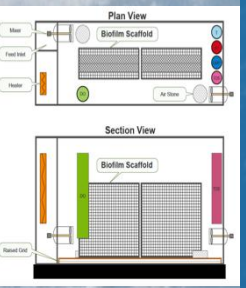
Next Generation Wastewater System for NASA



2016 WaterJAM

Va. Beach, VA

September 15, 2016

PANCOPIA
RESOURCEFUL. SUSTAINABLE. SOLUTIONS.

What's the big deal about water in space?

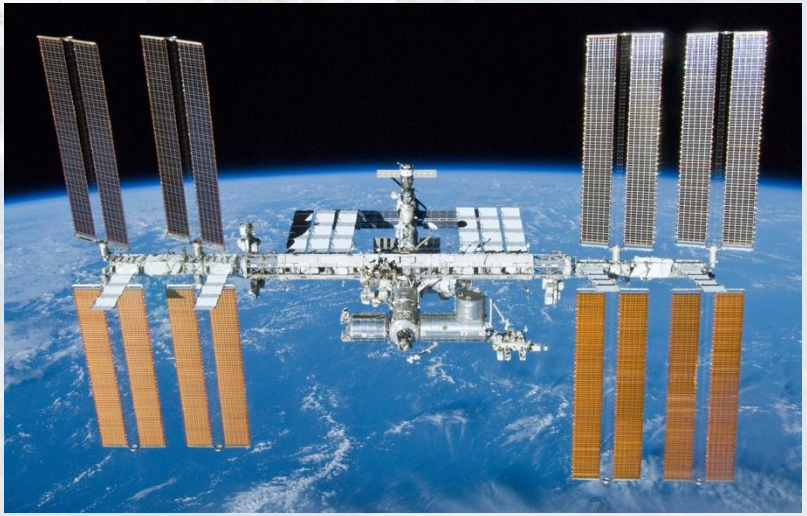
- $10,000 a pound to deliver an item to the space station
- $83,000 per gallon of water
- Water is 92 % of living costs in space
- Bottle of water (16 oz) costs $10,000 in space!

If you could use “space water” to pay for things

- You could fund the Federal government ($3.8T) for a year with 46 million gallons of water (less than half of what HRSD treats each day)!
- You could be a “water millionaire” by owning 15 gallons of water!
- Or you could send your kid to college with a few liter bottles of water for room board and tuition!

Facts about the International Space Station

- Announced during Reagan's 1984 State of the Union Address.
- First module launched in 1998; continuously occupied since 2000.
- Five different space agencies representing 15 countries built the $100-billion International Space Station and continue to operate it today.



Water and the International Space Station

- Feces is separated out from recycling system and is released in spent containers to burn up in the earth's atmosphere.
- Typical crew size is 4 to 6; each person consumes approximately 3 gallons (11 liters) per day.
- Urine is treated through vacuum distillation via the Urine Processing Assembly (UPA).
- Water Processing Assembly (WPA) filters UPA water, condensate, and other sources.
- Russian side of station does not treat urine – they send it to the Americans.

How much water is needed?

- Each astronaut requires about 3 gallons per day
- The current recycling system is able to recycle about 85% of the wastewater generated
- Approximately 444 gallons of additional water is needed each year – at a cost of $43 million a year

444 gallons is 8 barrels, each valued at $5 million!

Recycling efficiency is extremely important!

- Improving recycling from 85% to NASA's goal of 95% will reduce annual resupply costs by $24M!
- Difficult to increase mechanical/chemical recycling efficiency by 10% without excessive energy usage and consumables.
- A biological system removing organic carbon and nitrogen could permit the use of reverse or forward osmosis to achieve the target of 95% recycling.

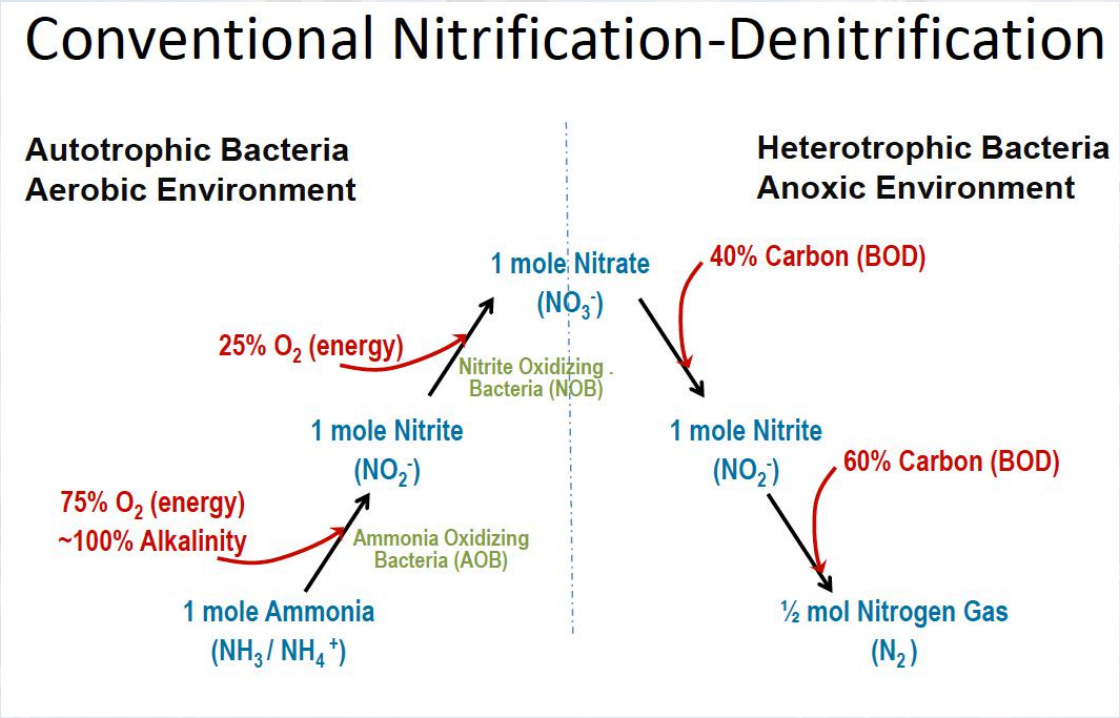
Overview of Project

- NASA's Requirements
- Current wastewater technology
- Anammox
- Pancopia's Phase I feasibility testing
- Results of Phase I research
- Phase II research and current status
- What next?

NASA's Requirements

- System to precondition wastewater to make is suitable for final filtration use RO or FO
  - Wastewater high in ammonia (about 600 mg/l as N) and an organic carbon (about 900 mg/l COD)
  - Target removal of between 85% to 95% N and TOC
- Low level of consumables
- Shut down for long periods of time (up to a year)
- Start up quickly and reliably (less than 45 days; preferably 15 days)

Current nitrogen removal technology
(95%+ WWTPs that remove nitrogen use this or similar technology)



Advantages:

- Current system being tested for past decade (membrane aerated system)

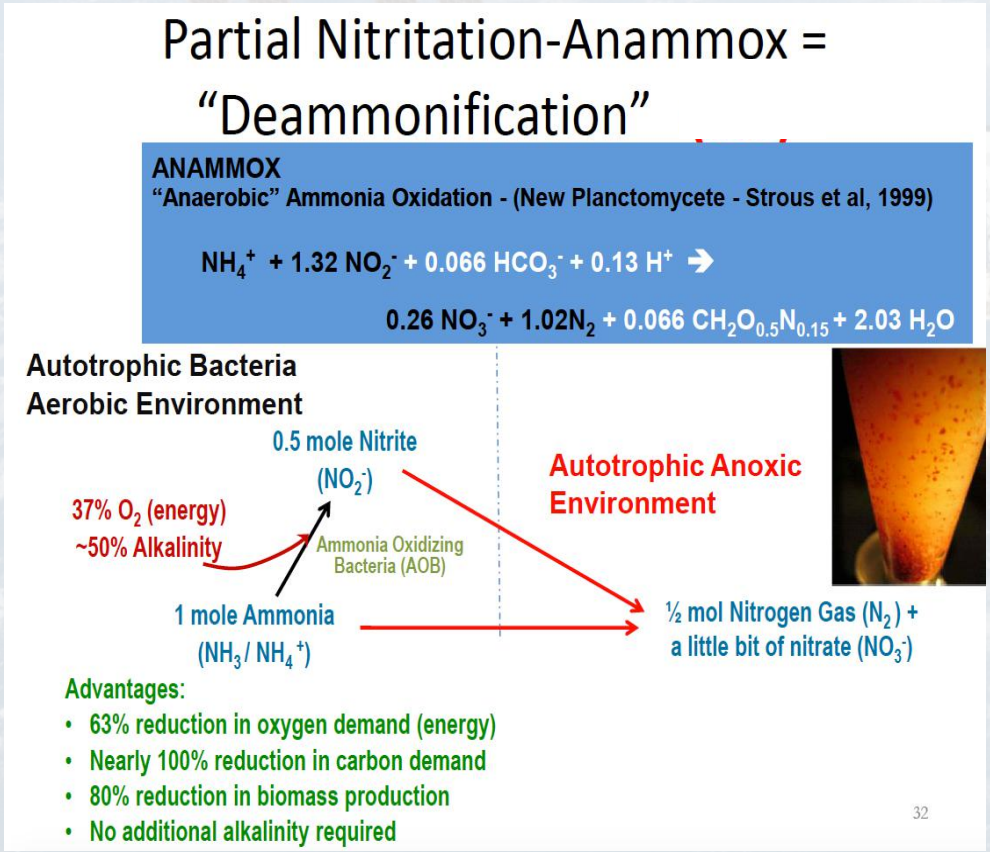
Challenges for NASA:

- Requires high levels of energy (O_2)
- Requires additional carbon
- High O_2 requirements could cause phase flow problems in microgravity

Nitrogen removal with anammox

- **AN**aerobic **AMM**onia **OX**idizing Bacteria.
- Predicted in 1977 by Broda.
- Discovered in 1995 at a plant that was removing ammonia but shouldn't have been.
- Delayed discovery due to long reproduction time (2 to 3 weeks) and highest concentrations of organisms are in inaccessible locations (deep ocean upwellings).
- Deammonification is a nascent technology(<100 plants in 2014) – but can remove nitrogen for 1/3 of current costs!
- Adoption has been delayed by:
  - limited supply of organisms
  - advanced control requirements more suitable for larger plants (both problems are being worked on!)

Deammonification with Anammox



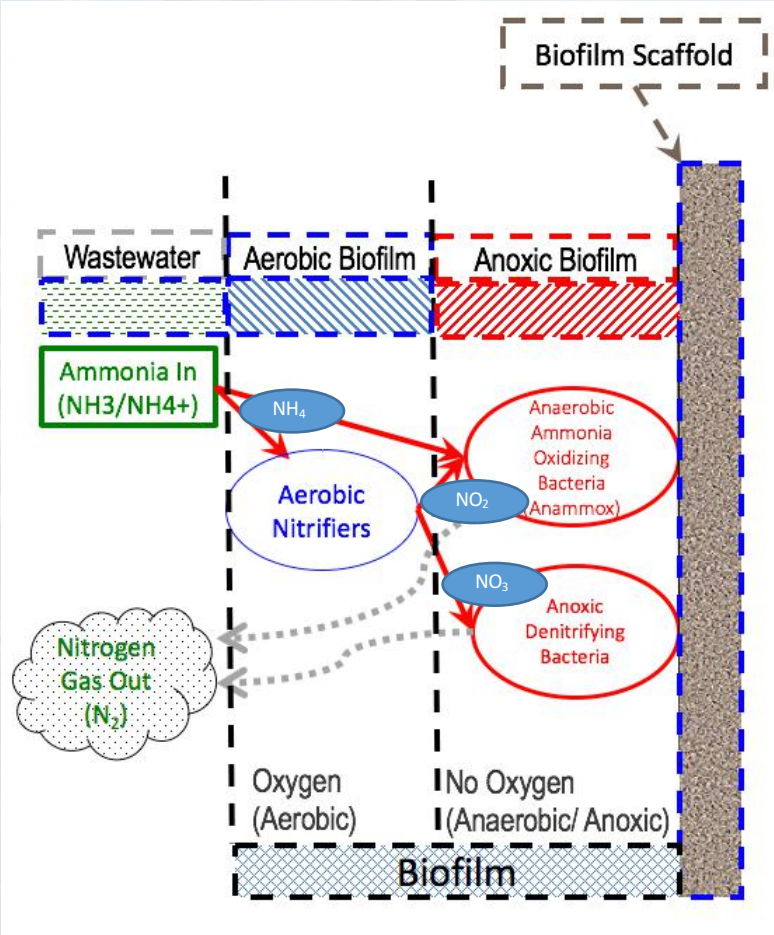
Advantages for NASA:

- Very low energy costs (less aeration needed) and low biosolids production
- Lower O_2 requirements could help resolve phase flow problems related to microgravity

Challenges for NASA:

- Does not remove organic carbon
- Requires high level of control

Treatment system used for NASA bioreactors



Use of three sets of organisms, nitrifiers, denitrifiers, and anammox to remove both carbon and nitrogen

Advantages :

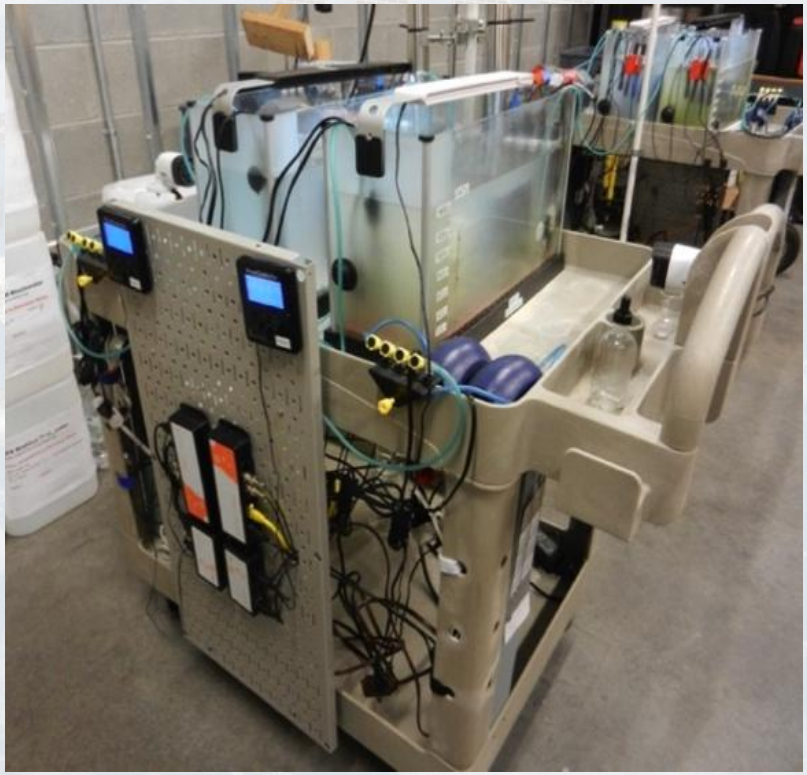
- Low energy costs (less aeration) and low biosolids production
- Lower O_2 requirements could help resolve phase flow problems related to microgravity

Challenges for NASA:

- The ability to balance these three sets of organisms is relatively untested

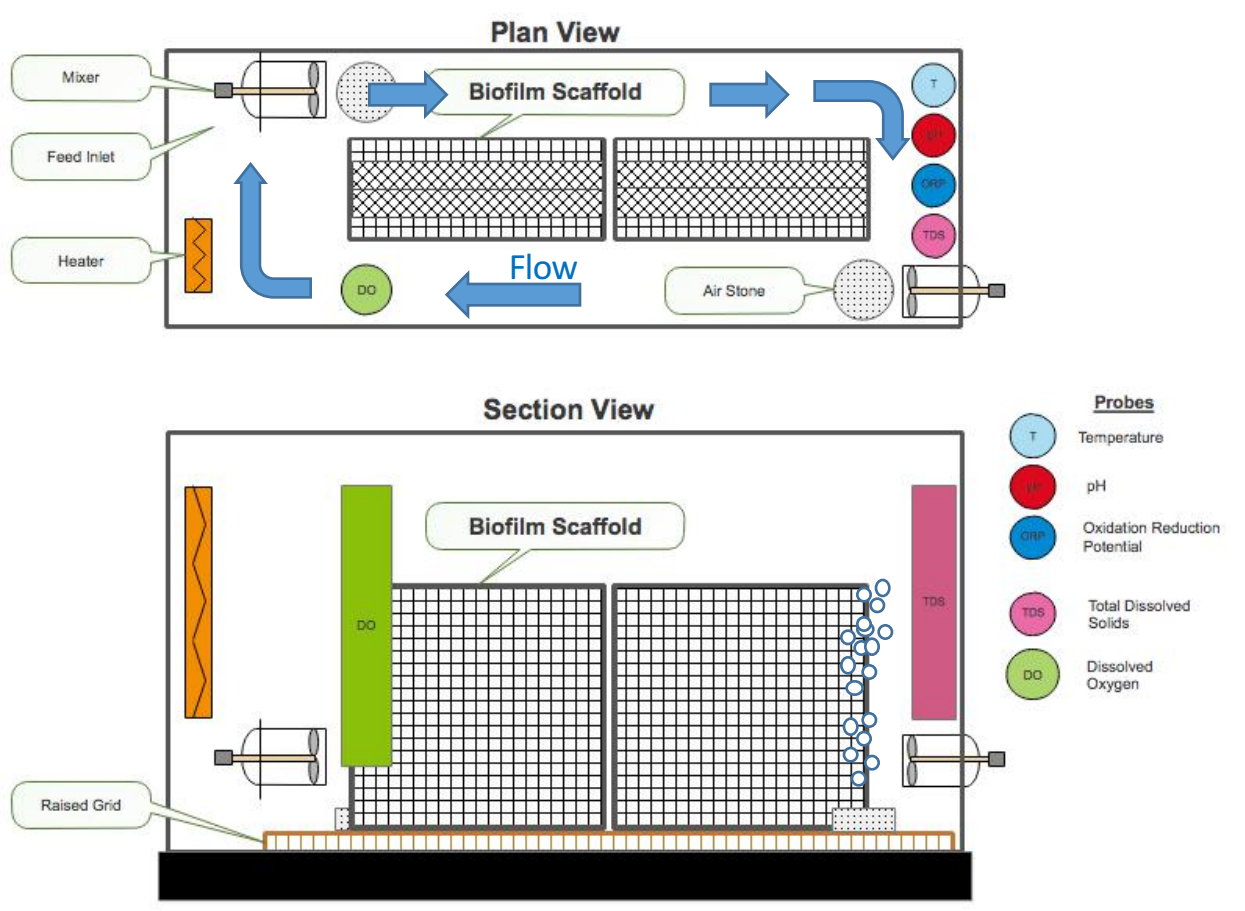
Phase I feasibility testing

- Six reactors
- Three sets of two
- Each set:
  - One reactor with organisms poured into reactor
  - One reactor with organisms embedded in the scaffold
- One set (R1/R2) test for induced dormancy for >45 days
- Two sets (R3/R4 and R5/R6) using lyophilized organisms

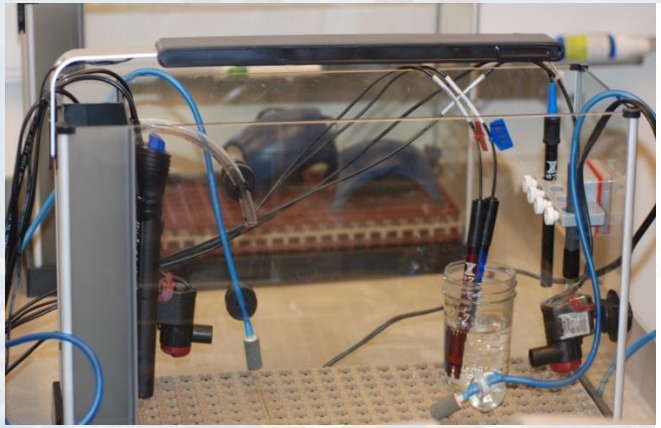


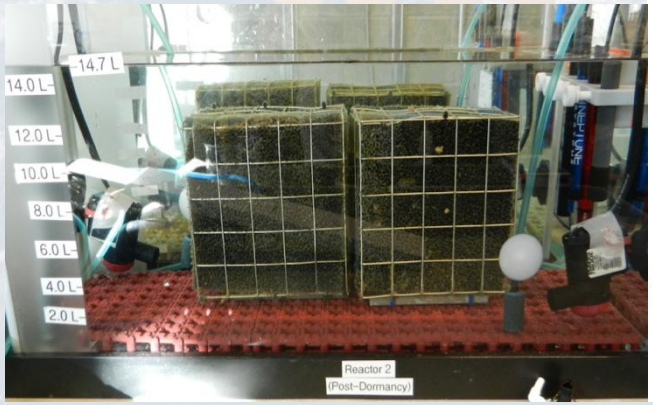
Phase I Bioreactors

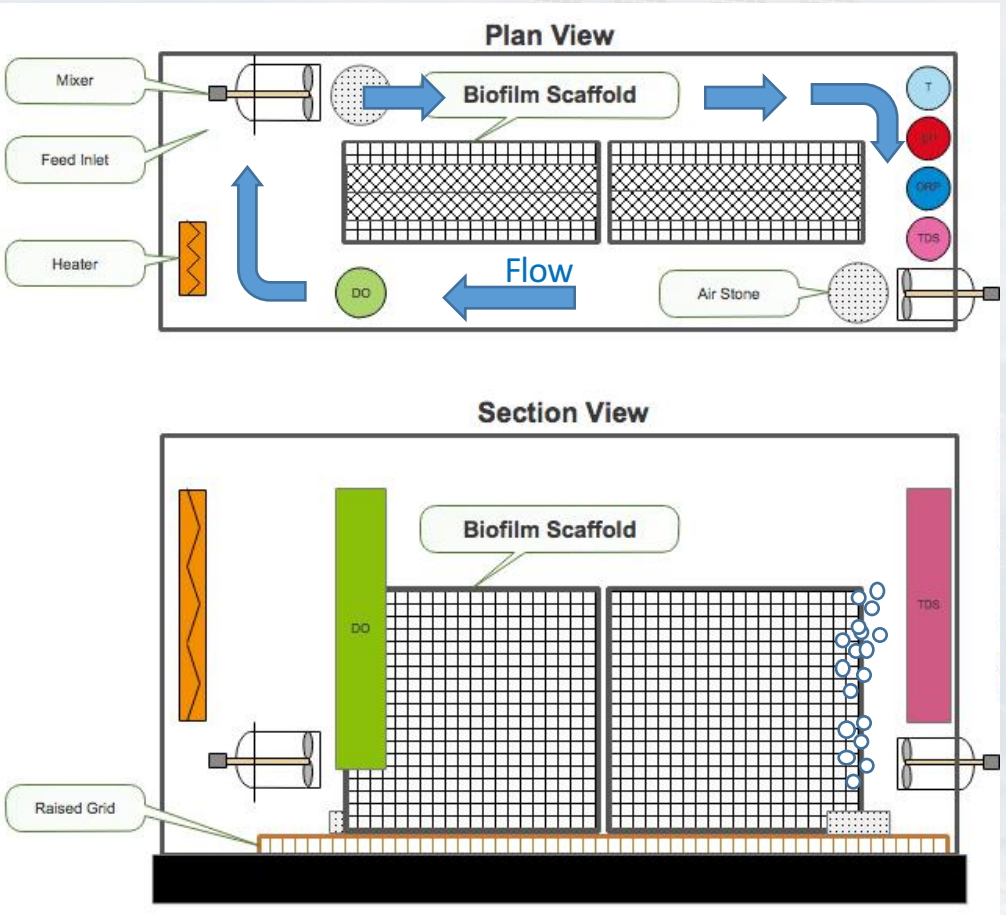
- Fourteen liter volume with continuous mixing (two mixers) and intermittent aeration (two airstones)
- Continuous video monitoring
- Continuous DO, T, pH, ORP, and TDS monitoring
- Daily testing of NH_4^+, NO_3^-, NO_2^-, and COD



Phase I Bioreactors







Phase I Bioreactor Testing Protocol

1. Start each tank with half-strength Early Planetary Base (EPB)wastewater (WW generated on space station)
   - EPB approx. 600 mg/l NH_4-N and 900 mg/l COD
2. No EPB addition until half N and C consumed
3. Feed full strength EPB until steady state (SS) reached
4. Test for 15 days once steady state is reached

For induced dormancy (R1/R2):

