

# Novel Electrocatalytic System for Urea and Ammonia Removal at Varying Wastewater Conditions

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An Electrocatalytic System (ES) has been developed that efficiently recovers wastewater while avoiding common issues that the current environmental control and life support system (ECLSS) experiences. The novel system comprises custom electrode pairs and catalysts optimized to selectively target molecules of specific contaminants within the wastewater and disaggregate them into their benign constituent gasses. The resulting gas components can then be safely vented or captured for re-use. Benefits include low physical weight and size, insensitivity to contaminant load (effective on both high and low concentrations), insensitivity to wastewater age and to environmental conditions (e.g., not affected by wastewater temperatures and time-changing composition), no solid or liquid waste by-products, “instant on/off” operation allowing discontinuous operation only when needed or according to power availability, no consumables, and extreme reliability and stability with no moving parts and based on long-life materials. This paper presents experimental results of a joint KBR-Purammon research project conducted in Israel and the US using an ES optimized for nitrogen compounds typical to manned spaceflight wastewater (urea and ammonia). The results indicate that ES is an extremely promising next-generation technology providing the ability to process and achieve complete decomposition of high to low strength wastewater pollutants over broad and dynamic conditions in a small footprint and while requiring only modest electrical power.

## Nomenclature

CFD	=	computational fluid dynamics
COD	=	chemical oxygen demand
ECLSS	=	environmental control and life support system
ES	=	electrocatalytic system
ESM	=	equivalent system mass
ISS	=	International Space Station
mgN/L	=	milligrams of nitrogen per liter of wastewater
M.W.	=	molecular weight
TAN	=	total ammonia nitrogen
TDS	=	total dissolved solids
TN	=	total nitrogen
TOC	=	total organic carbon

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## I. Introduction

Current water recovery technologies in manned spaceflight have well-known mission-cost and operational shortcomings. Manned spaceflight wastewater includes many components of human metabolic processes that must be removed before achieving terminal water recycling to potable water. The primary challenging contaminants for existing technologies are nitrogenous compounds.

Several wastewater treatment processes are currently available for nitrogen removal from wastewater in zero gravity<sup>1-2</sup>. The ISS' ECLSS currently uses a distillation method for the separation of water and the urea-containing brine to achieve <85% water recovery in the Urine Processing Assembly<sup>1</sup>. While achieving good recovery rates, this process becomes ineffectual at low temperatures and therefore requires significant energy investment. Applying this process in zero gravity and remote applications has inherent drawbacks. These drawbacks include the inability to treat mixed pollutants (e.g. ammonia and urea), use of consumables (strong acid to prevent nitrification), need for safe brine disposal, suboptimal water recovery rates, process failure due to toxic shocks (e.g. pH change, low or high temperatures, toxic contaminants), saline background which reduces metabolism and creates scaling, poor flexibility to fluctuations in wastewater flow and composition, high operational complexity, long implementation time, large footprint, and more. These shortcomings are especially pronounced in deep space exploration where process reliability, manageability, launch-weight, operational expenditures, scalability, and controllability are the foundation for efficient operation. Long-term exploration and utilization of space, extending human presence in orbit, as well as missions to the Moon, Mars, and beyond will require the processing of high strength wastewater in a variety of harsh environmental conditions, all while minimizing launch weight and maximizing reliability. Terrestrial applications with similar challenges have also been identified in polar, subsea, and other frigid and constrained locations.

A novel electrolytic-based approach for treating wastewater is gaining popularity for terrestrial and extraterrestrial applications due to its high efficiency and low system complexity. It represents a fundamental paradigm shift in the processing approach. In contrast to current terrestrial biological based systems, this new method uses electricity rather than “bugs” to transfer electrons. In contrast to current extraterrestrial distillation-based systems such as in the ISS UPA, the new process removes contaminants from the water rather than the other way around. The benefits of this new paradigm are especially valuable for long term missions where water recovery and mineral reuse is of high importance.

