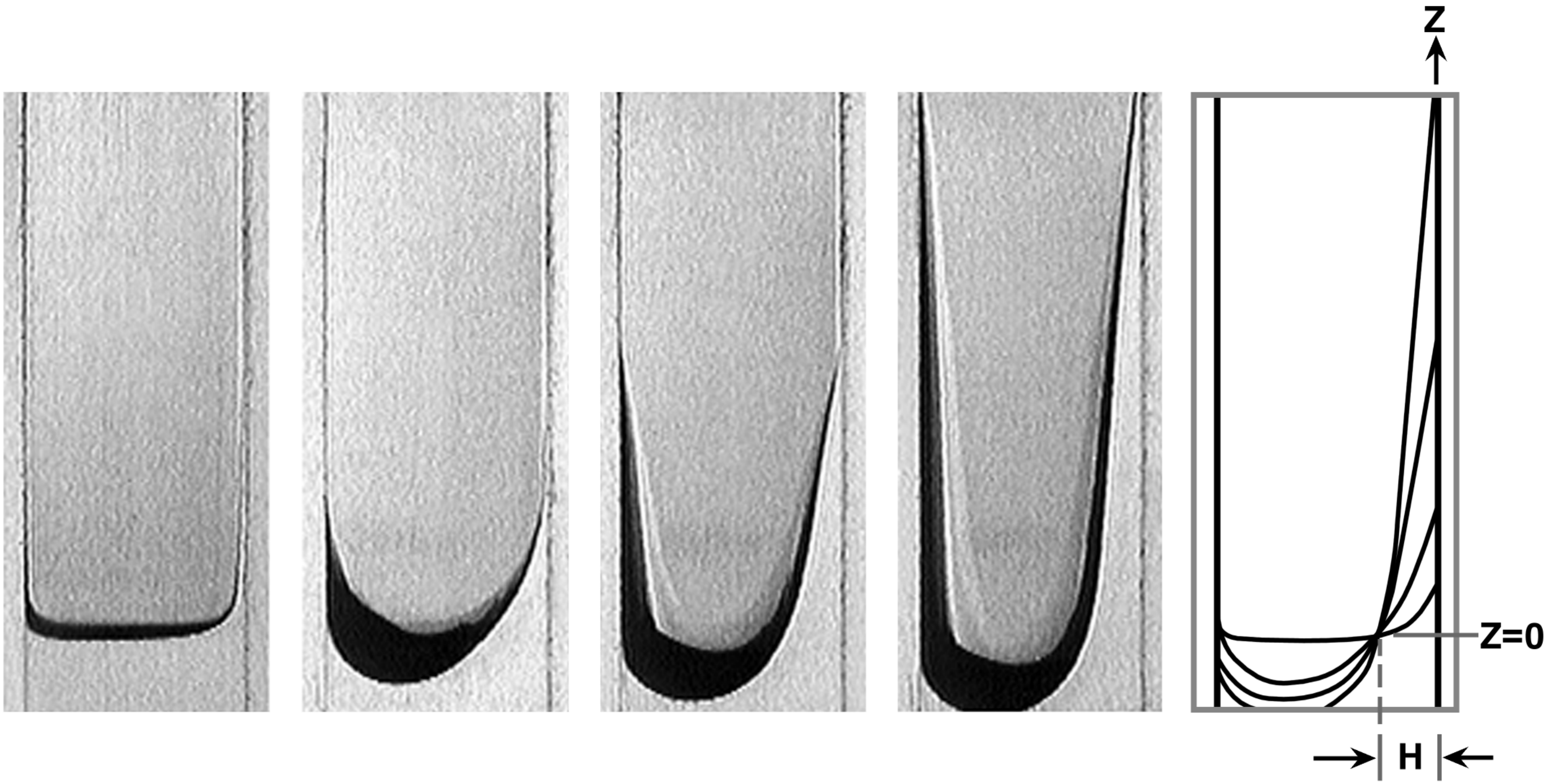
Repeatability Demonstration



www.se-fit.com (open source)

Capillary Rise (imbibition)





CFE story…

Initially part of Unscheduled Payloads Program…

- Zero hazard
- Low mass < 2.5kg
- Low volume < 2liters
- Minimal to no electrical interfaces and power requirements
- Minimal to no crew training
- Short hardware delivery schedule (~ months)

Since…

Short operations window, < 3 hrs…

- Approaching 50 operations
- > 10 astronauts
- 8 test cells with 7 more to launch
- Publications, Patents, Applications, Insight…(earth and space)