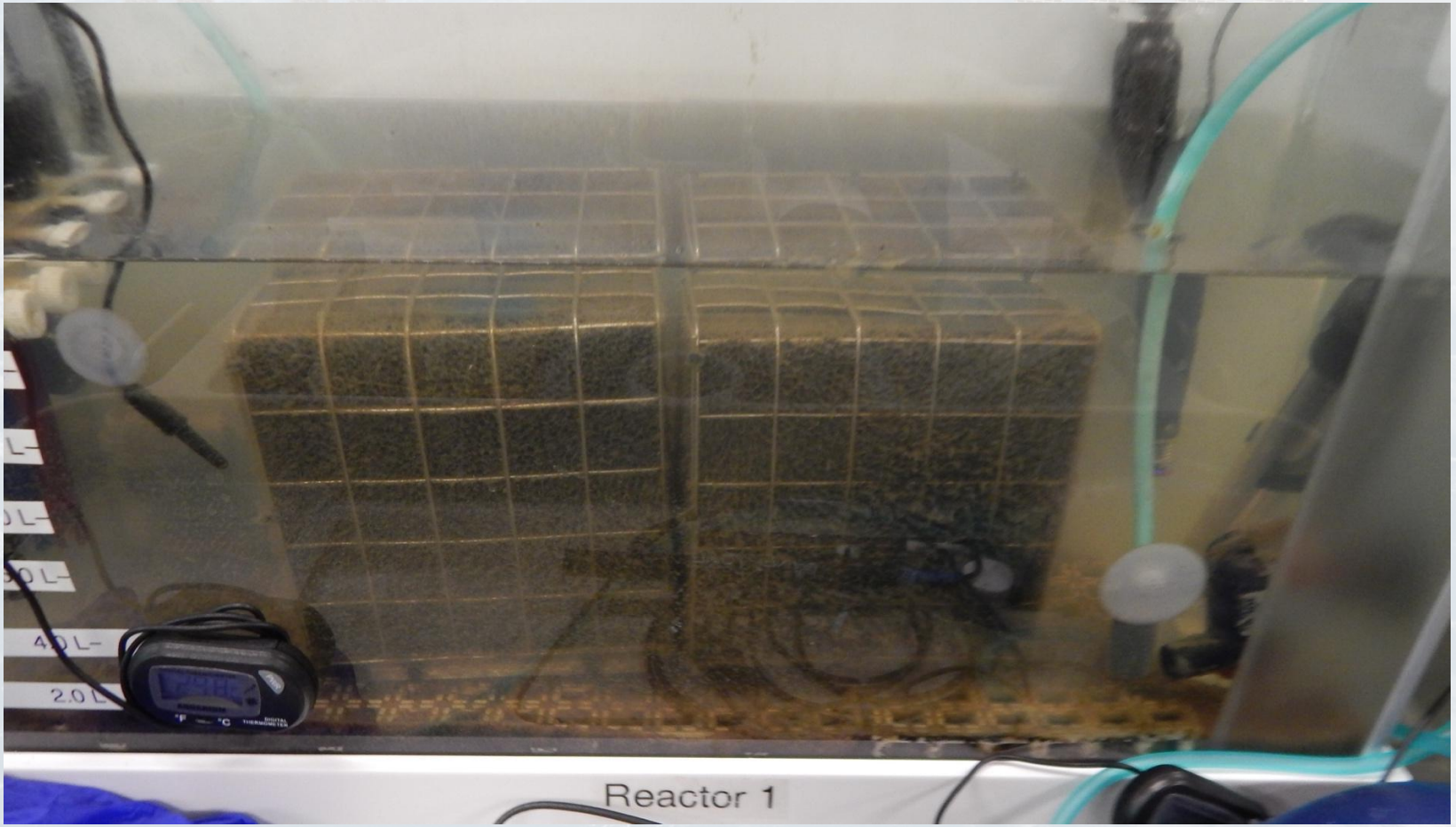
- Startup, reach SS, induce dormancy, restart, reach SS, 15 day test

For lyophilized testing (R3/R4 and R5/R6):

