Breathable membrane enclosures for faecal sludge stabilization

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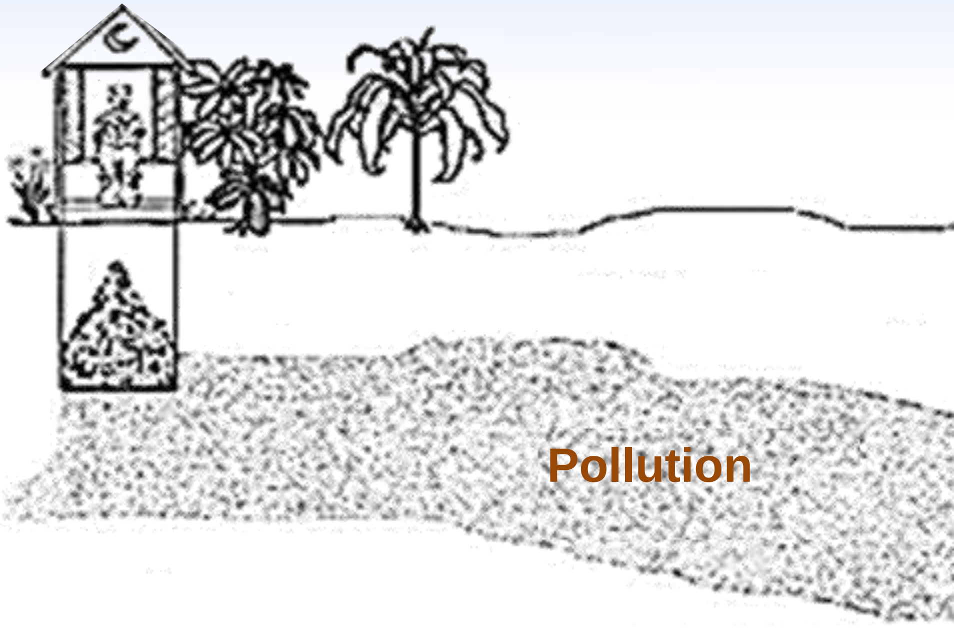
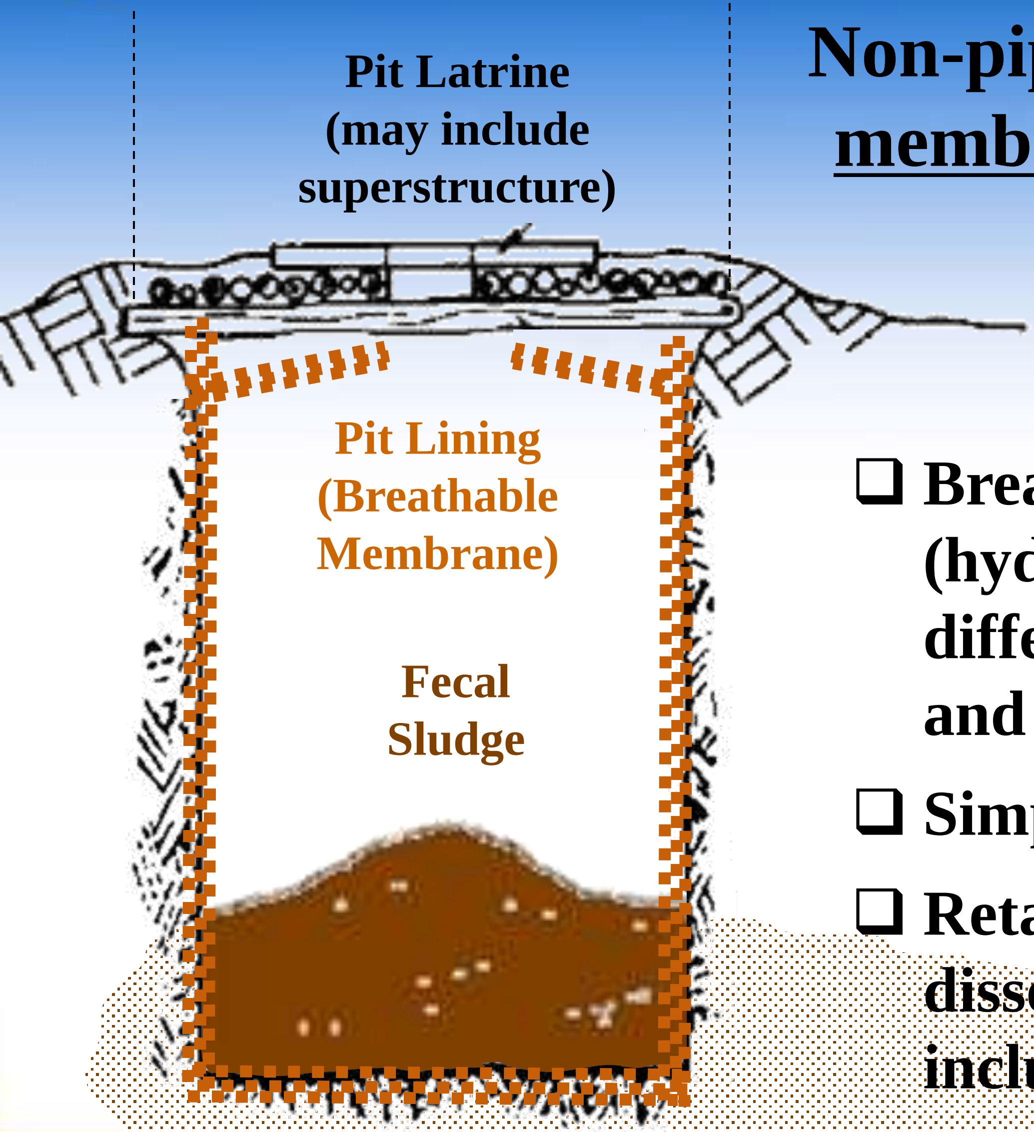
Problems with basic pit latrines

- Spread of pathogens and pollution through soil or during high water conditions
- Unsanitary conditions for clearing filled pits



Graphic: Franceys, R. et al. (1992). A Guide to the Development of On-Site Sanitation. World Health Organization, Geneva.

Proposed Improvement

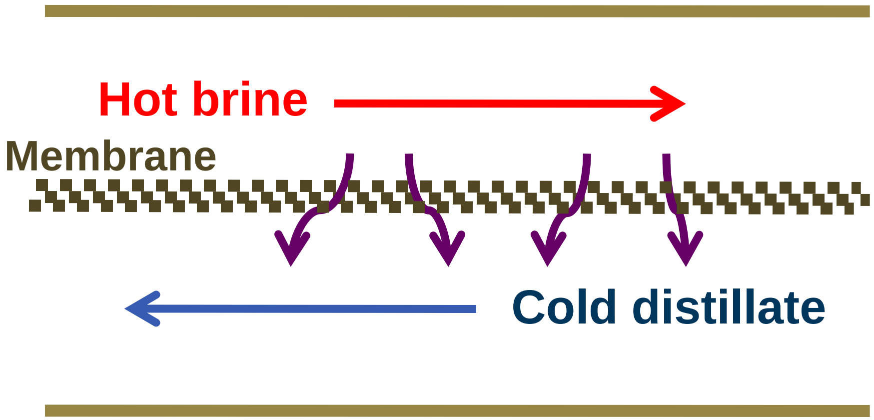


Non-piped toilet equipped with <u>membrane distillation</u> system

- Breathable membrane lining (hydrophobic, nonwetting – differs from geomembranes, RO and filtration membranes)
- Simple, appropriate technology
- Retains particulate and dissolved contaminants including pathogens

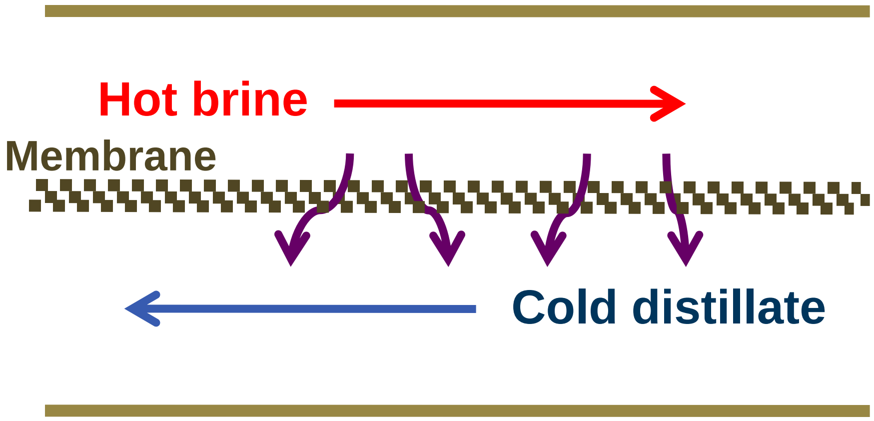
How Membrane Distillation Works

- **MD is an emerging technology for desalination**
- **Uses a temperature gradient as the driving force for pure water production**

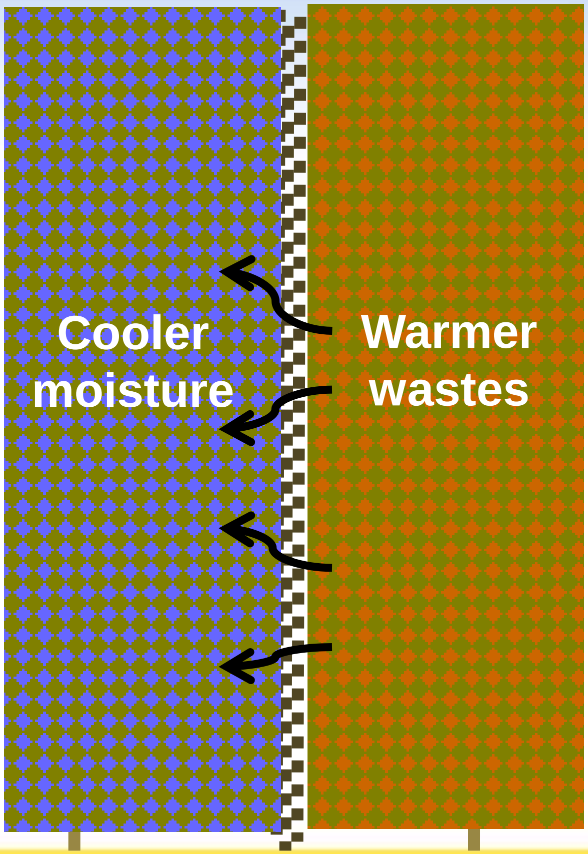


1. **The process uses a hydrophobic membrane, only permeable to water vapor.**
2. **On one side of the membrane, hot seawater or brine flows through the compartment .**
3. **On the other side, cold distillate flows in a countercurrent direction.**
4. **The temperature difference leads to different vapor pressures, causing water vapor transport across the membrane**
5. **The vapor re-condenses to form distilled water on the distillate side**