The expected merits of the electrolytic process include a combined lower equivalent system mass (ESM) compared to contemporary systems. Additionally, the improved water purity is expected to further reduce the ESM of the balance of plant (polishing beds) and required consumables (g/L product water). Enabling downstream nutrient recovery along with H<sub>2</sub> production in the electrolysis cell would support calcium, magnesium, potassium, carbon, sulfate, and phosphate recovery, creating a reduction in fertilizer resupply for plant growth systems. This same system can further recycle plant nutrients via leaching of waste plant mass and help reduce sodium in hydroponic brines.

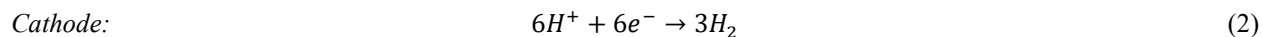
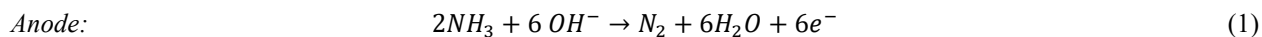
Electrochemistry is the science of the relationship between electricity and chemical reactions: producing electricity with spontaneous chemical reactions and producing non-spontaneous chemical reactions with electricity. In an electrolytic cell, an external source of voltage is used to drive chemical reactions. Some electrochemical processes, such as ammonia and urea oxidation, are so slow kinetically at low voltages that extra potential or overpotential must be applied. Products of electrolysis depend on the nature of material being electrolyzed and the type of electrodes being used. The novel process detailed in this document used catalytic electrode materials that successfully overcame issues with high overpotentials.

### A. Electrolytic reactor for urea and ammonia removal

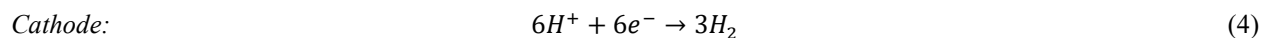
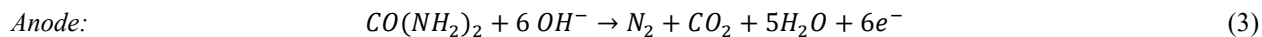
Electrolytic processes have been successfully implemented in terrestrial wastewater applications. As a replacement or adjunct to biological systems, they can greatly increase system reliability, avoid the cost and environmental impacts of sludge generation and disposal, and eliminate the need for external carbon dosing to inorganic wastewater.

In a typical electrolytic treatment process, wastewater is pumped through pipes that are embedded with specialized electrodes (anodes and cathodes). The electrodes are fed by direct current that is adjusted to the load. The catalytic electrodes are coated with current collectors. Anodic oxidation reactions disaggregate the pollutant molecules into their constituent elements: hydrogen, carbon dioxide and nitrogen gas. The gases are then removed for use or discharge, leaving the remaining water free of the pollutants. For space-specific operations, the byproduct gases are discharged, but future research may examine optional capture and utilization of the gases. The electrolytic process does not need to be continuous and can be started and stopped at will, for example, according to energy availability. The half reactions are shown below in Eq. 1-4:

TAN removal:



Urea removal:



Urea decomposition requires minimal consumables besides electricity whereas ammonia decomposition consumes alkalinity (as NaOH) on a 1:1 molar basis. The cathodic reaction produces the required alkalinity which allows ammonia oxidation to proceed without additional consumables. Competing processes require consumables for similar ammonia decomposition reactions.

The electrolytic reactor has one inlet through which wastewater enters, and one outlet, where the effluent and formed gases, resulting from protons reduction and contaminants oxidation, are discharged. Figure 1 provides an example of a terrestrial electrolytic-based wastewater treatment plant scheme. Electrode-studded horizontal pipes with relatively large diameter comprise the electrolytic reactors.