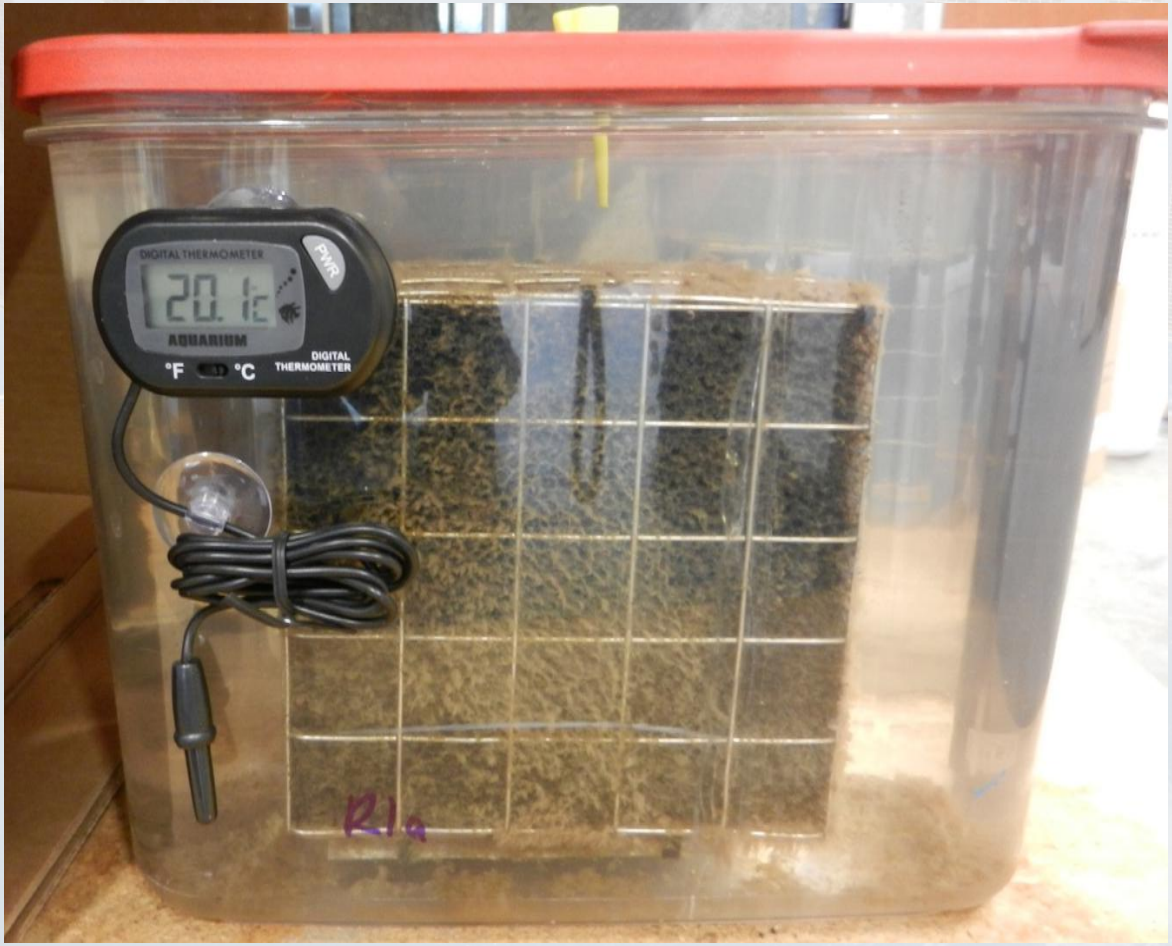
- Startup, reach SS, 15 day test

Bioreactor R1: Adding nitrifiers

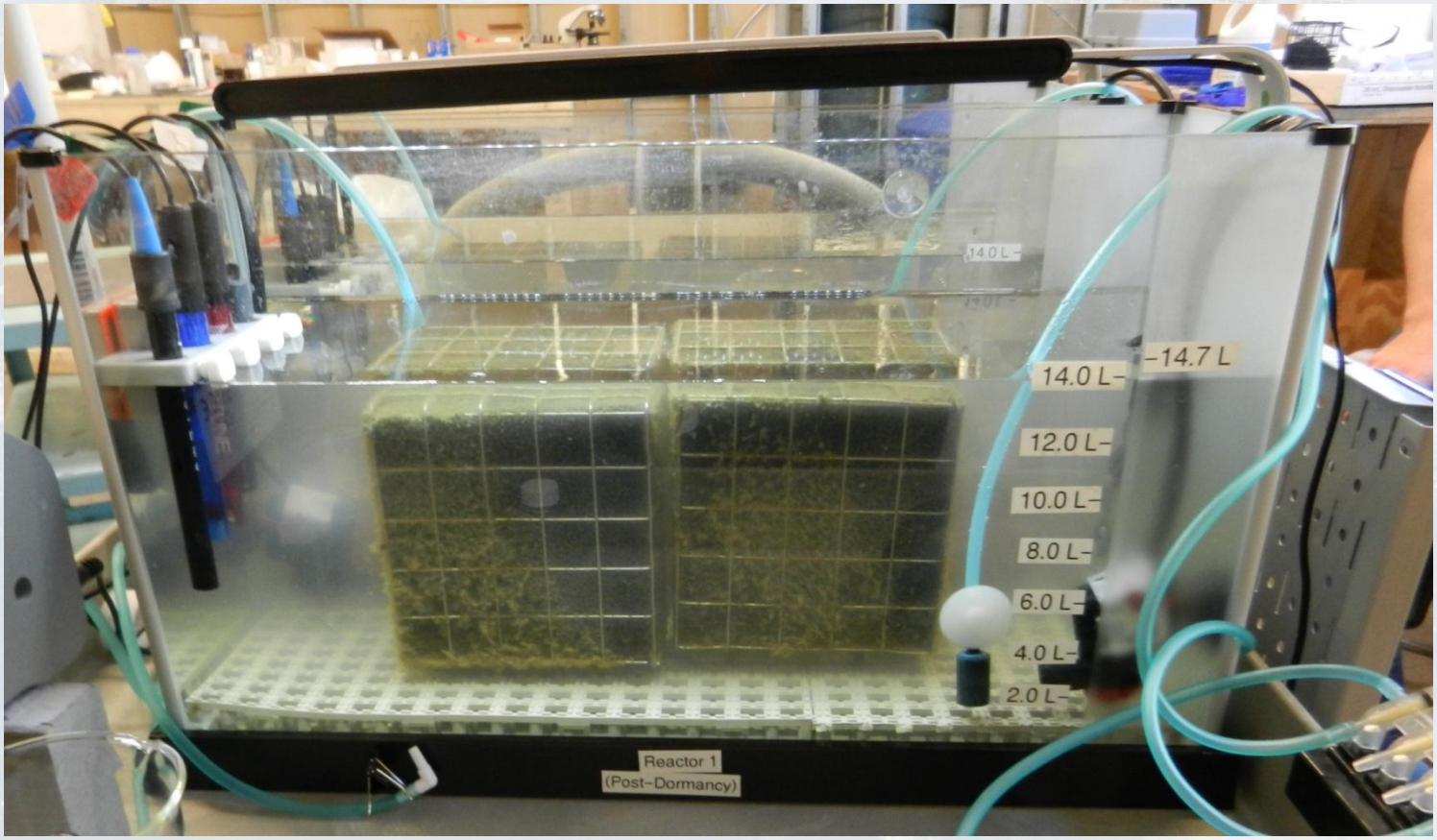
Bioreactor R1: 9 days after starting



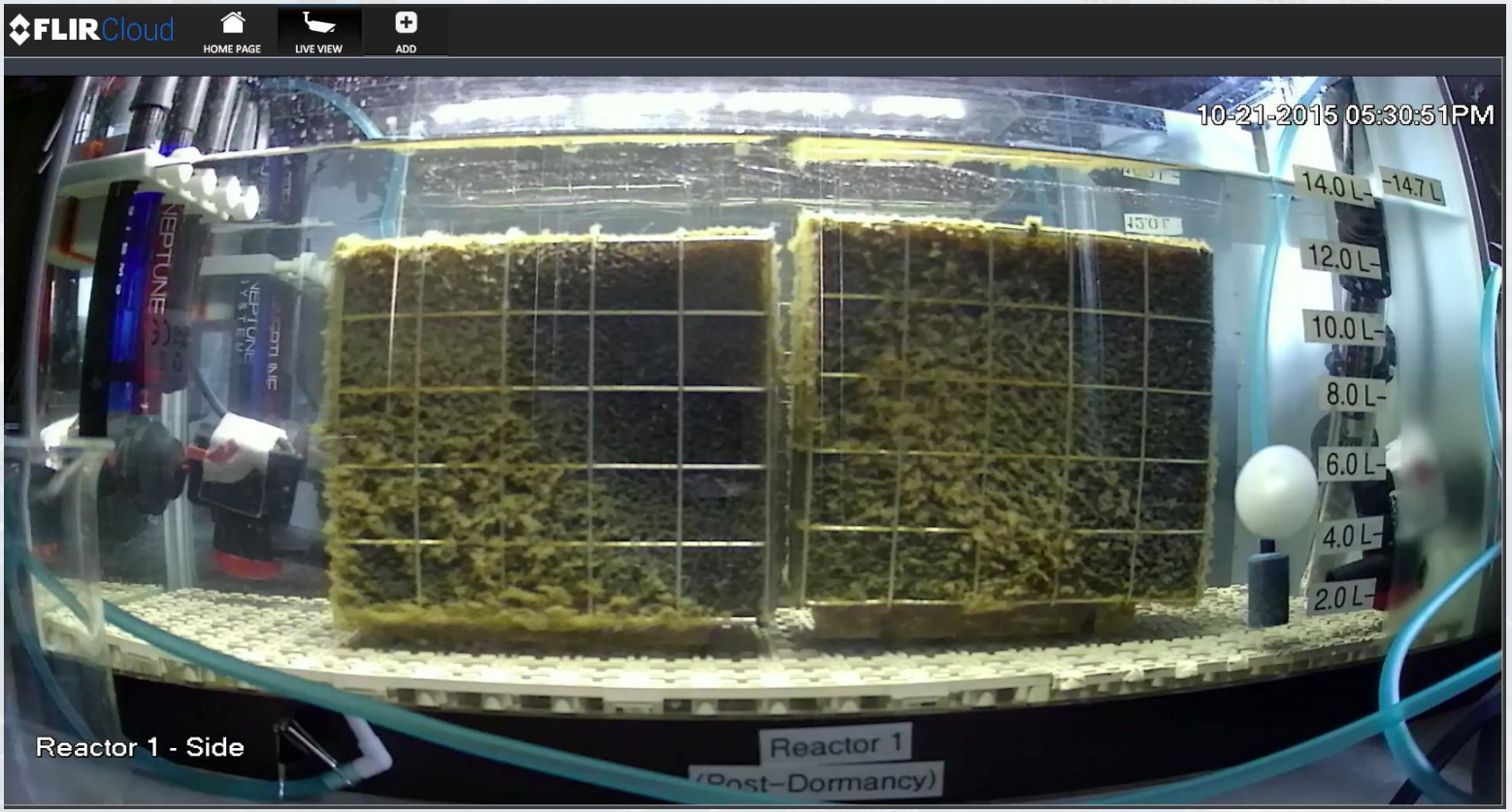
Bioreactor R1: Scaffold stored (47 days) for induced dormancy



Bioreactor R1: Post-dormancy



Bioreactor R1: Post-dormancy (video monitoring)



R1 Data
(Induced Dormancy, organisms added to reactor)

Phases:

A – 12 days startup

B – 25 days steady state

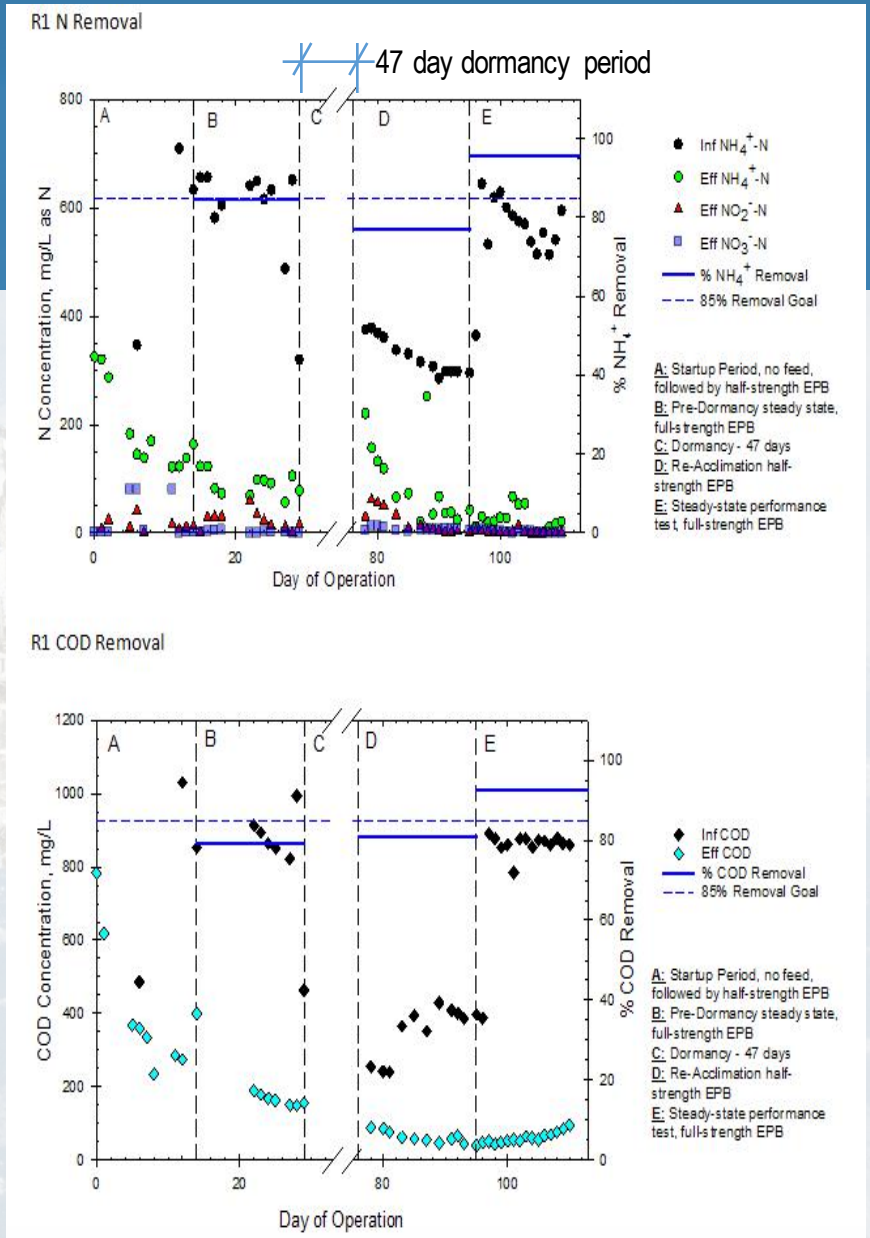
- 85% NH_4^+ removal
- 80% COD removal

C – 47 days dormancy

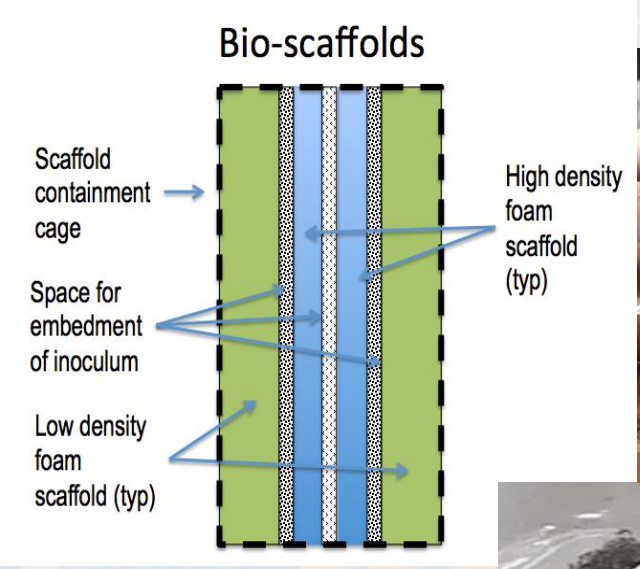
D – 19 days reacclimatization

E – 15 days steady state

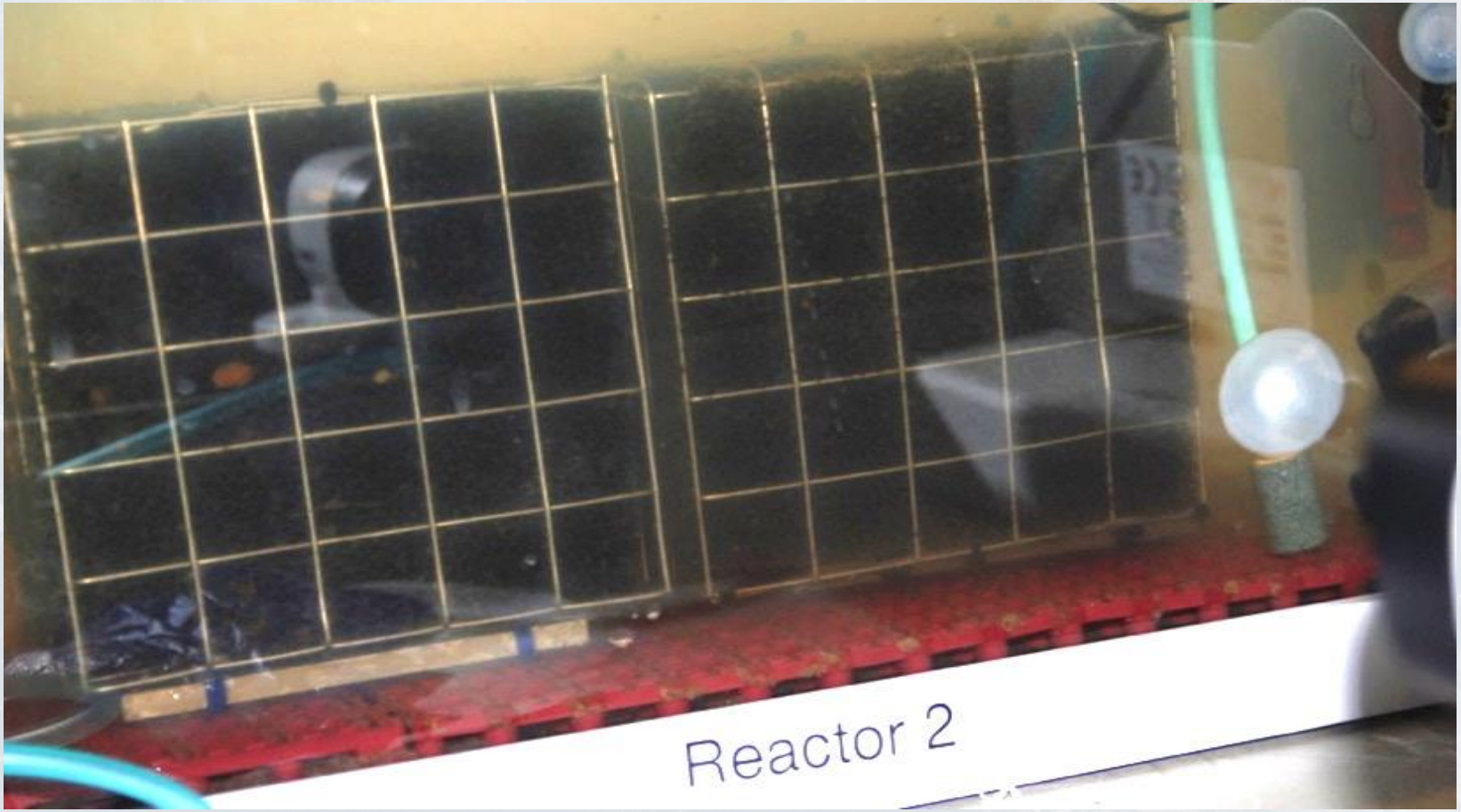
- 95% NH_4^+ removal
- 92% COD removal



Bioreactor R2: Embedment of organisms in scaffold



Bioreactor R2: Scaffolds with embedded organisms



R2 Data
(Induced Dormancy, organisms embedded in scaffold)

Phases:

A – 12 days startup

B – 25 days steady state

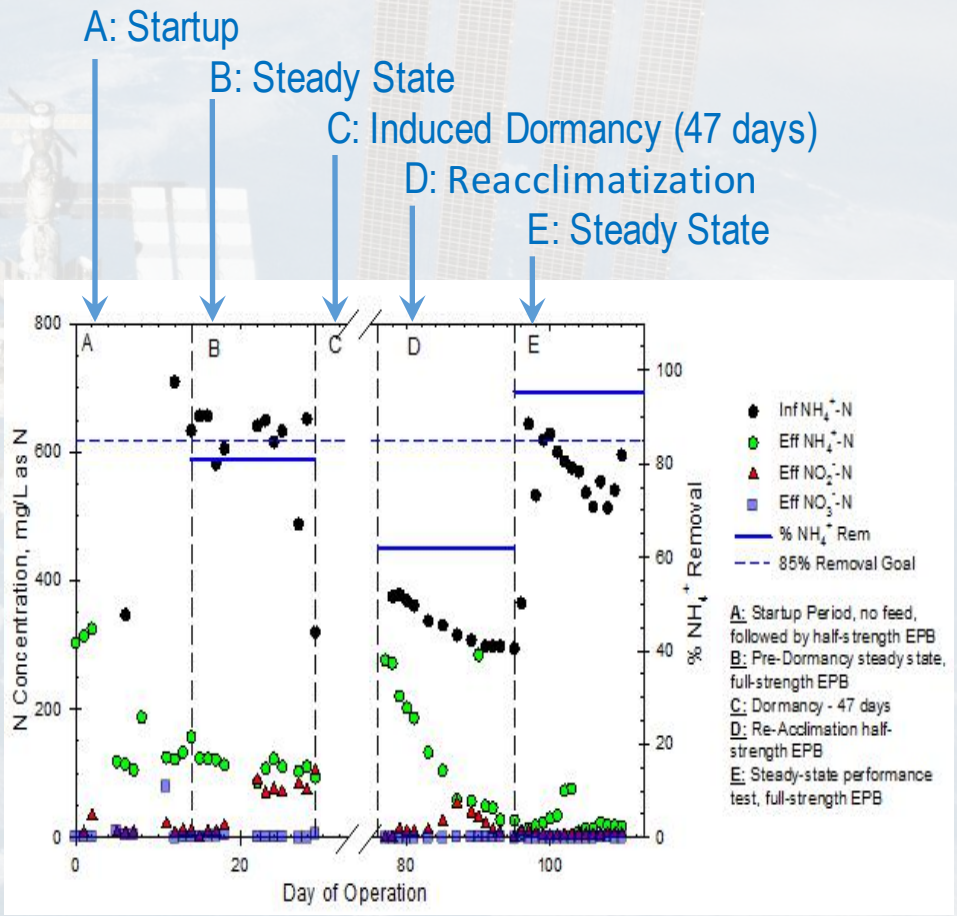
- 80% NH_4^+ removal
- 78% COD removal

C – 47 days dormancy

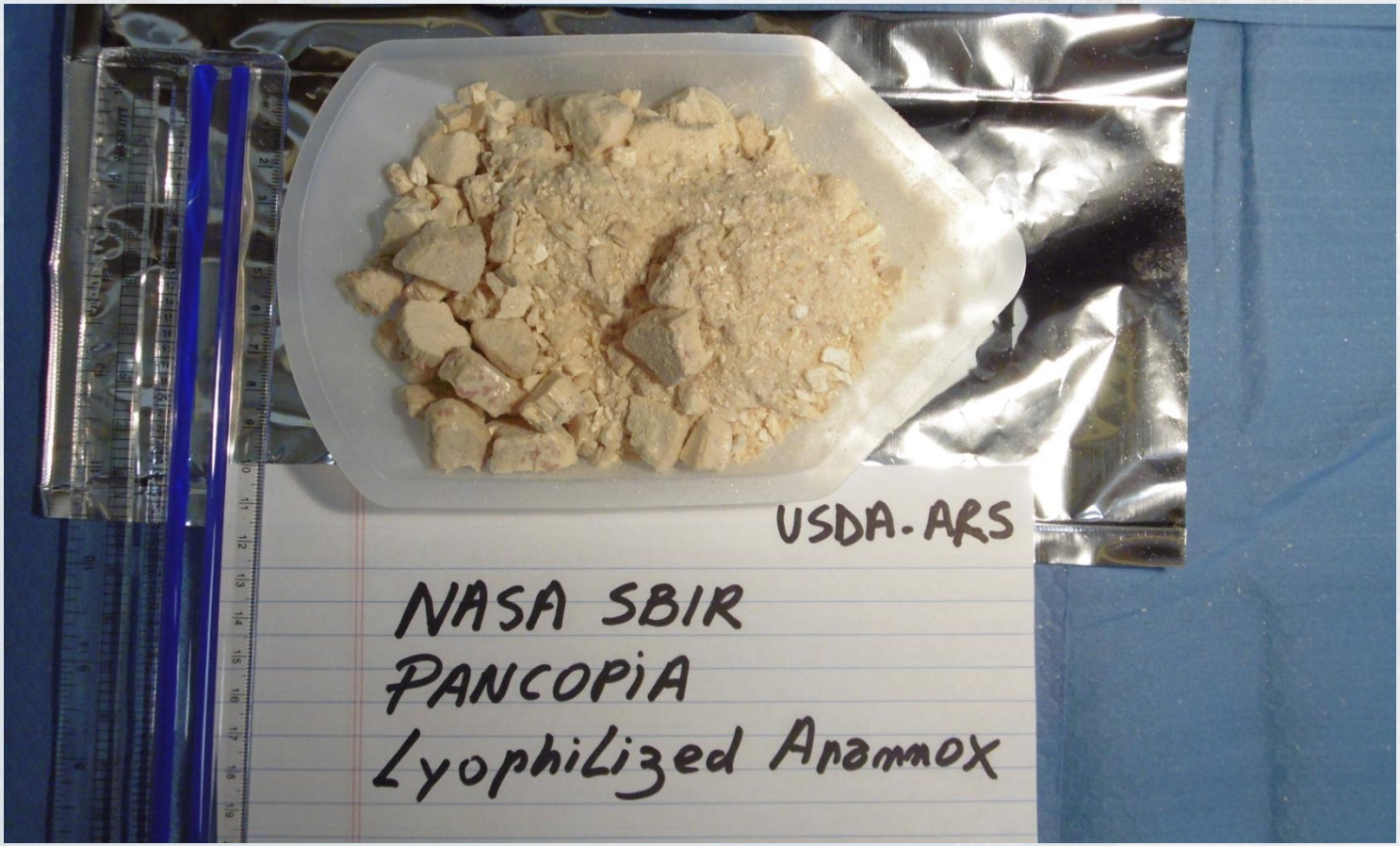
D – 19 days reacclimatization

E – 15 days steady state

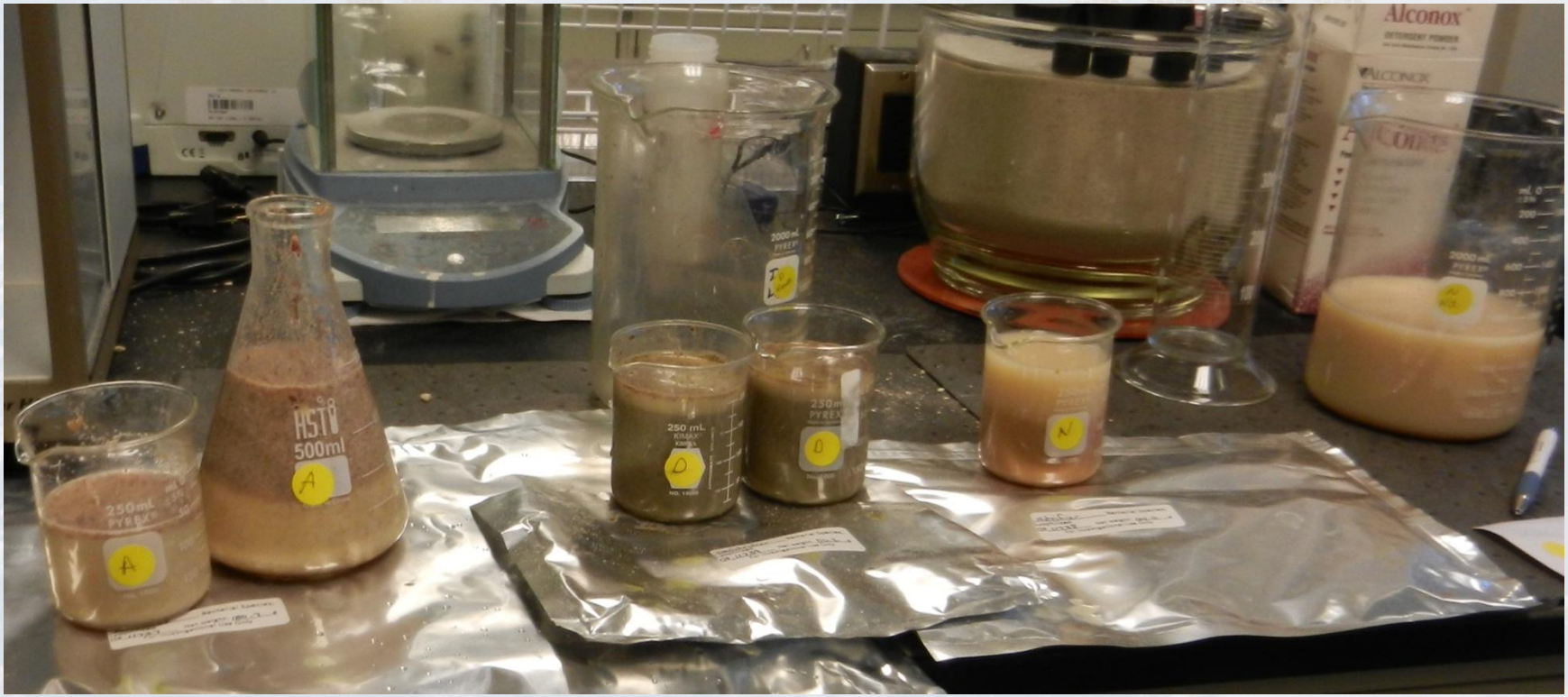
- 94% NH_4^+ removal
- 88% COD removal



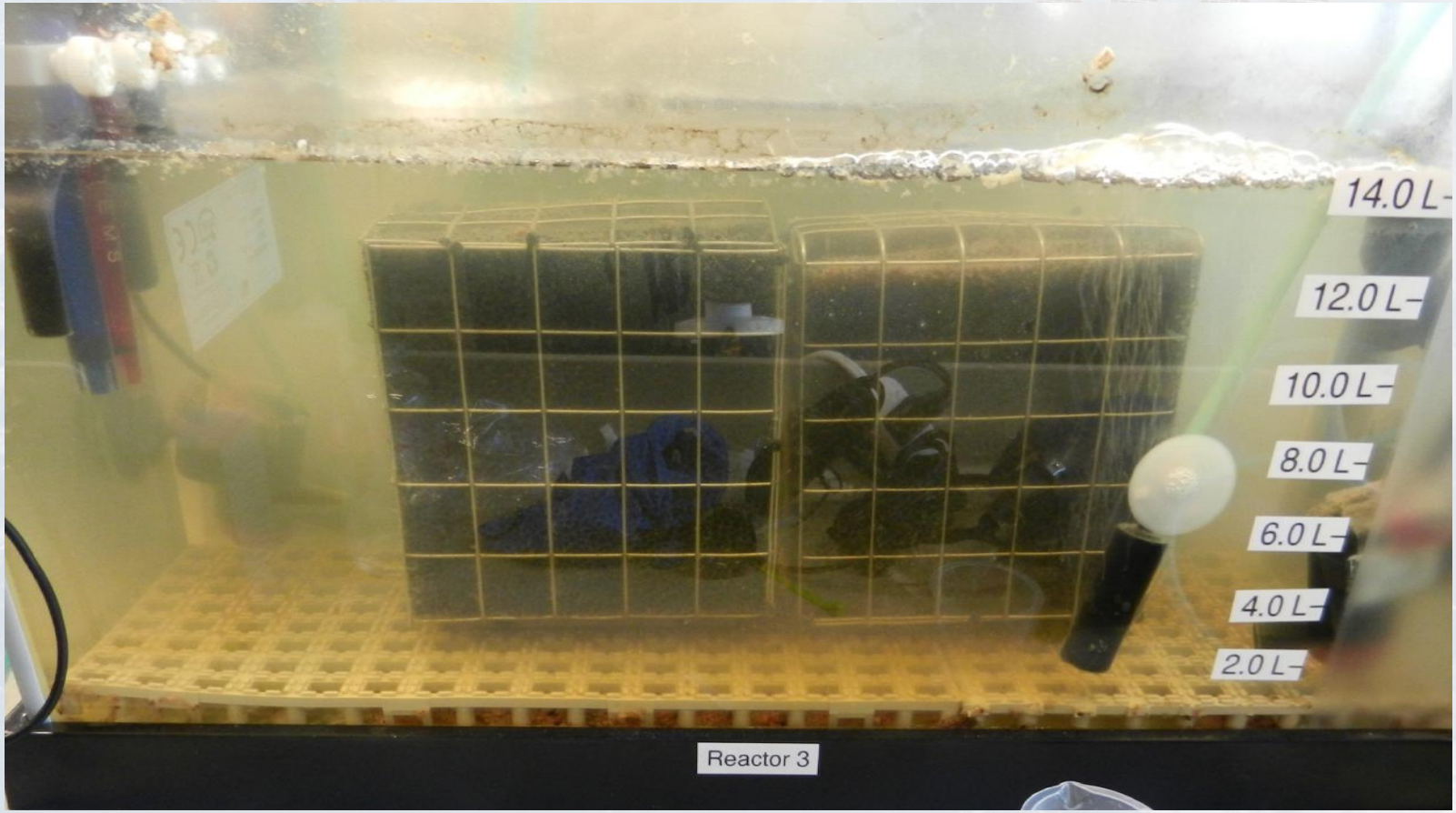
R3/R4/R5/R6 Lyophilized Anammox



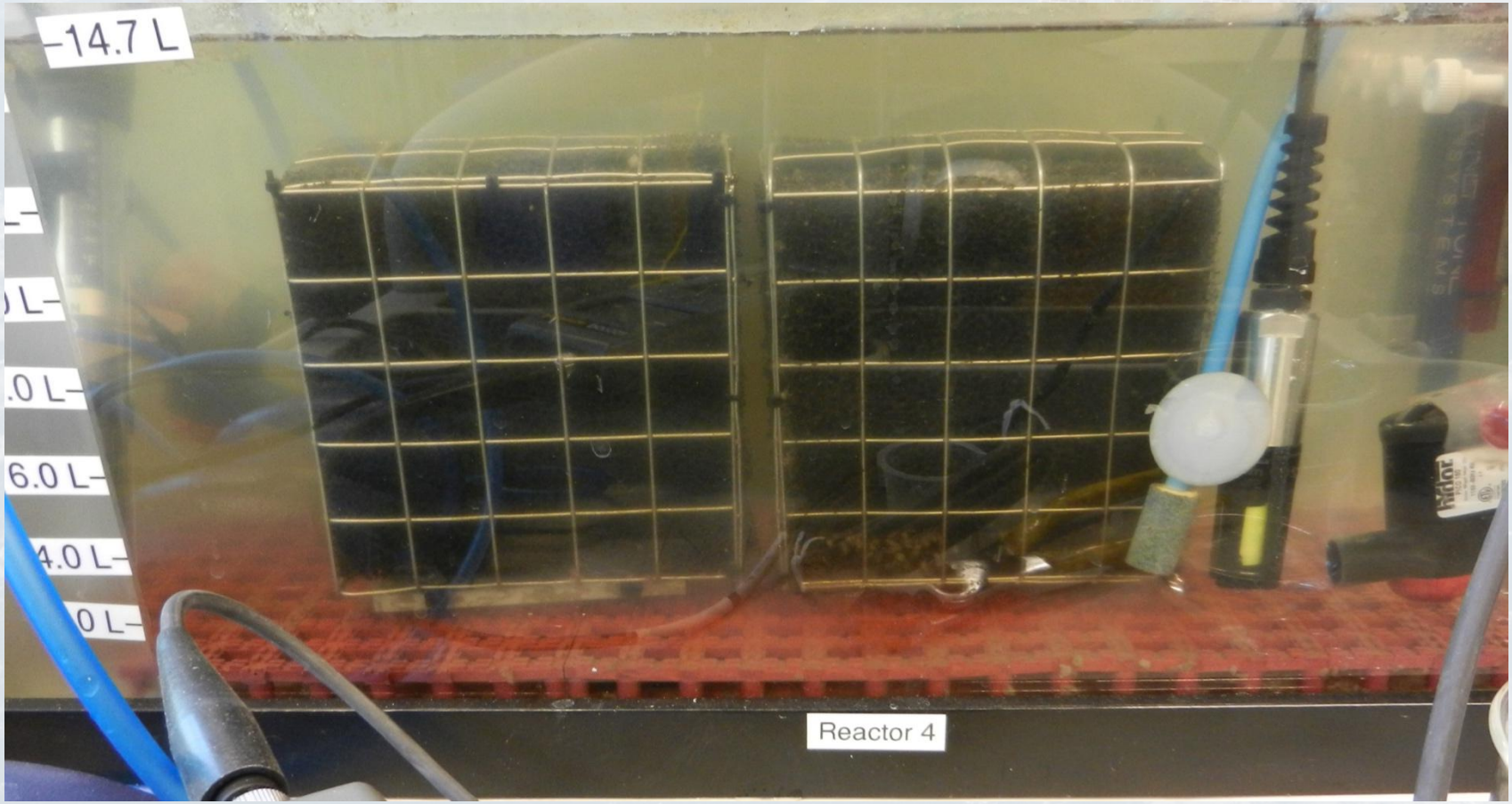
R3/R4/R5/R6 Reconstituted Lyophilized Organisms