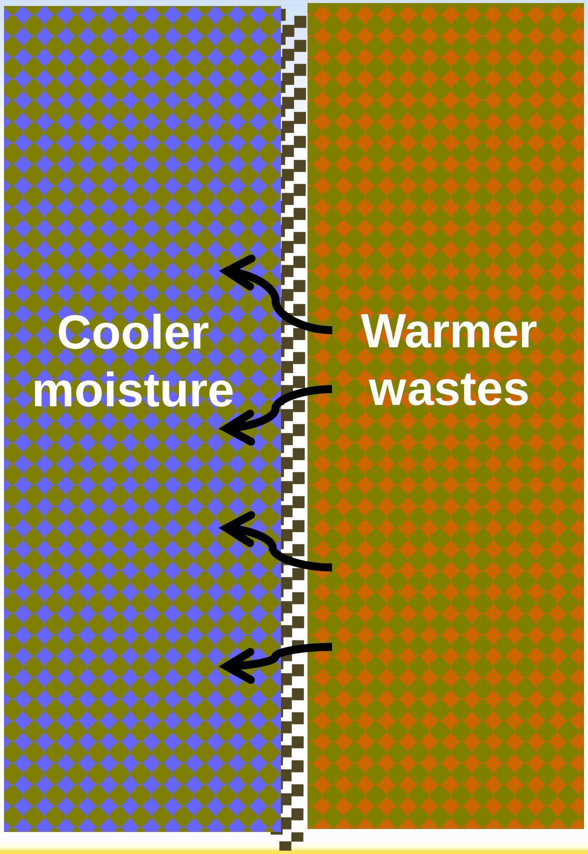
Apply this to sanitation needs



Apply this to sanitation needs



Features

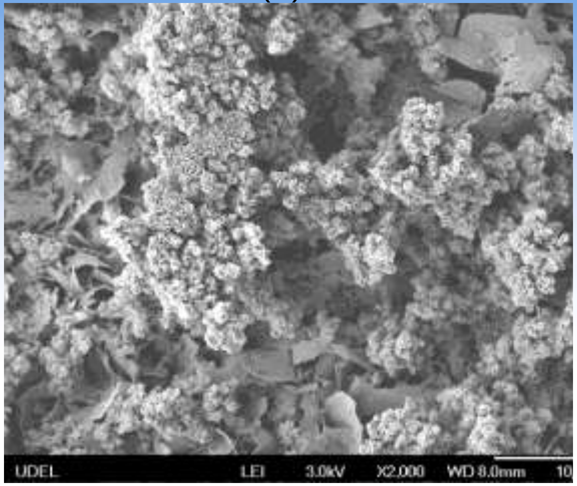


- <u>Small</u> temperature gradient
- <u>Gradual</u> escape of water vapour
- Enclosure prevents release of pathogens and dissolved constituents
- Drying is facilitated
- Resists fouling and scaling – reusable (tests confirm)

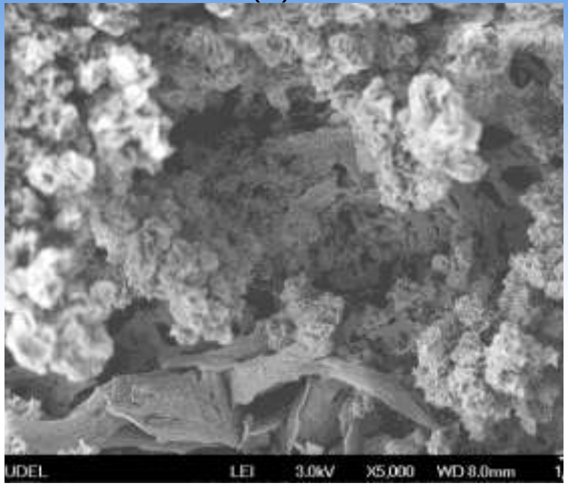
Temperature difference could be from biodegradation or passive solar

Hydrophobic membrane after 2,000 hours in desalination process

(A)



(B)



SEM images of PVDF membrane surface (A) and (B) and cross section (C) and (D) after 1200 hours DCMD of instant ocean salt.

But:

- **Faecal sludge is different from salt water.**
- **Drying is different from desalination.**
- **Privies are different from industrial processes.**
- **Much to do!**

Understanding the Process

- **Initial feasibility**
- **Characterization**
- **Material and condition optimization**
- **Practicality**
- **Scale-up**

Initial Feasibility:

- Thumb cut-out from a breathable membrane glove
- Filled with sludge, placed on warm hot plate (ΔT=15C)
- Lost 50% of moisture in 24 hr
- Conductivity of water on filter pad same as distilled water

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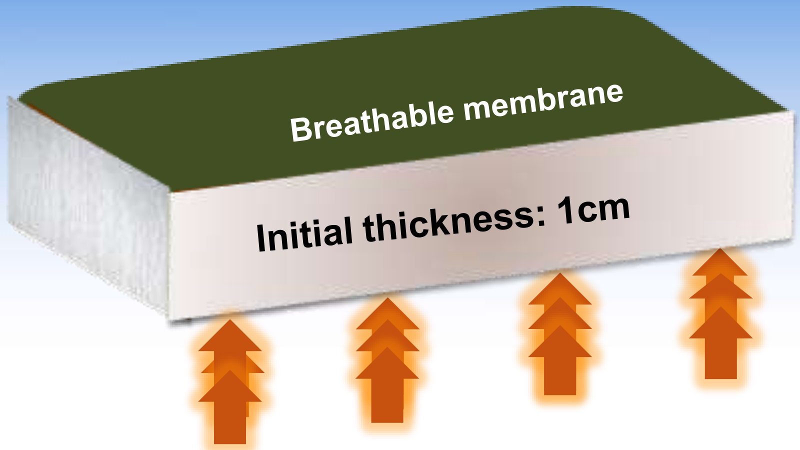
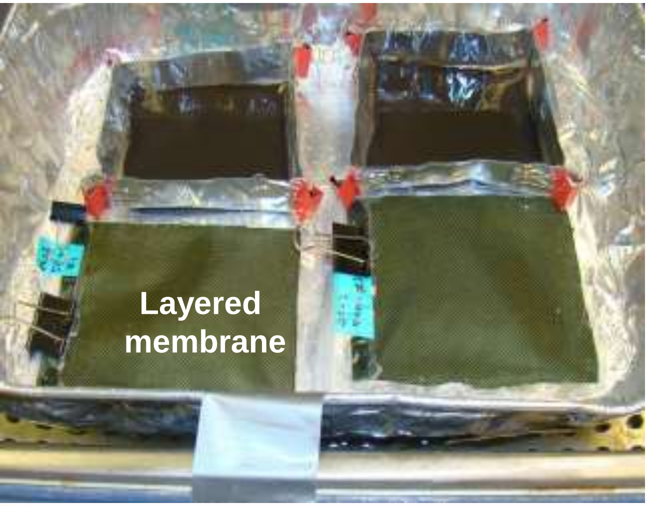
Experimental Setup-1: Membrane Enclosures



