Executive summary

The URINIT (**intensified and robust water and nutrient recovery from urine for space exploration**) project aimed to develop a robust and sustainable approach to treat urine in space for crewed space flights and extended durations. Our approach builds on several innovative inputs:

1. The URIDIS is a chemical-free, electrochemical process that alkalinizes urine thereby inhibiting ureolysis, while producing disinfectants
2. A nutrient recovery bioreactor using a bio-mineral forming microorganism in biocatalyst form, enabling bio-struvite precipitation
3. A nitrification reactor employing novel nitrifying bacteria in biocatalyst form
4. A reverse osmosis process to recover water

The overall urine treatment can be done with different combinations of these processes, that have been untried for urine processing (except URIDIS), allowing for intensification, minimize chemical needs and create a better and safer space toilet. Cranfield University and HYDROHM tackled the challenge of connecting the different treatment steps to determine the best approach in terms of efficiency, power consumption, reliability and recovery potential. This was done by combining laboratory experiments, treating real urine, with the different processes to produce mass and energy balances and completing calculations to understand the feasibility and potential of the combined processes for mission scenario of 650 days for 1 astronaut.

Summary of main results

Each process was tested in the laboratory using real urine in mixed population conditions. The key results for the unit processes are:

- URIDIS was most successful when bringing the urine pH to 12 for long term stability
- The biostruvite reactor was successful at removing and recovering >90% of the phosphorus. Urea hydrolysis occurred within several hours. The precipitates were identified as biostruvite crystals with sizes between 100-300 micron, with high purity. The biostruvite production was enhanced by magnesium dosing and supplementation of the URIDIS precipitate
- The nitrification was in general successful, the high concentration of nitrogen remained challenging for further intensification. The main products were nitrite and residual ammonia at about 50/50 ratio
- Reverse osmosis was successfully performed with a water recovery of about 75%.

The URINIT technology was tested with the 4 processes in different combinations. Based on our analysis, the configuration where URIDIS is followed by biostruvite, subsequent nitrification followed by reverse osmosis was deemed most successful to maximise resource recovery and process efficiency. Other configurations had limitations due to either lack of organic matter, safety or phosphorus limitation. Through mass and energy

balances and considering a mission scenario of 650 days for 1 astronaut (producing 1.2L of urine per day and 0.3L of flush water), we were able to calculate the liquid weight of the reactor systems as ranging from 16-17.5 kg per astronaut, for a daily energy input of 0.29-0.57 kWh/d including electrochemistry, pumping and aeration. The URIDIS system is taking up about half of the energy investment but is essential to enable collection of the urine and pathogen inactivation. The resources recovered were estimated at: 660L of water for re-use, 220L of concentrate from the reverse osmosis with high concentrations of nutrients and salts, 3.3 kg of high purity bio-struvite and toilet disinfecting solution. To maximise phosphorus removal and recovery, the MgO requirements were estimated at 0.8 kg.

Scientific outcomes beyond mass balances

The project has delivered several scientific insights beyond the expected outcomes that are very significant:

1. The urine that was stabilized by URIDIS could be stored for months and was enabling downstream conversion, indicating the high level of microbial inactivation
2. The selected microorganism for biostruvite production was highly active both in producing struvite and hydrolyzing urea. The bio-struvite nucleation points were expelled from the biocatalyst framework, enabling the recovery of sizable crystals
3. The nitrification allowed ammonia oxidation at efficiencies that can be steered by the level of initial stabilization towards a blend of ammonia and nitrite. This combination may be ideal for production of nitrogen gas via anammox which can resolve part of the N_2 needs during the mission.

Overall, in relationship to other known approaches for the treatment of urine, we see, the key of the URINIT technology advantages:

- Relative to current ISS / space: no need for filtration pretreatment; no toxic chemical usage (CrO_3); no or limited water distillation; no toxic residues
- Relative to terrestrial applications: no need for distillation; limited odour formation; intensified and controllable process; limited chemical input; high phosphorus recovery as qualitative biostruvite; potential destruction of N; recovery of water via RO; disinfection products for toilet flushing

ALiSSE criteria based analysis

Risk for Human Global risk index	Reliability Global system reliability	Sustainability Need coverage level. Energy/Matter external dependence
Scenarios range from 16-17.5 kg/d as reactor liquid weights	Power consumption including pumping, aeration; electrochemistry ranges from 0.29-0.57 kWh/d	Avoid use of (dangerous) chemicals Only electricity input High intensity > low system mass Low GHG emissions through novel nitrification pathway
Mass Coverage Mass Ratio: total system mass over total allocated mass	**Energy & Power** Mean & Max power consumed in mission	**Crew Time** Total Crew Time for operation and maintenance of the ECLSS
Avoid use of CrO_3 Pathogen inactivation pH12 Multibarrier concept	Long term storable biocatalyst URIDIS tested > 3 years High quality struvite Biostruvite tested > 2 years	Systems are robust Sludge production low Limited toilet maintenance

Conclusions

The combination of URIDIS, bio-struvite, nitrification and RO is able to treat urine to enable the recovery of water for re-use, produce high purity bio-struvite and facilitates safe toilet utilisation in space **For mission scenario of 650 days for 1 astronaut (producing 1.2L of urine per day and 0.3L of flush water), URINIT produces 660L of water, 220L of concentrate nutrients/salts, 3.3 kg of bio-struvite and toilet disinfecting solution. The requirements are 189-370 kWh energy and 0.8 kg of MgO.**

Reflections and recommendations

- URIDIS is required to ensure safety and fulfil requirements of space applications
- URIDIS produces a disinfection solution that could be incorporated in the overall scheme
- Toilet flushing has advantages in the tested configurations, especially for nitrification
- Nitrification with the biocatalyst, using novel pathways, remains challenging
- Fate of pathogens and micropollutants must be clarified
- Full nitrification was not observed and reject water is rich in nitrites and ammonia, recovered water also contains nitrogen compounds. This must be solved.
- Knowledge transfer and link to terrestrial applications must be explored as there is great potential
- Value and need for IP protection must be clarified shortly

Way forward

For space application, we foresee the need for the following steps:

- URIDIS:
    - Produce disinfection products and test them
    - Development of space hardware for electrochemistry
- Biostruvite reactor:
    - Test biocatalysts continuously and optimize product harvest
    - Test activity and storability in space (radiation, microgravity, etc)
    - Develop space hardware for flight tests
- Nitrogen conversion: Re-think fully nitrogen management to move away from fertiliser production to nitrogen gas production – this is an attractive and safe route enabling more applications and broader scope for water re-use.

Overall:

- The selected configuration must be verified in a continuous process at breadboard level looking to integrate with a space hardware provider (verify mass and energy balances, footprint, further developments, stability and resilience, etc)
- Pitch project to technology development partners to understand value and markets, to inform IP protection strategy (and wider project dissemination).