R3: 17 days after startup



R4: 17 days after startup



R3 Data
(Lyophilized,
organisms added to reactor)

Phases:

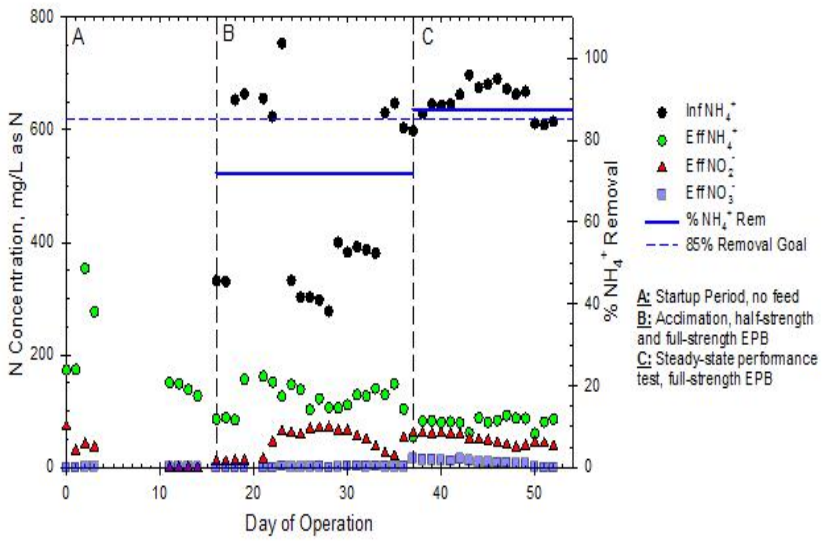
A – 18 days startup

B – 21 days acclimation

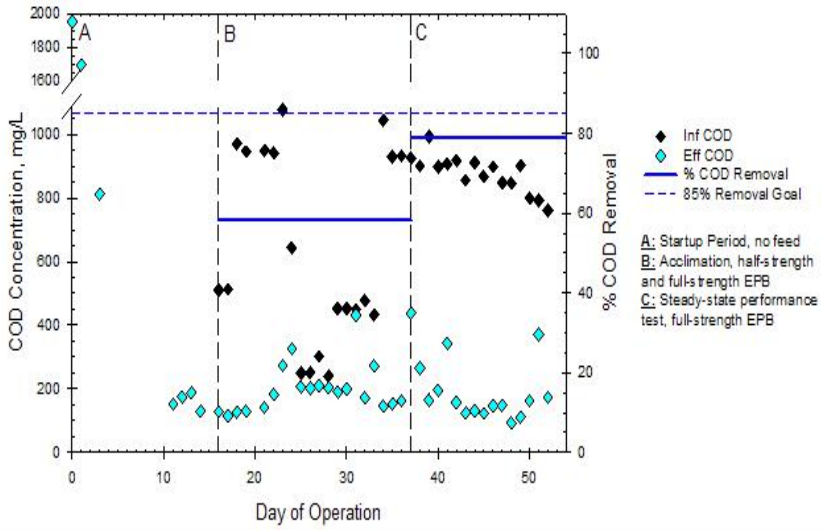
C – 15 days steady state

- 88% NH_4^+ removal
- 79% COD removal

R3 N Removal:



R3 COD Removal:



R4 Data
(Lyophilized, organisms embedded in scaffold)

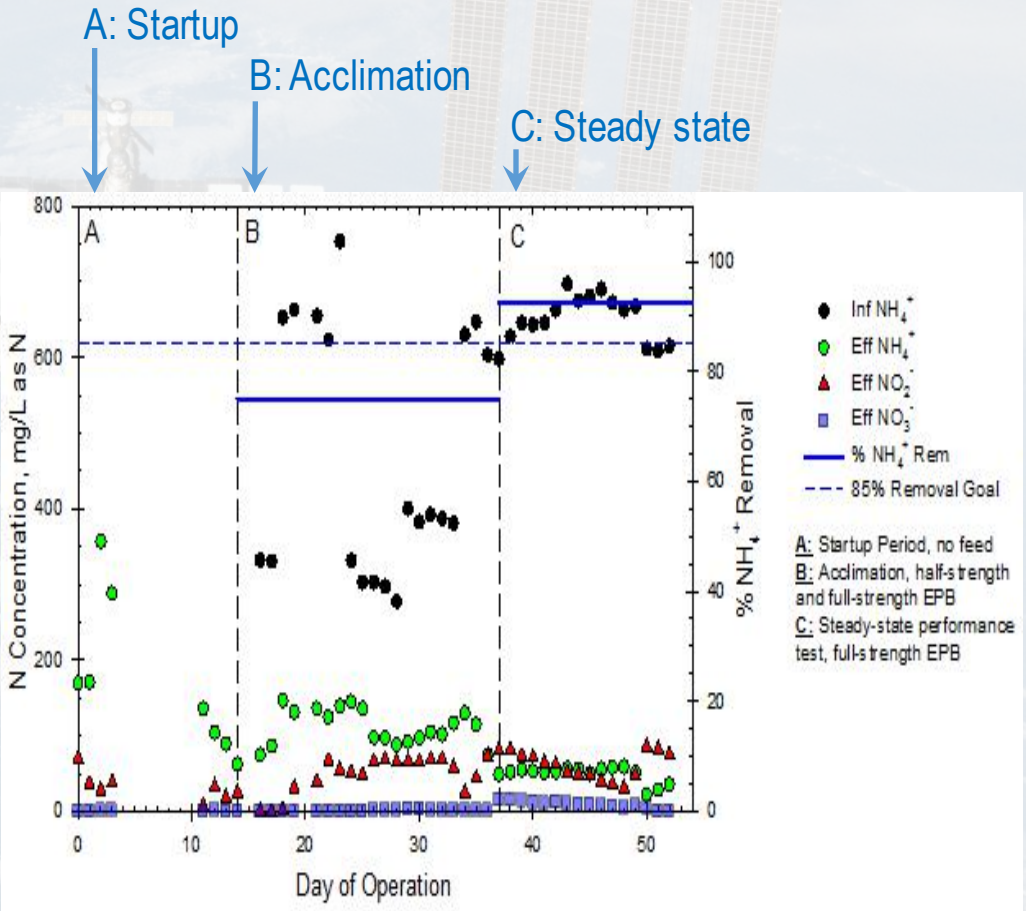
Phases:

A – 18 days startup

B – 23 days acclimation

C – 15 days steady state

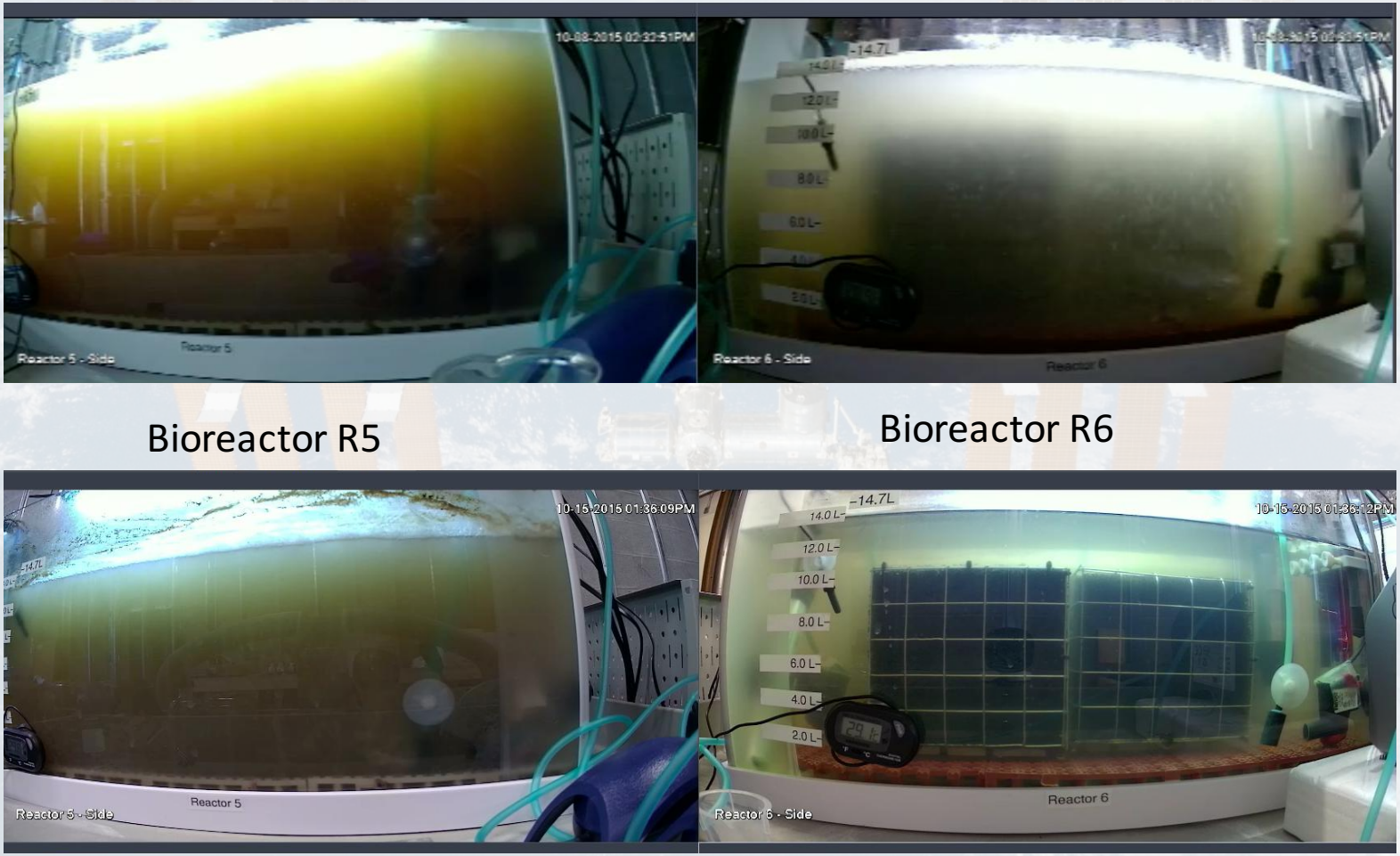
- 93% NH_4^+ removal
- 82% COD removal



R5/R6: Second set of lyophilized reactors

1. Reconstituted lyophilized organisms but did not remove all of the cryoprotectant (skim milk)
2. Bioreactor R5 was particularly affected and did not begin to treat EPB wastewater for two weeks
3. Bioreactor R5 also had levels of organic carbon and nitrogen significantly higher than the EPB wastewater contained. This was due to organic matter in the cryoprotectant.

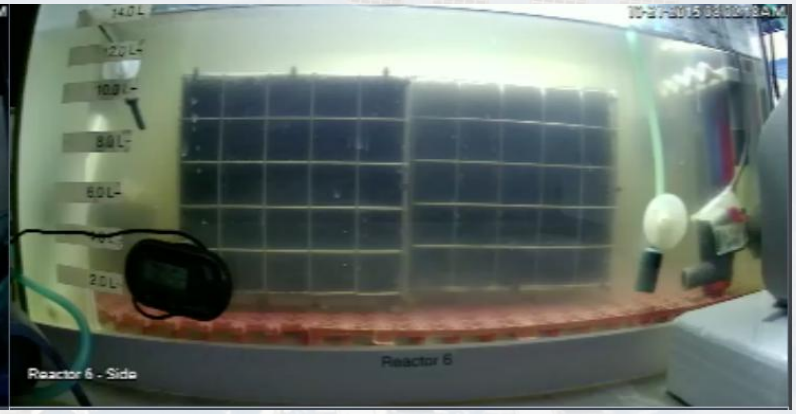
R5/R6: 1 and 8 days after startup



Bioreactor R5

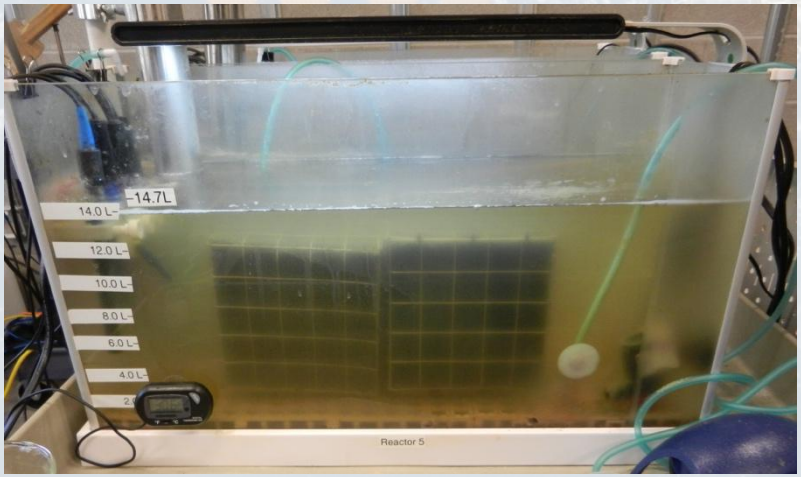
Bioreactor R6

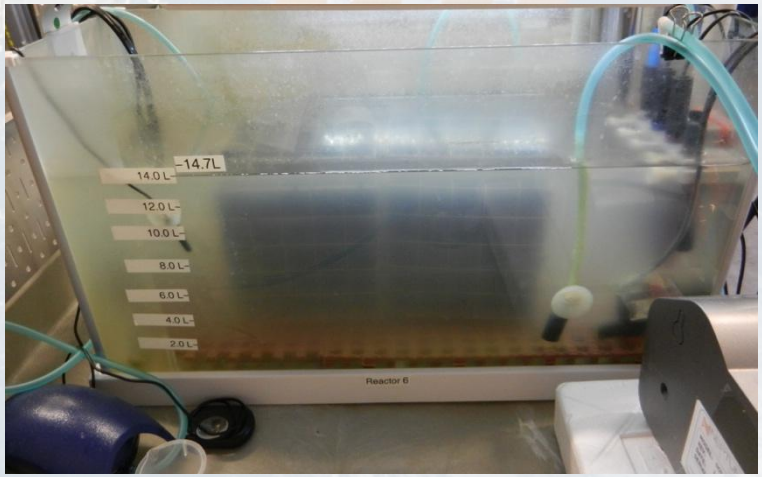
R5/R6: 14 and 42 days after startup



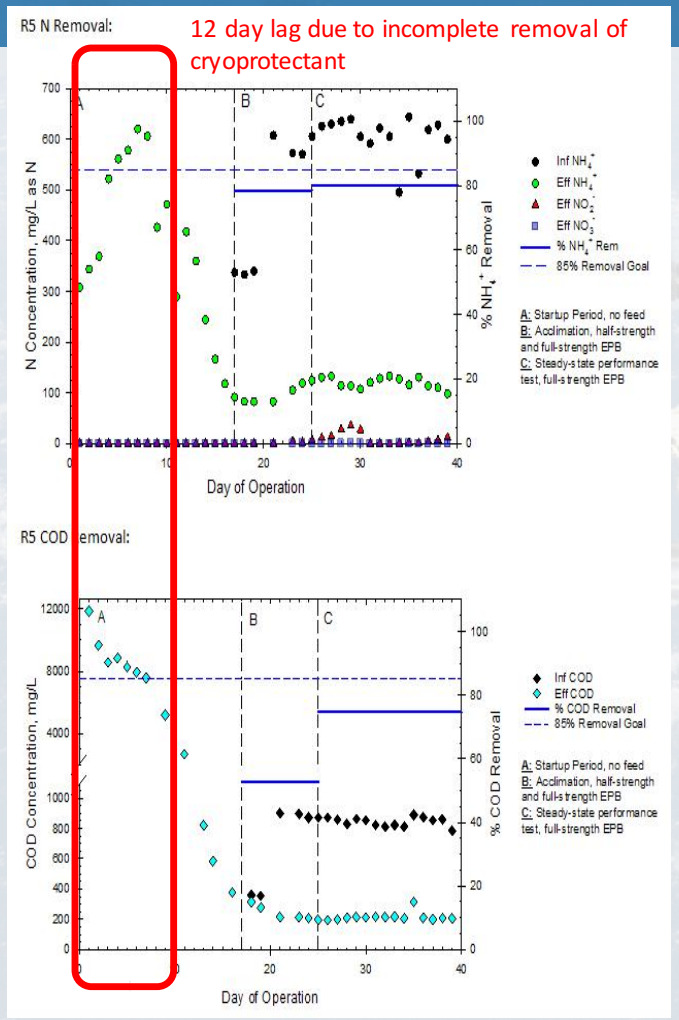
Bioreactor R5

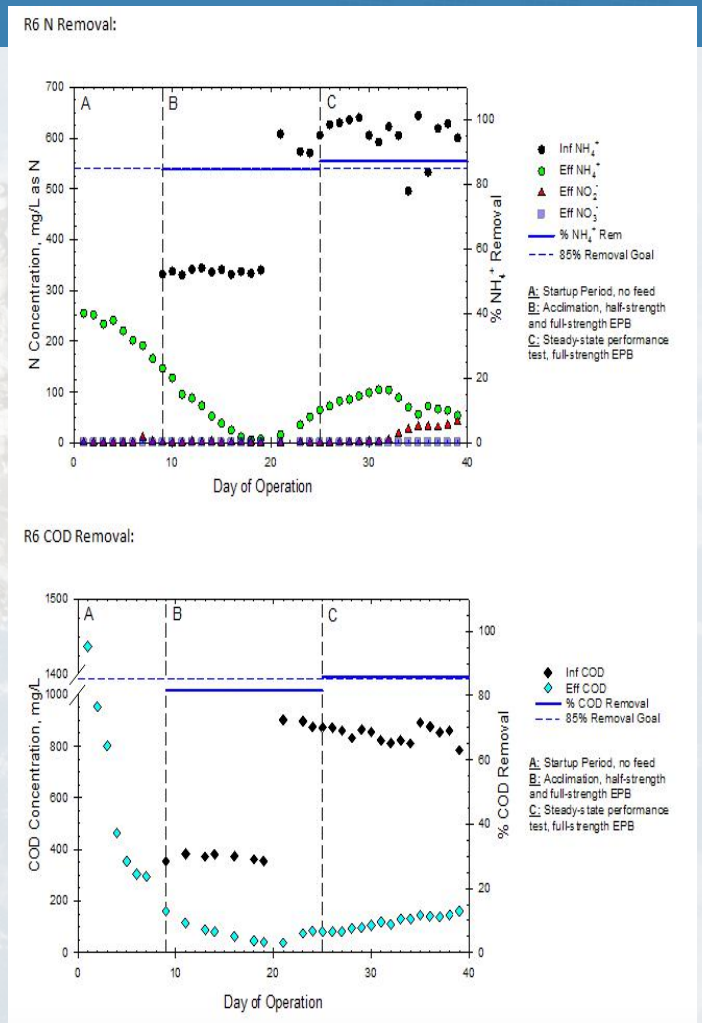
Bioreactor R6





Comparison of R5/R6 Data
(Incomplete removal of cryoprotectant in R5)





R5 Data
(Lyophilized,
organisms added to reactor)

Phases:

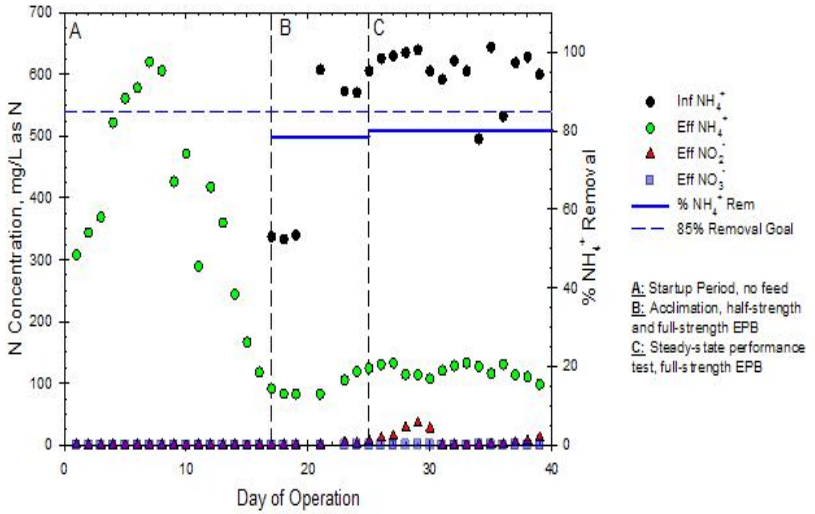
A – 18 days startup

B – 7 days acclimation

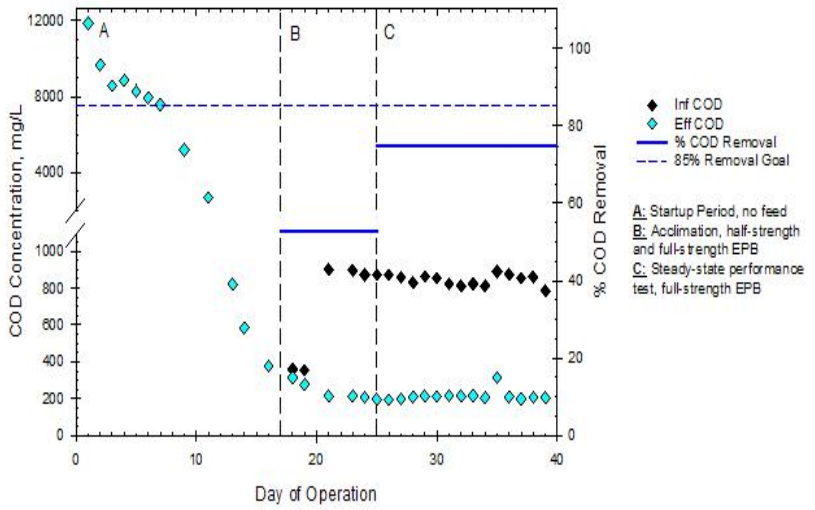
C – 15 days steady state

- 80% NH_4^+ removal
- 75% COD removal

R5 N Removal:



R5 COD Removal:



R6 Data
(Lyophilized, organisms embedded)

Phases:

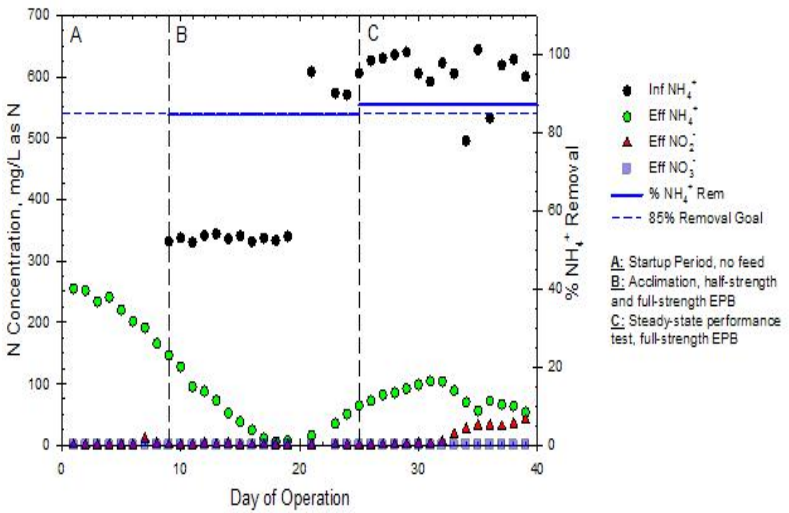
A – 9 days startup

B – 16 days acclimation

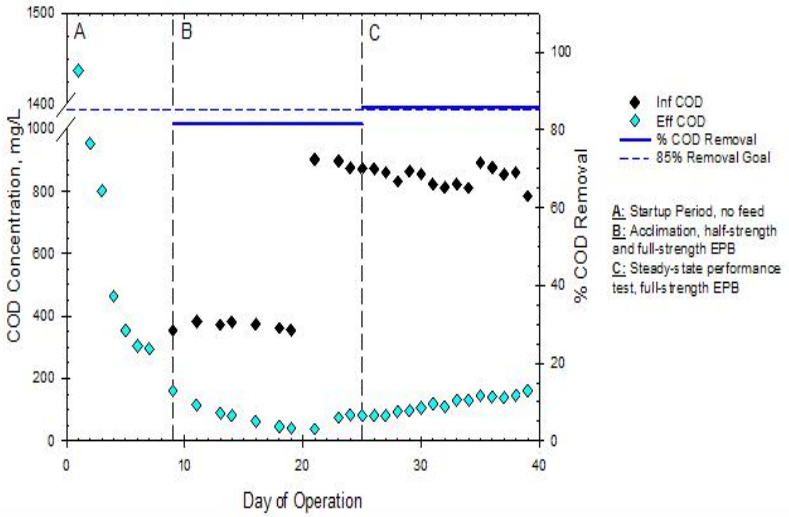
C – 15 days steady state

- 88% NH_4^+ removal
- 85% COD removal

R6 N Removal:



R6 COD Removal:



Phase I research results

- Five of the 6 reactors surpassed the ammonia removal/transformation criteria of 85%
- Three of the 6 reactors surpassed the organic carbon removal criteria of 85%
- All reactors removed at least 75% of ammonia and organic carbon
- All reactors met the criterion of successful startup in less than 45 days

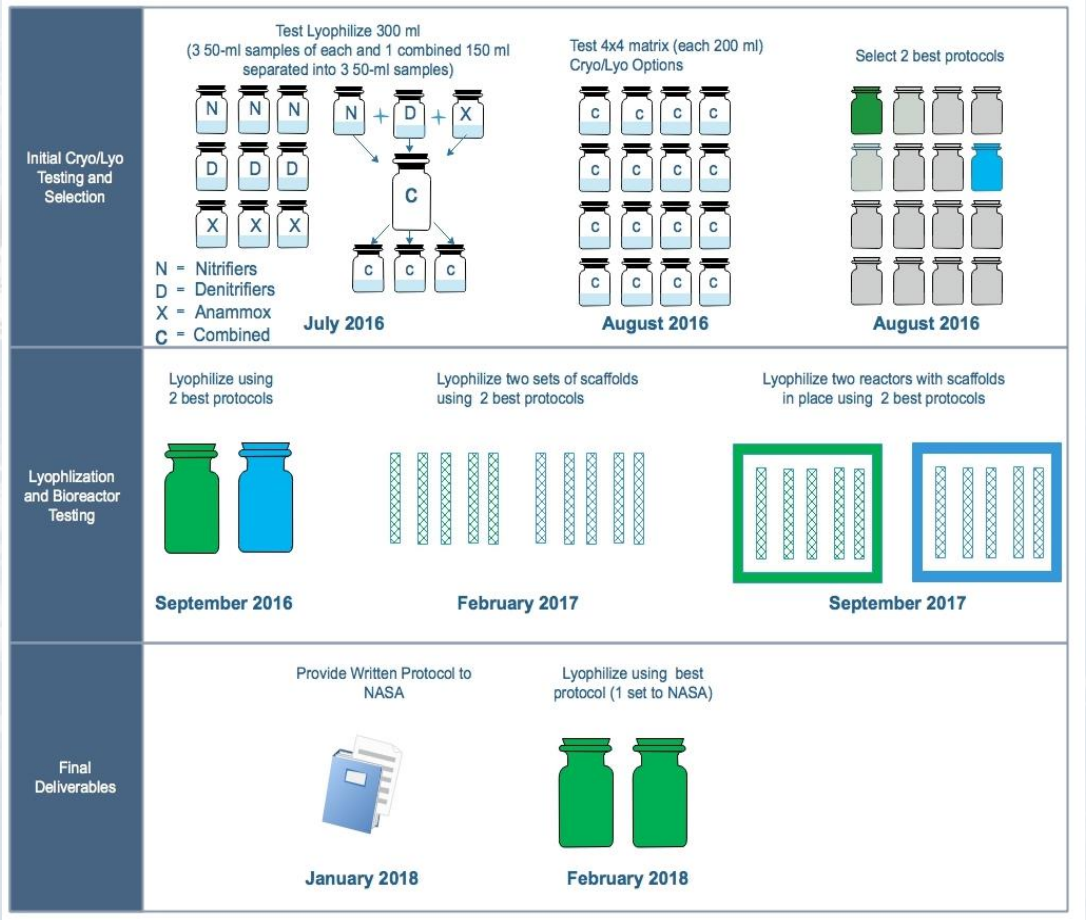
Phase II research and current status

Three Tasks

1. Optimize lyophilization
2. Construct reactor suitable for use in space
3. Develop operations manual for system

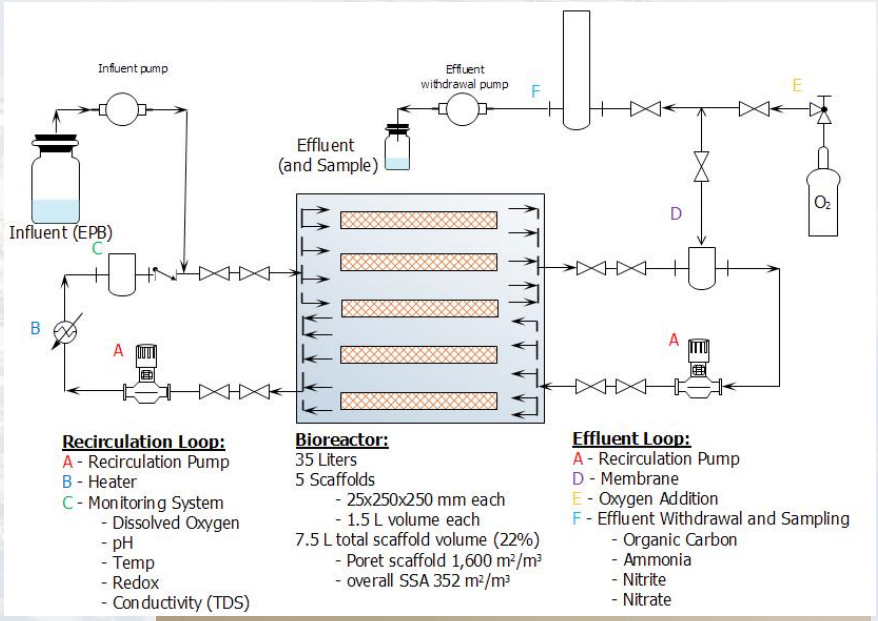
Phase II, Task 1: Optimize Lyophilization

- Test 4 cryoprotectants and 4 methods of lyophilization
- Select two best combinations for further testing
- Test lyophilizing organisms and lyophilizing scaffolds with biofilms



Phase II, Task 2: Bioreactors for Microgravity

- 35-L capacity with 5 scaffolds (1”x10”x10”)
- Recirculation loop
  (used to add influent, maintain temp, measure DO, pH, temp, Redox, Conductivity)
- Effluent loop
  (used to add dissolved oxygen, extract effluent, measure TOC, COD, NH_4^+, NO_3^-, NO_2^-)

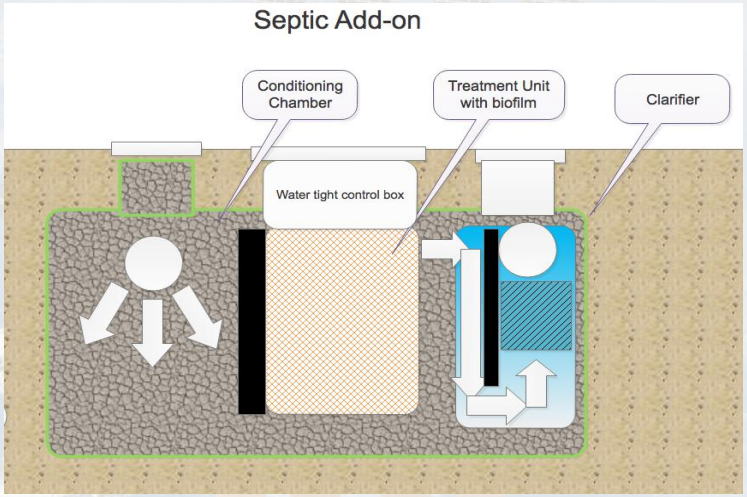


Phase II, Task 3: Develop operations manual

1. Run bioreactor for one year varying:
   - Temperature
   - Oxygen
   - pH
   - Feed and feed rate
2. Develop Operations manual

What Next?

- Adapting technology to small decentralized wastewater systems and septic tanks
- Developing a retrofit for small wastewater systems to upgrade secondary treatment to also remove nitrogen in one unit



What Next?

- Adapting and applying technology for use in developing countries
- Applying technology to treat animal waste such as swine lagoons
- Coupling technology with other energy saving and resource recovery systems

Project Team and Partners

PANCOPIA
RESOURCEFUL. SUSTAINABLE. SOLUTIONS.

Bill Cumbie, PE – Principal Investigator
Suzanne Zaremski – Laboratory manager
Curtis Goodnight – Reactor construction and operation

Coauthors and Partners

NASA

USDA

HRSD

Bucknell UNIVERSITY

Dr. Karen Pickering
(NASA project manager and technical resource)

Dr. Matias Vanotti
(Sr. Consultant and provided nitrifiers and anammox &lab analyses)

Dr. Charles Bott, PE
(Sr. Consultant; also Andy Nelson /HRSD York River WWTP provided denitrifiers)

Dr. Kevin Gilmore, PE
(Primary Sr. Consultant; also for reactor design, operation, and data analysis)

Business guidance, facilities, and financial assistance

PENINSULA TECHNOLOGY INCUBATOR

NATIONAL INSTITUTE OF AEROSPACE

CITY OF HAMPTON JULY 9, 1610

CIT
CENTER FOR INNOVATIVE TECHNOLOGY