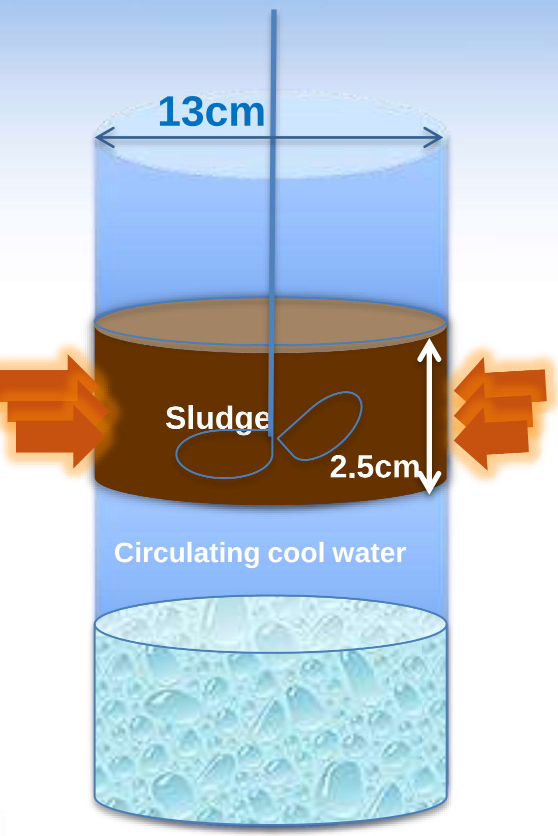


- Scale
- Temperature Gradients
- Control Experiments
- Measurement

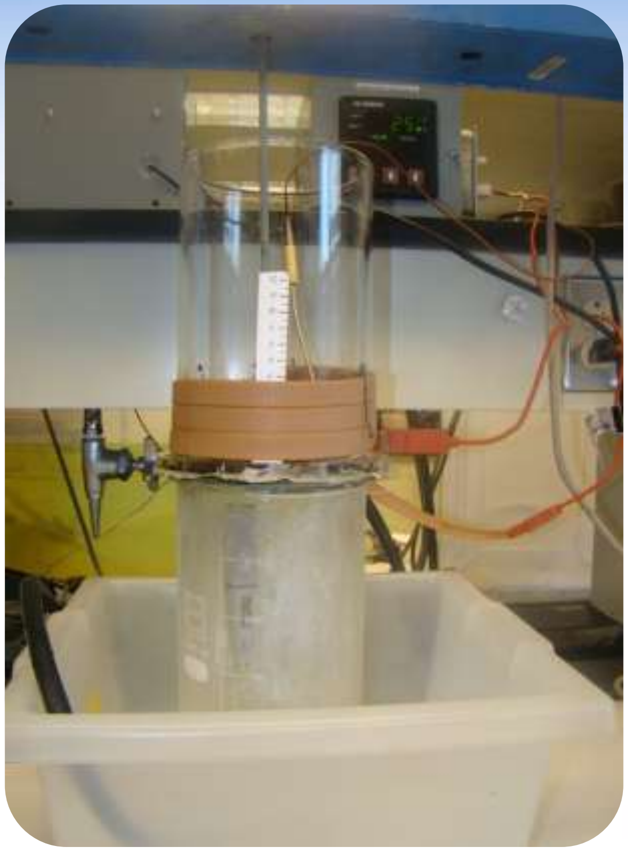
Water bath heating

Hot plate heating

Experimental Setup-2: Two-Column Configuration

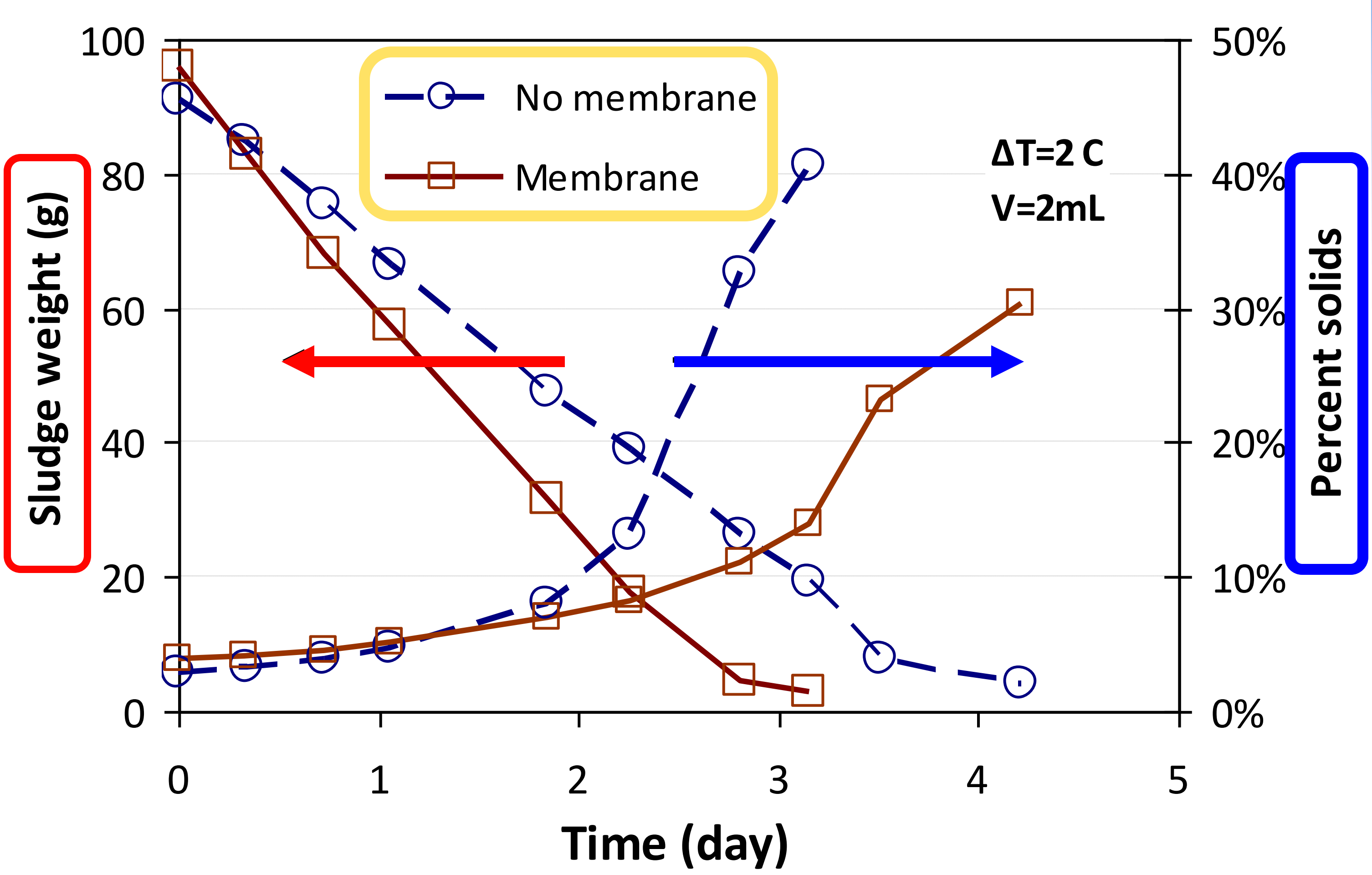


- ❑ Scale
- ❑ Applied Temperature
- ❑ Measurement



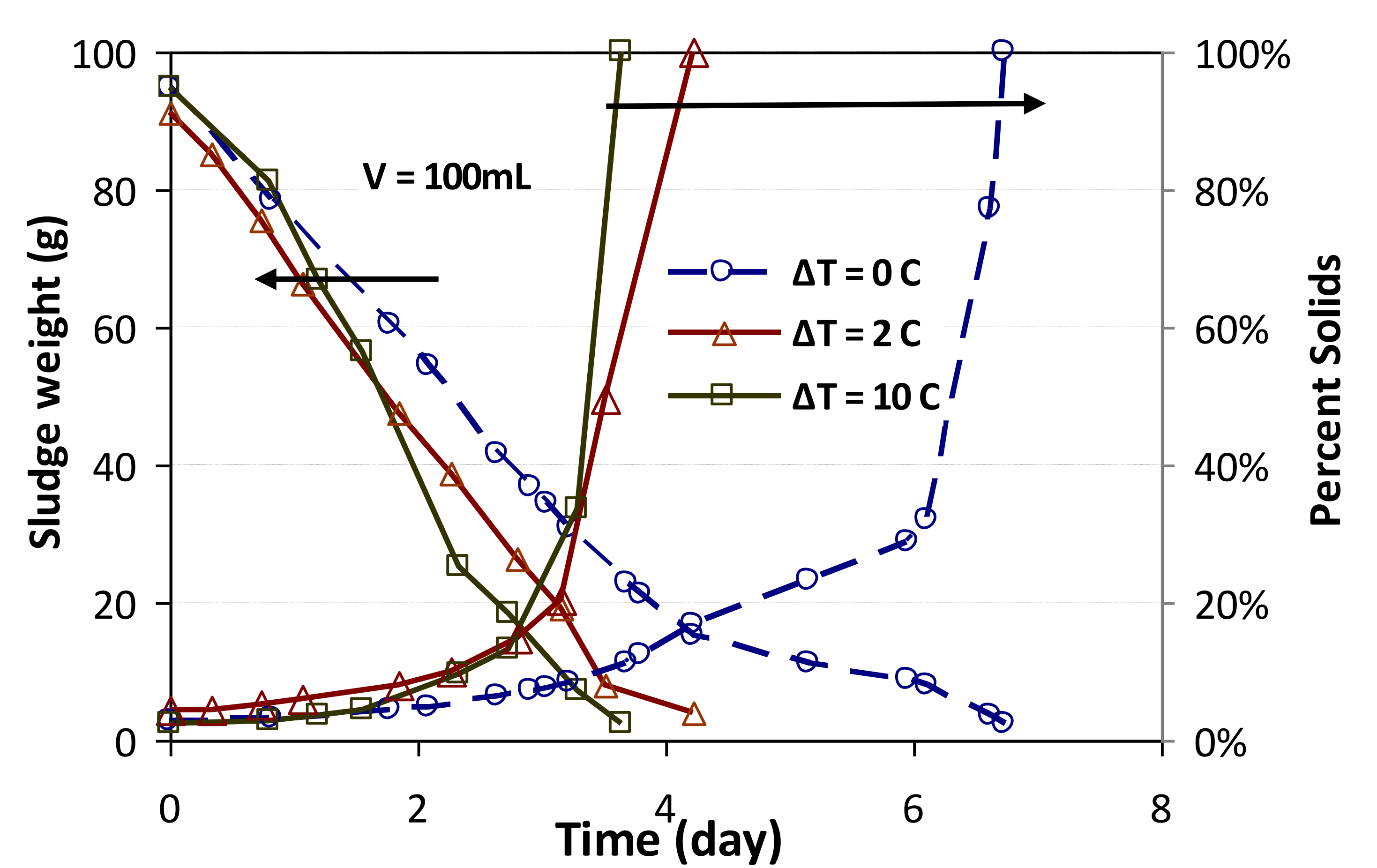
Results

Drying with/without membrane



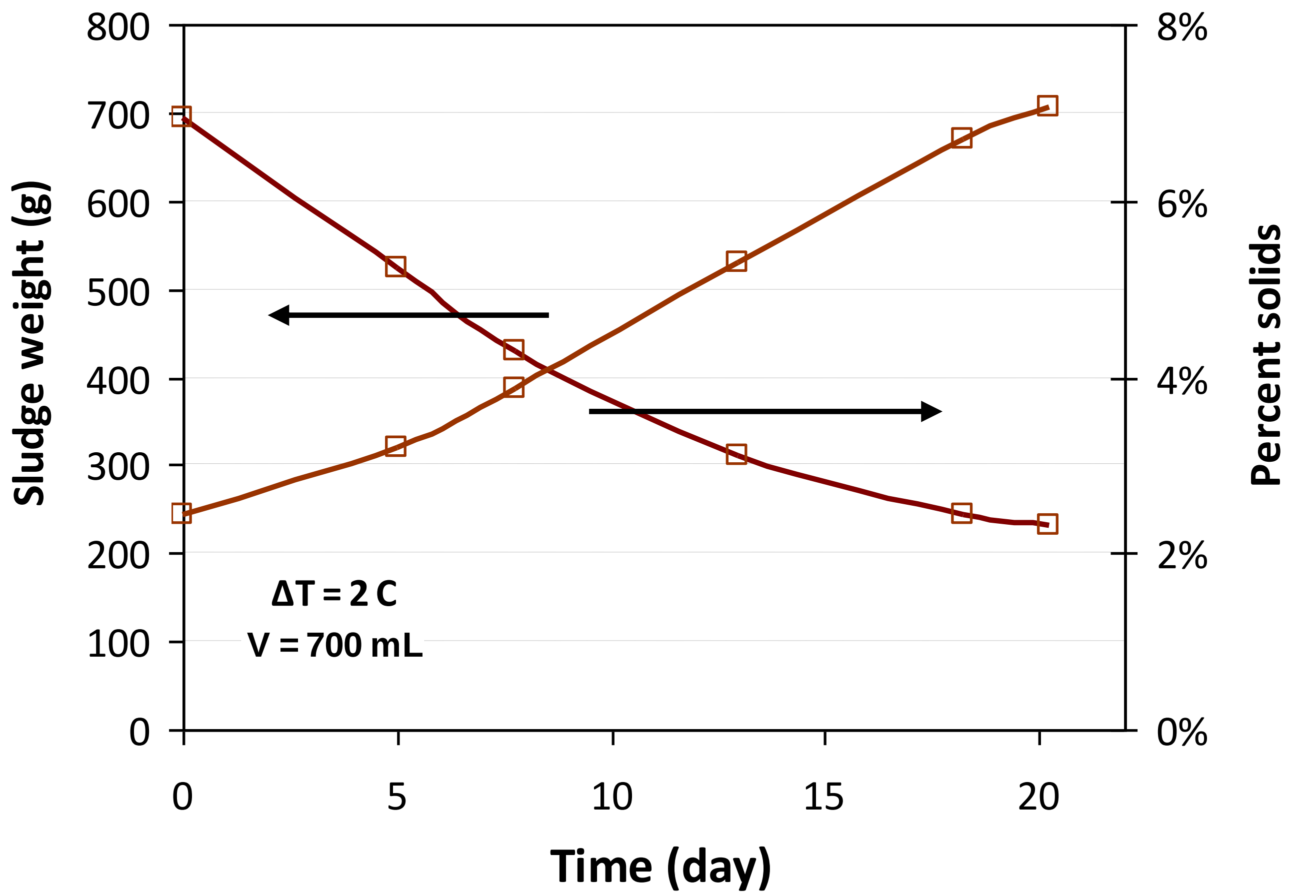
Easily attained complete dryness

Effect of temperature difference (ΔT)



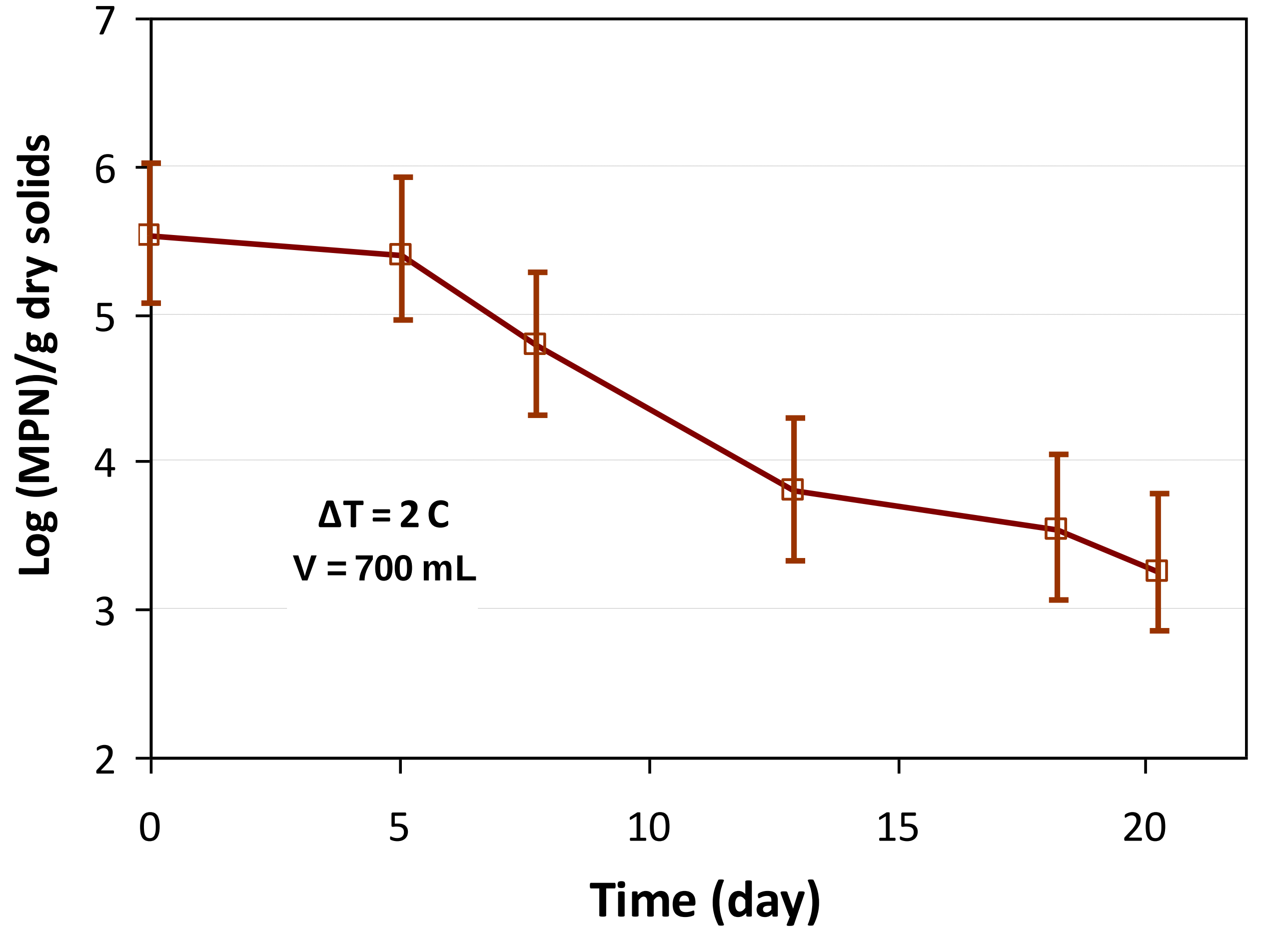
Greater ΔT speeds up drying, but 2C difference seems sufficient

In contact with water instead of air



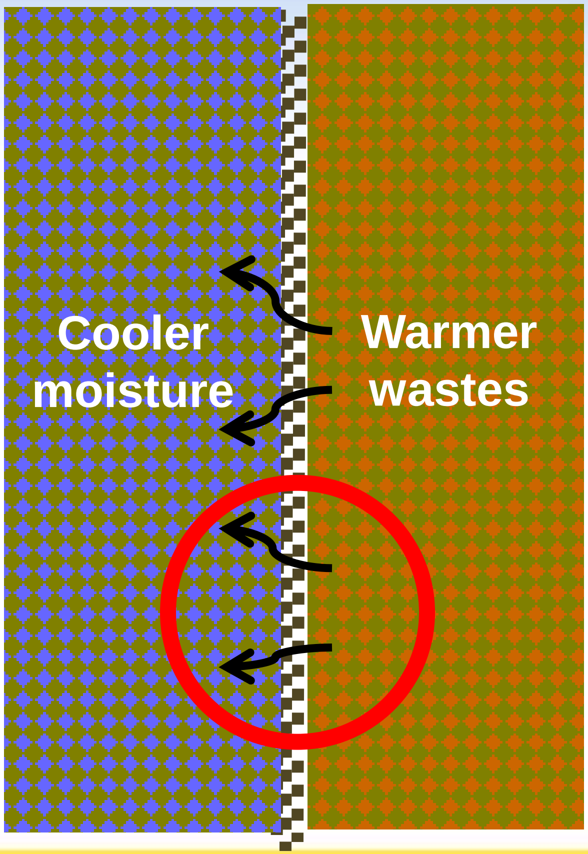
Slower water removal, but 2/3 of water is still removed

Bacterial die-off



99.4% removal of fecal coliform. ND across membrane.

Understanding the Process



- Initial feasibility
- Characterization
- Material and condition optimization
- Practicality
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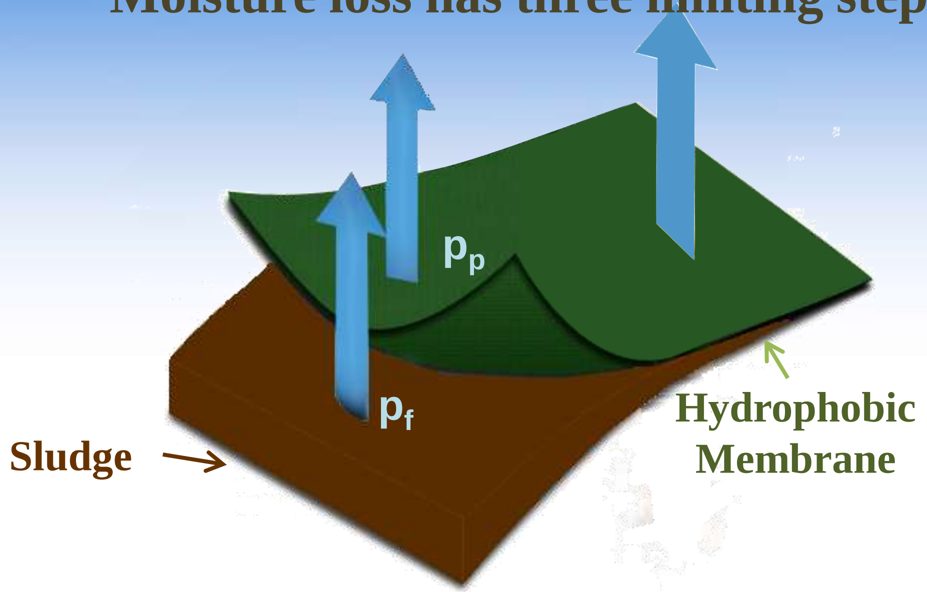
Studies of rate-limiting factors

Moisture loss has three limiting steps

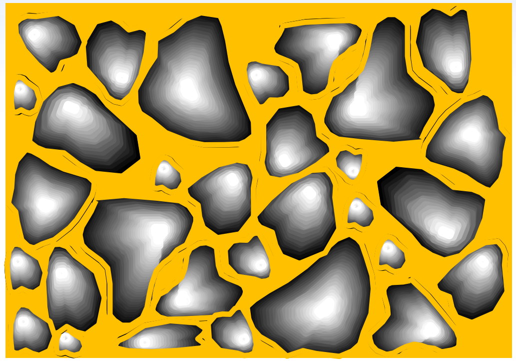


I. Moisture transfer in sludge

II. Vapor transfer across membrane

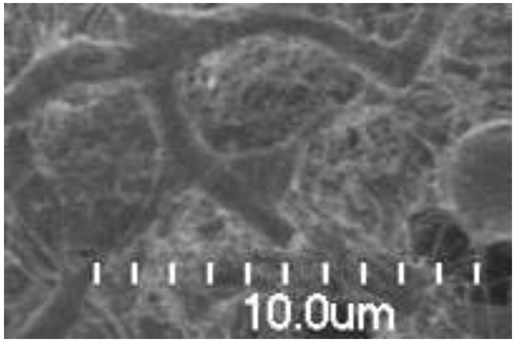
III. Vapor transport from membrane surface to surrounding area

Water Distribution in Sludge



Free Water

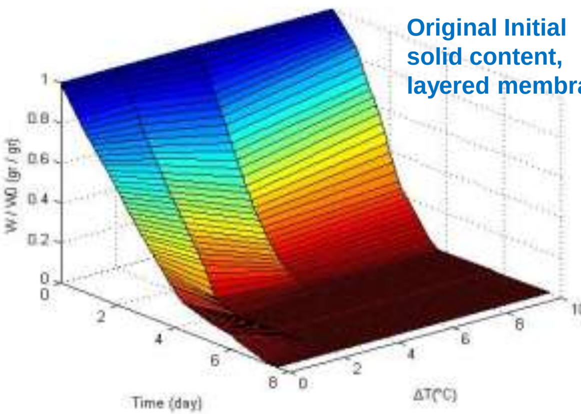
Capillary and Surface-Bound Water



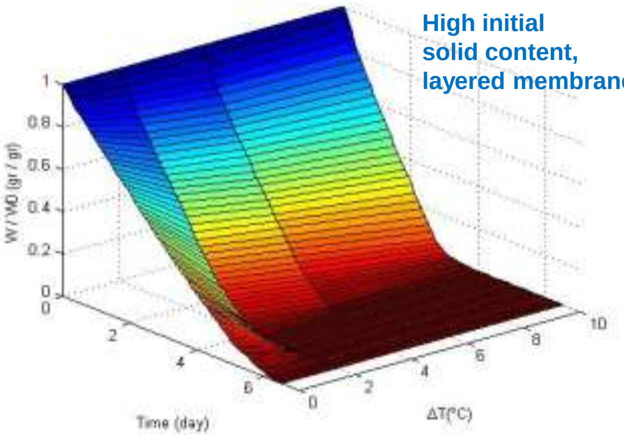
Biopolymer-Associated Water

Experimental Results

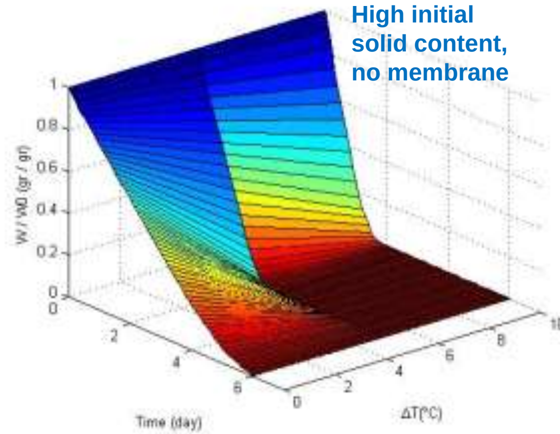
Typical Drying Curves



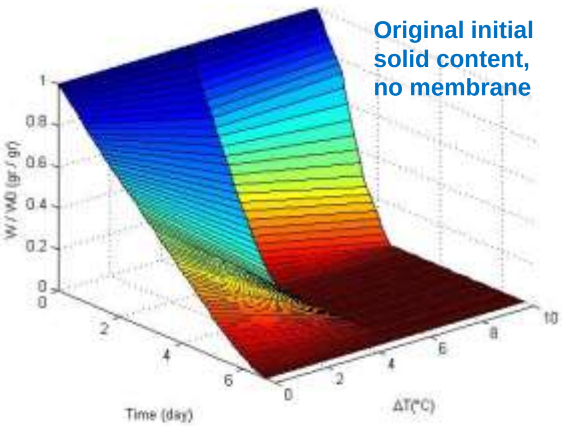
Original Initial solid content, layered membrane



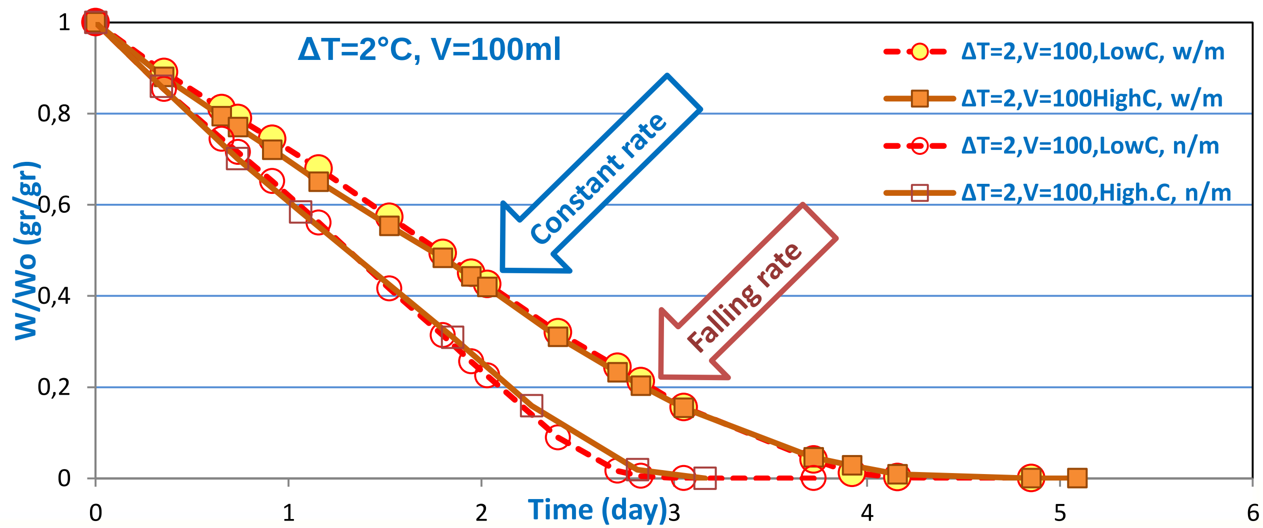
High initial solid content, layered membrane



High initial solid content, no membrane



Original initial solid content, no membrane



Sludge Drying Kinetics

I. Two Period Model

$$\frac{w}{w_0} = \underbrace{(1 - N_0 \frac{t}{w_0})}_{\text{constant rate period}} + \underbrace{\frac{N_0 \sigma \sqrt{\pi}}{2 w_0}(1 - erf\,\frac{t_f - t}{\sigma})}_{\text{falling rate period}}$$

(Efremov,1998)

$$\sigma = \frac{2}{\sqrt{\pi}}(t_f - \frac{w_0 - w_{eq}}{N_0})$$

Characteristic time (day)

II. Fick's Second Law

$$\frac{\partial w}{\partial t} = div(D.grad w) \xrightarrow{\text{One-dimensional isotropic diffusion}} \boxed{\frac{\partial w}{\partial t} = D_{eff}\frac{\partial^2 w}{\partial x^2}}$$

BC1: x=0 (surface) $N = -D_{eff}\frac{\partial w}{\partial x} = k(w^* - w)$

BC2: x=L (bottom) $\frac{\partial w}{\partial x} = 0$

$$\frac{w - w_{eq}}{w_0 - w_{eq}} = erf\,(\frac{x}{2\sqrt{D_{eff} t}}) + e^{(\frac{k}{D_{eff}})x + (\frac{k^2}{D})t}\, erfc(k\sqrt{\frac{t}{D_{eff}}} + \frac{x}{2\sqrt{D_{eff} t}})$$

Including power "*n*" to account for convection

$$MR = \frac{w - w^*}{w_0 - w^*} = \exp\left[\frac{1}{\pi}(\frac{t}{\sigma})^n\right] erfc\left(\sqrt{\frac{1}{\pi}(\frac{t}{\sigma})^n}\right)$$

$$\sigma = \frac{D_{eff}}{\pi k^2}$$

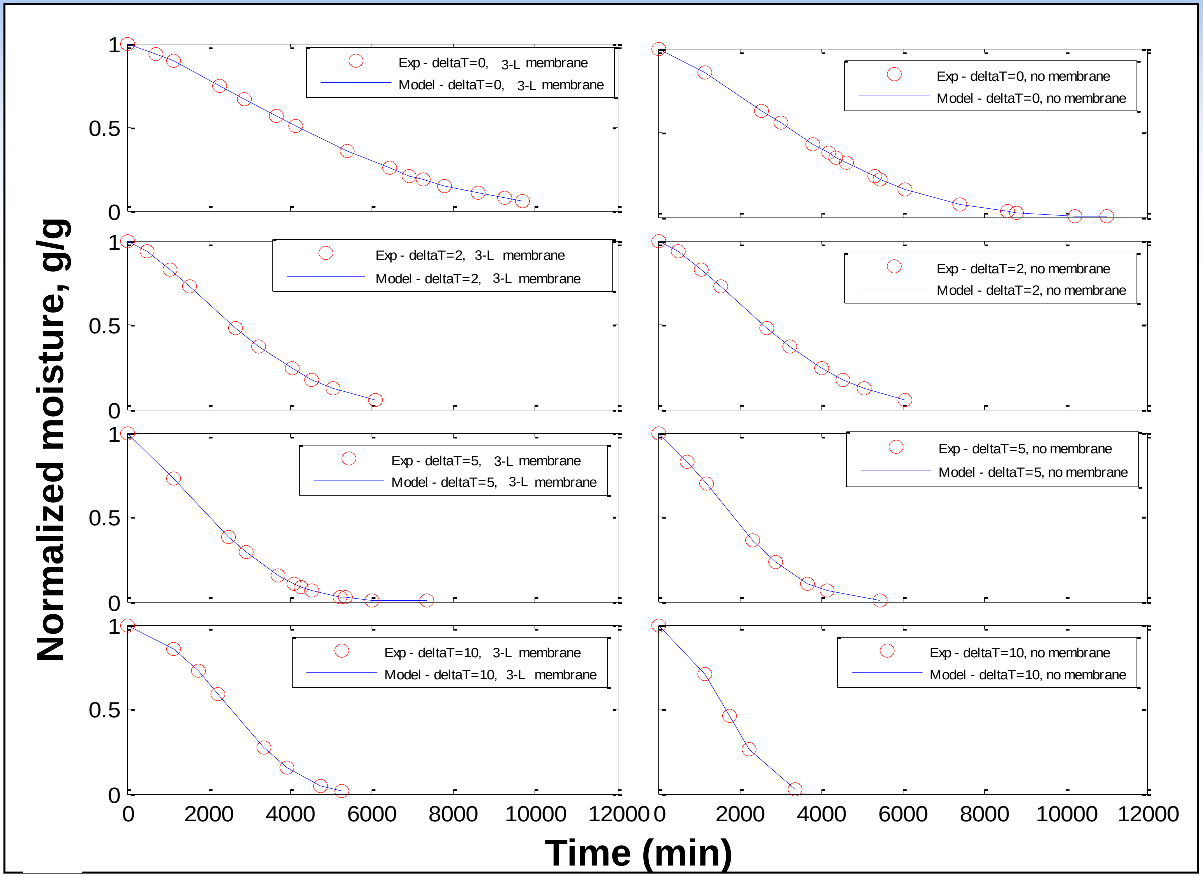
Characteristic time (day)

- w solid based moisture content (g/g)
- w_0 initial moisture content (g/g)
- w_{eq} equilibrium moisture content (g/g)
- N_0 constant drying intensity (1/d)
- t drying time (d)
- x location (m)
- D diffusivity of water in sludge (m^2/d)
- D_{eff} effective diffusion constant (m^2/d)
- k mass transfer coefficient (m/d)
- MR: moisture reduction (g/g)

Characteristic Time (σ) Estimation

$$MR = \frac{w - w^*}{w_0 - w^*} = \exp\left[\frac{1}{\pi}\left(\frac{t}{\sigma}\right)^n\right]\operatorname{erfc}\sqrt{\frac{1}{\pi}\left(\frac{t}{\sigma}\right)^n}$$

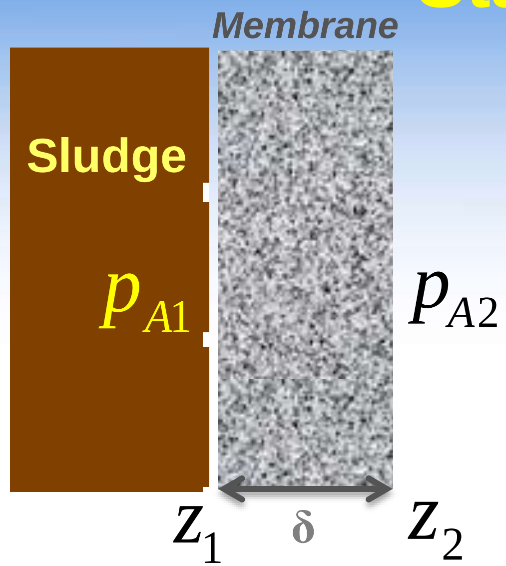
$$\sigma = \frac{D_{eff}}{\pi k^2} =$$ *Characteristic time (min)*



n = 2.5	σ (min)	
ΔT (° C)	Membrane	No Membrane
0	11,630	9,440
2	7,2130	4,990
5	5,620	5090
10	5,300	3450

i. Vapor transfer across the membrane:

Stagnant Film Model



$$N_A = k^* \ln\left(\frac{P - p_{A1}}{P - p_{A2}}\right)$$

$$k^* = \frac{D_{eff} P}{RTavg\,\delta} =$$ Stagnant film mass transfer coefficient

$$D_{eff} = D_{AB} \frac{\varepsilon}{\tau}$$

N_A	=	flux of water across membrane ($\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$)
P	=	total pressure of water vapor and air (Pa)
p_{A2}	=	partial pressure of water vapor on feed side (Pa)
p_{A2}	=	partial pressure of water vapor on exit side (Pa)
D_{AB}	=	diffusivity of water vaport in air ($\mathrm{m^2 \cdot s}$)
D_{eff}	=	effective diffusion constant ($\mathrm{m^2 \cdot s}$)

R	=	gas constant ($\mathrm{J \cdot K^{-1} mol^{-1}}$)
T_{avg}	=	avg. membrane temperature (K)
ε	=	membrane porosity (-)
τ	=	membrane tortuosity (-)
δ	=	membrane thickness (m)

Stagnant Film Model Validation

$$N_A = k^* = 12{,}187 \frac{D_{AB@T\ avg}}{T_{avg}} \left(\frac{\varepsilon}{\delta\tau} \right) \ln \left(\frac{P - p_{A1}}{P - p_{A2}} \right)$$

$$\boxed{N_A = 12{,}187 \frac{D_{AB@T\ avg}}{T_{avg}} \left(\frac{1}{\lambda} \right) \ln \left(\frac{P - p_{A1}}{P - p_{A2}} \right)}$$

$\lambda = \delta\tau / \varepsilon =$ membrane diffusion resistance (m)

Understanding the Process

- Initial feasibility
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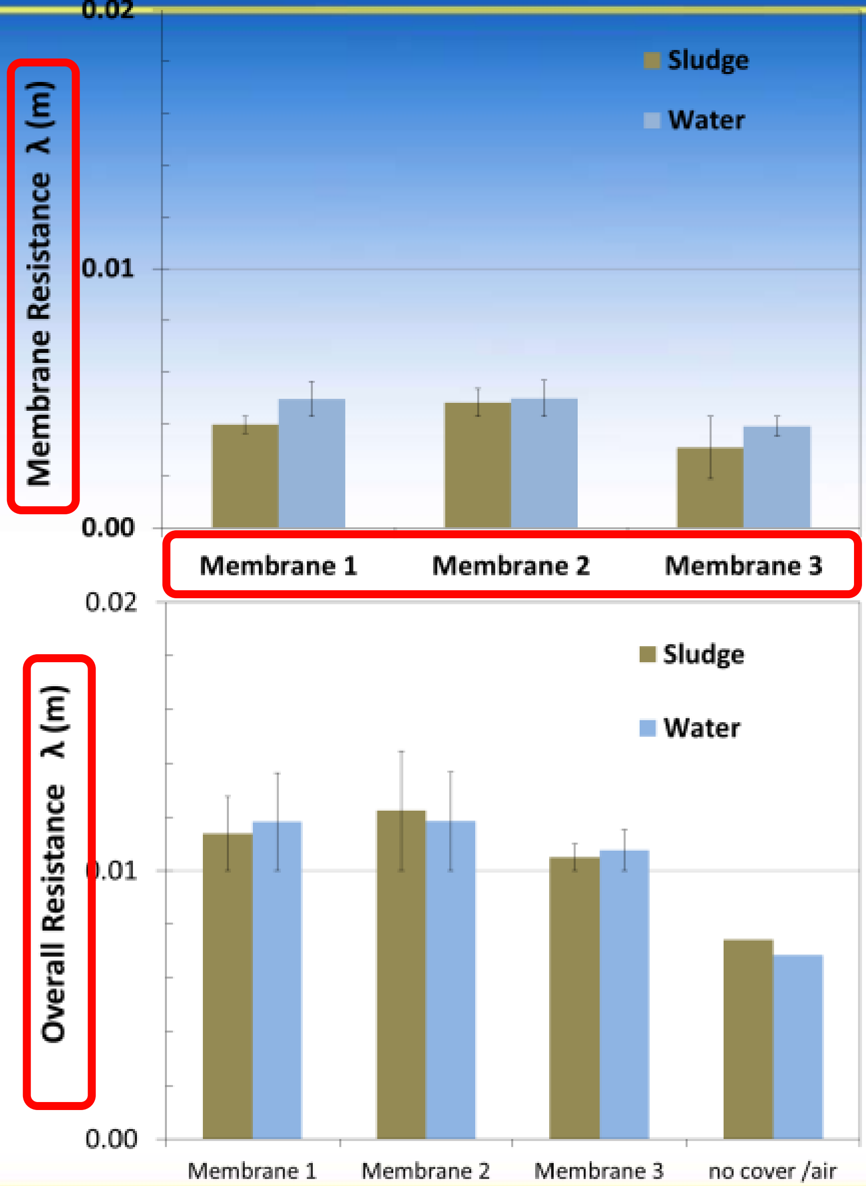
- Practicality
- Scale-up

Process quantification using stagnant film model



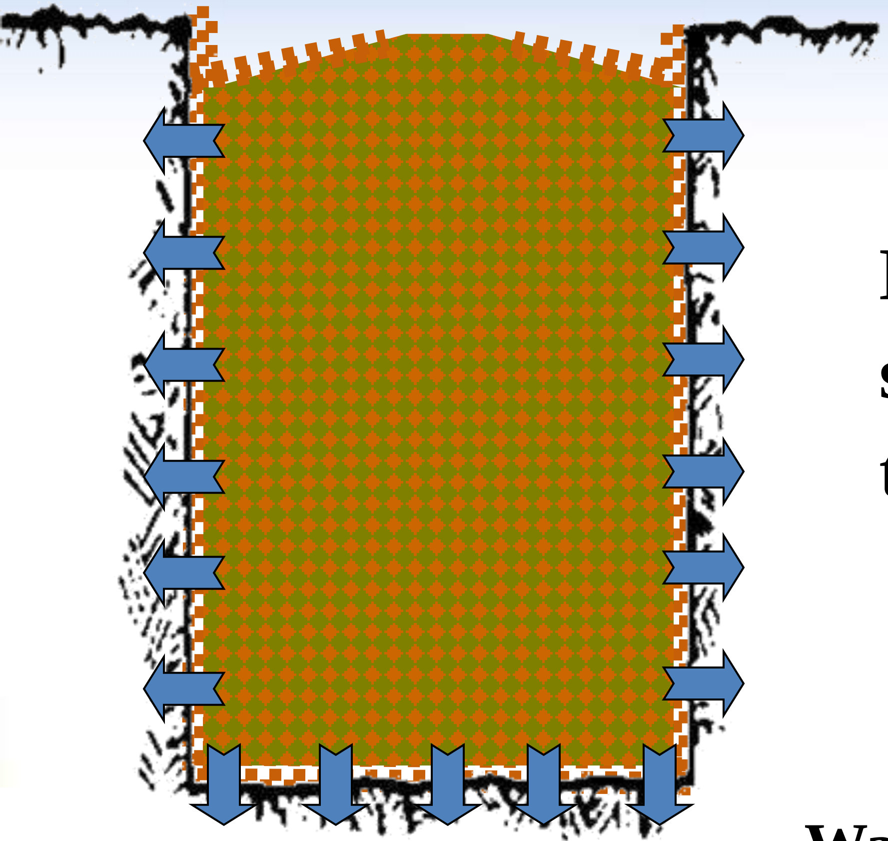
Three different membranes have similar resistances, ~ 1/3 of total

Understanding the Process

- Initial feasibility
- Characterization
- Material and condition optimization
- Practicality
- $\boxed{\text{Scale-up: initial estimates}}$

Predicting the Drying Rate

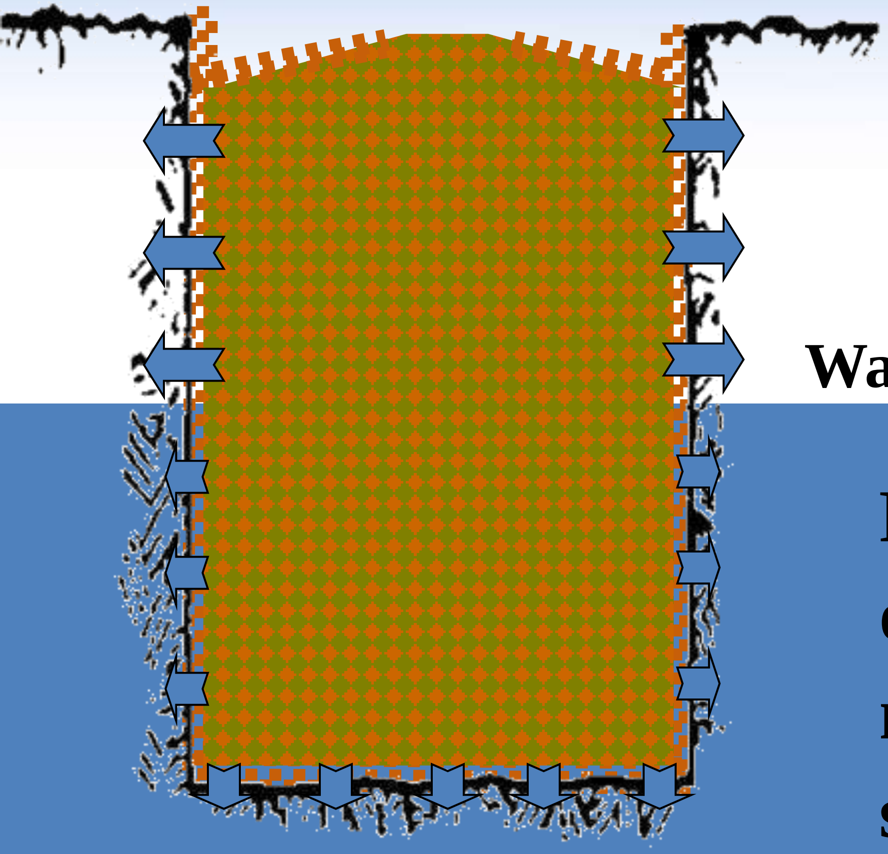
Is this process feasible ?



Drying rates now known for sludge/membrane/air: assume this applies unsaturated soil

Water Table

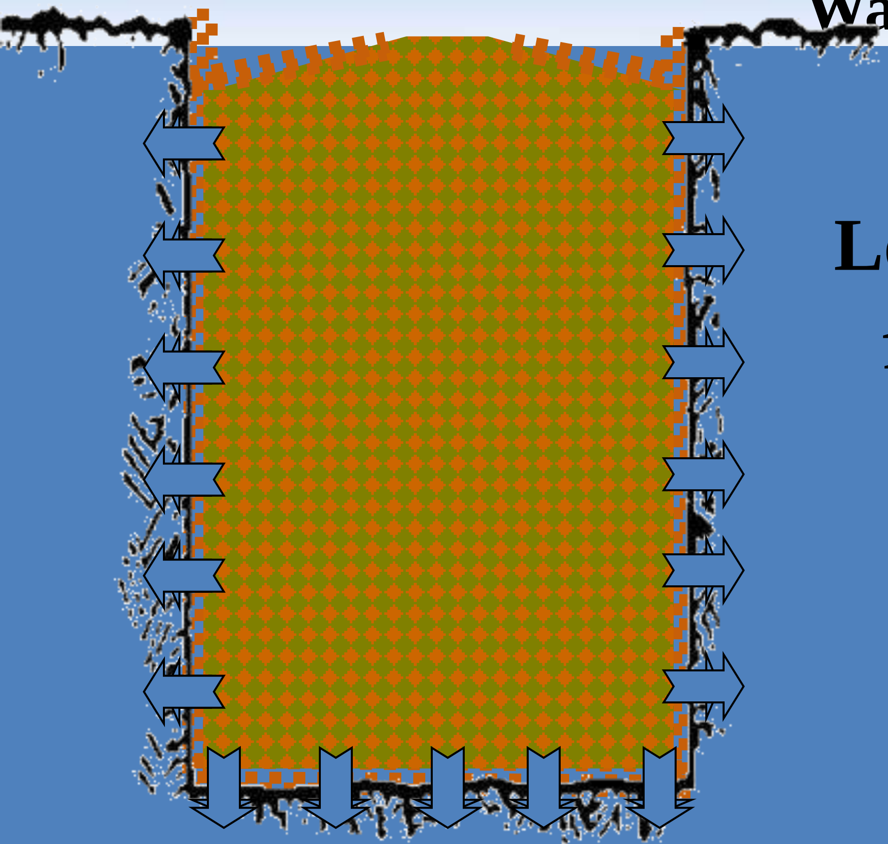
Predicting the Drying Rate



Water Table

Portions of pit in saturated or flooded depths only lose moisture at rate measured in sludge/membrane/water tests

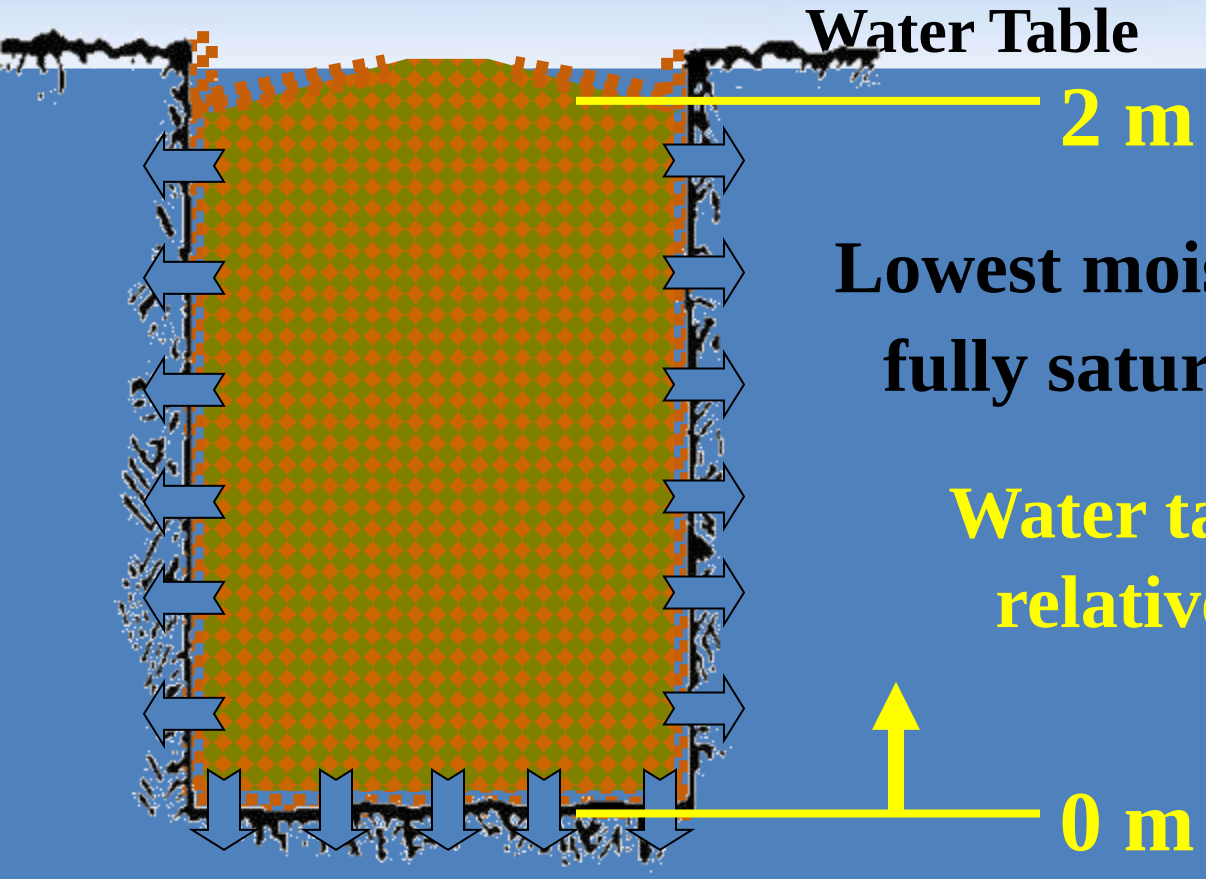
Predicting the Drying Rate



Lowest moisture loss if soil is fully saturated or flooded

Predict water removal vs. water elevation and vs. ΔT

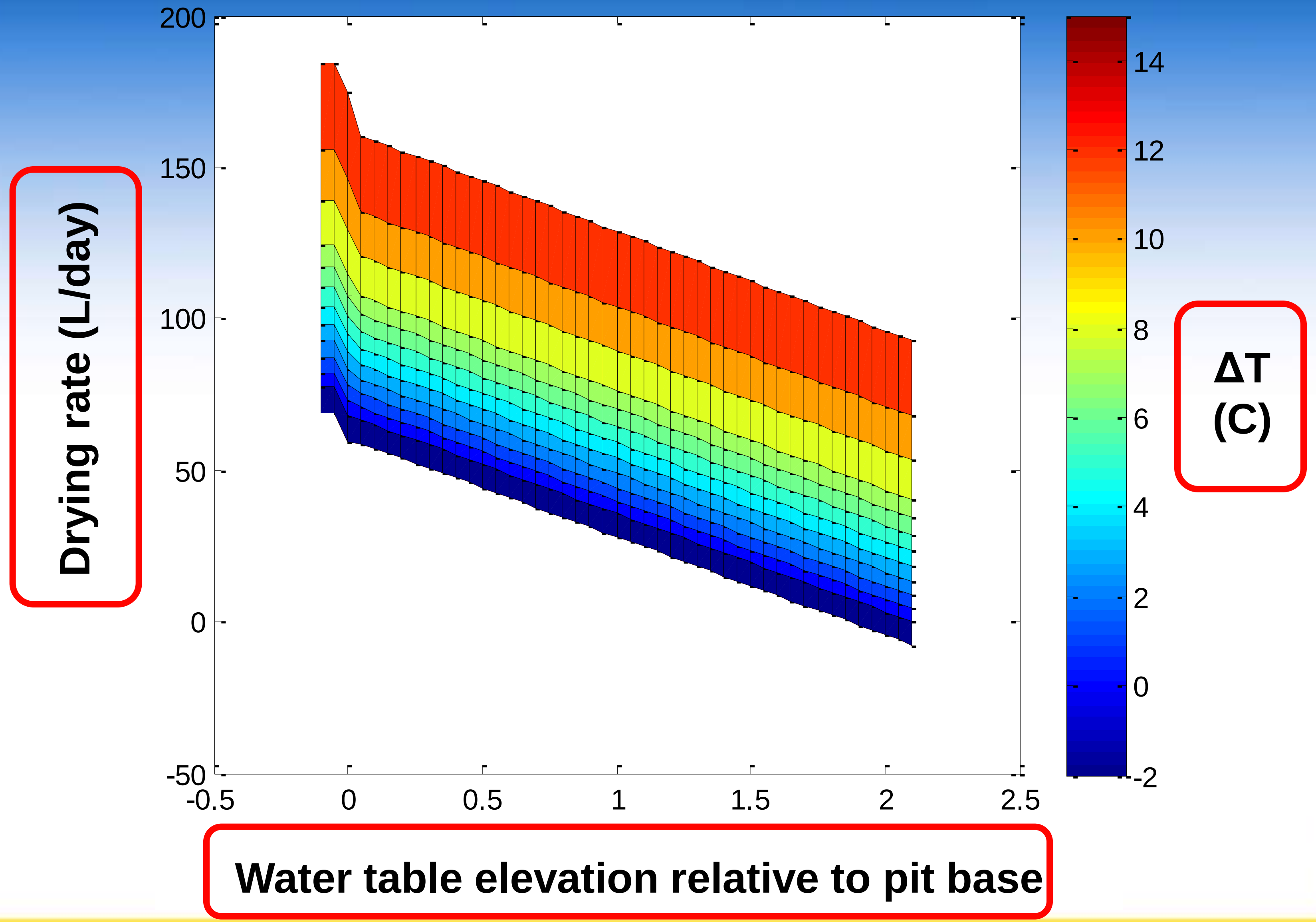
Predicting the Drying Rate



Lowest moisture loss if soil is fully saturated or flooded

Water table elevation relative to pit base

Performance Prediction



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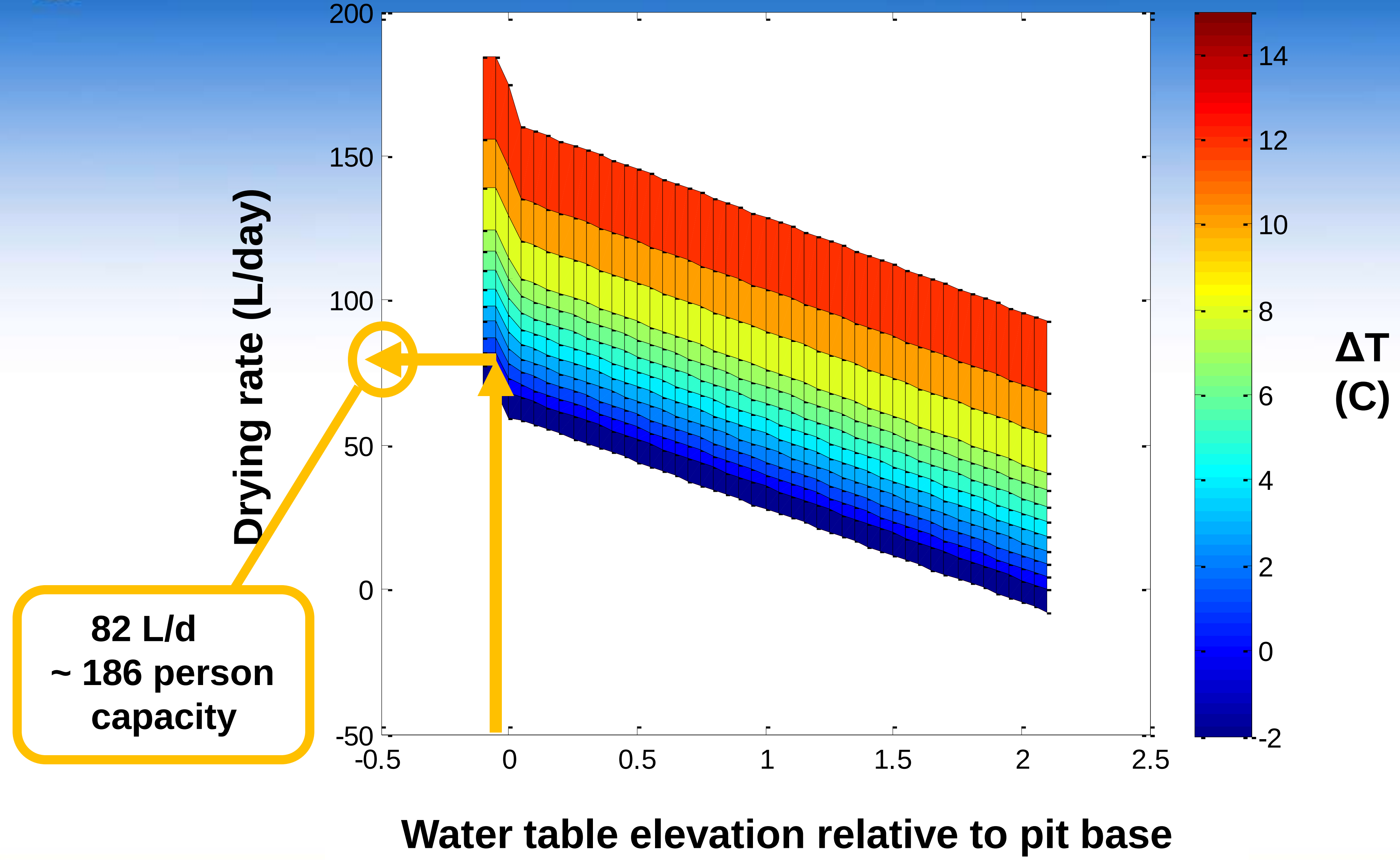


Even worst case assumptions give 18 person capacity

Summary

- Process is effective in lab tests with ΔT as little as 2C, in contact with air or water
- Water is lost from sludge while protecting the environment
- Membrane can be re-used

Future Plans

- Faecal sludge to be used in place of digested sludge
- Scale up/practicality tests
- Compare other important membrane properties (strength, heat conductivity, etc.)
- Work with membrane companies to assure affordable membrane

Applications not limited to basic pit toilets

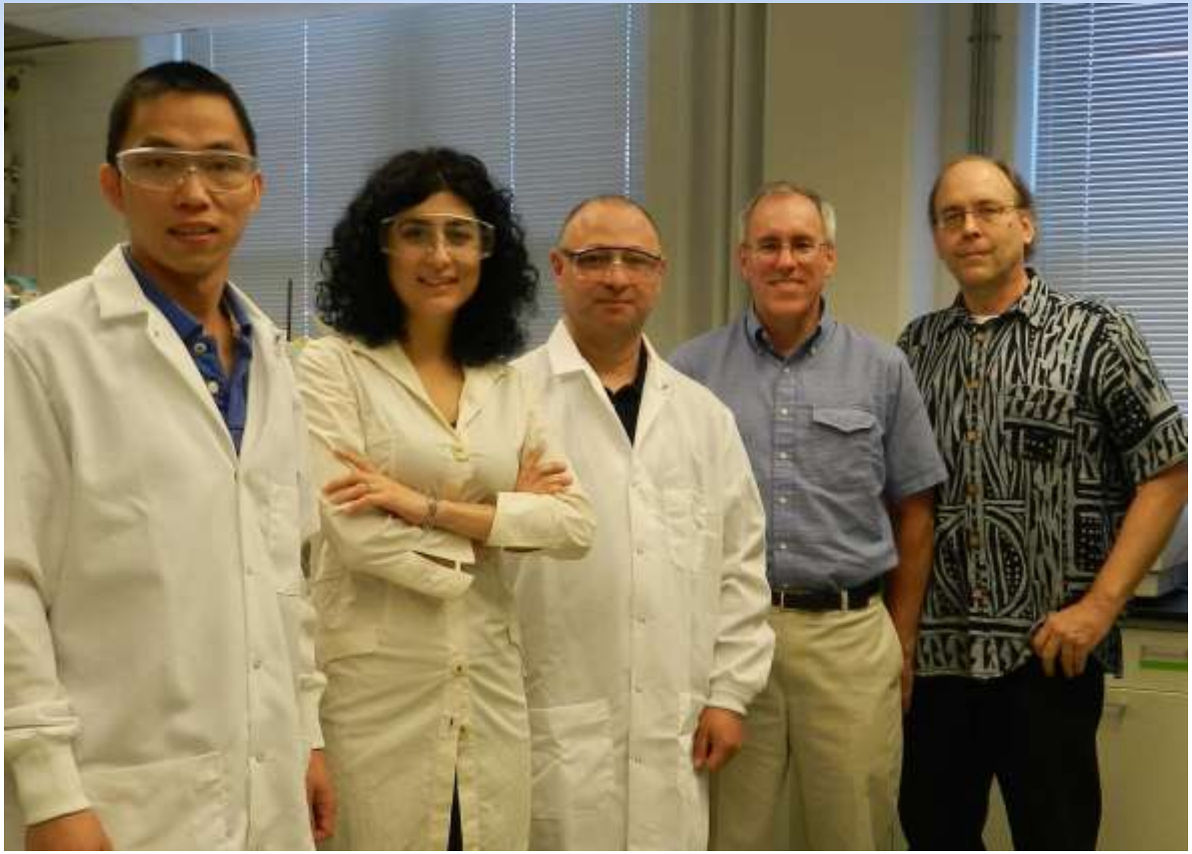
- With or without urine diversion
- Pumped latrine wastes
- Combined with other evolving toilet technologies
- Commercial applications at larger scale
- Et cetera

Discussions/collaborators welcome

Acknowledgements

- <u>**Bill and Melinda Gates Foundation**</u>
- **Dr. Paul Imhoff**
- **Dr. Rovshan Mahmudov**
- **Michael Davidson**

Thanks!



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