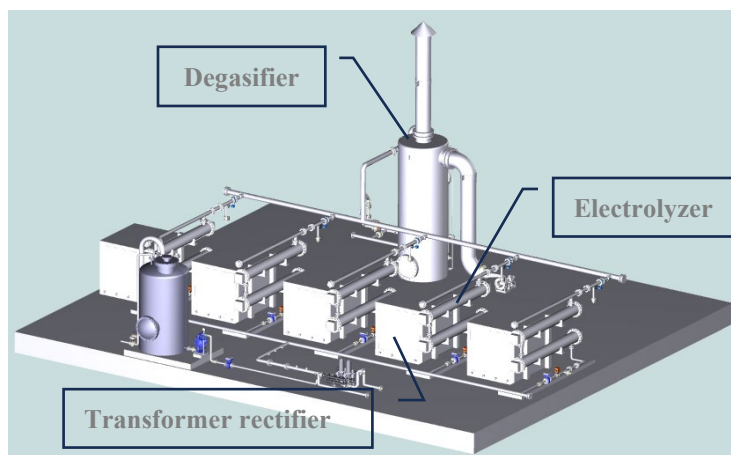


Figure 1. Electrolytic based terrestrial wastewater treatment

### B. Technological gap

While electrolytic reactors are effective for certain niches of terrestrial wastewater treatment, adjusting them to zero gravity requires overcoming two very significant challenges: gas clearance and concentration polarization.

As noted above, electrolytic reactions produce gas, both on the anodes and cathodes (Eq. 1-4). This gas reduces the reactor volume and the available electrode area for reaction. Specifically, hydrogen gas generated on the cathodes is sticky and requires drag forces for its evacuation<sup>3-6</sup>. Figure 2 presents hydrogen bubbles stacked on a titanium plate.

If turbulent flow cannot be introduced, concentration polarization near the anode is to be expected in zero gravity. This phenomenon leads to portions of wastewater not being treated sufficiently during a flow pass due to flow near the walls being too far removed from the anode and as a result, has wastewater flowing near the anode approaching 100% treatment, which implies significantly less gross efficiency than desired.

Increased fluid velocities are required to improve mass transfer and to allow produced gas at the anode and cathode surfaces to be entrained in the liquid to leave the reactor eventually in a 2-phase flow mixture.



Figure 2. Hydrogen gas bubbles on a titanium plate.

### C. Novel reactor and system for zero-gravity electrochemical operation

The KBR-Purammon team has developed a novel reactor design intended to enable the use of electrolytic processes in zero-gravity. This new reactor combines careful management of hydrodynamic effects and innovative electrode

geometries to prevent efficiency-reducing gas barriers from forming at the electrodes, and to remove the byproduct gasses rapidly and continuously from the reactor. The project was conducted in the following steps: validation of the new electrode geometries to treat urine and computational fluid dynamics (CFD) computing to result with the novel electrolytic hydrodynamics management system capabilities to treat urine.

## II. Methods

### A. CFD analysis

ANSYS Fluent (ANSYS) is an industry-leading fluid simulation software known for its advanced physics modeling capabilities and high accuracy. ANSYS was used to run CFD modelling of the new reactor. The software's multiphysics capabilities were used to model the chemical multi-phase flow process in microgravity, confirm basic functionality, and allow improvements to rheology and terminal conversion identifying any mass transfer issues in the proposed reactor design. Aspen HYSYS (HYSYS) is a chemical process simulator developed by AspenTech for mathematically modeling chemical processes. HYSYS was used for refining trade studies, balance of plant analysis, and model electrode kinetics.

### B. Laboratory Set-Up

Based on the ANSYS results, a prototype of a hydrocyclone system was built to test the flow-through operation (see Figure 3 below). The hydrocyclone body was prepared from unplasticized polyvinyl chloride piping with flanges at both ends. The electrodes were inserted through the top flange. Water entered horizontally and flowed out through a hole in the bottom flange. Gases were released through a central hole in the upper flange.

A batch operation was then used to calibrate and validate the CFD results. System capacity was set to treat 1 liter of urine per hour. In this set up, wastewater is fed to a tank (T1) used for sampling and storage. From the storage tank,

wastewater is pumped to the reactor body (T3) where ammonia and urea are oxidized. Gas leaves the reactor through a vent in its upper side. Treated fluid is flown through the bottom to an additional tank (T2). This tank is used to monitor treated fluid composition and to visualize gas bubbles (if any). The system allows for continuous or batch operation (via manual valves position changing). It also allows for internal circulation for examination of different treatment rates.

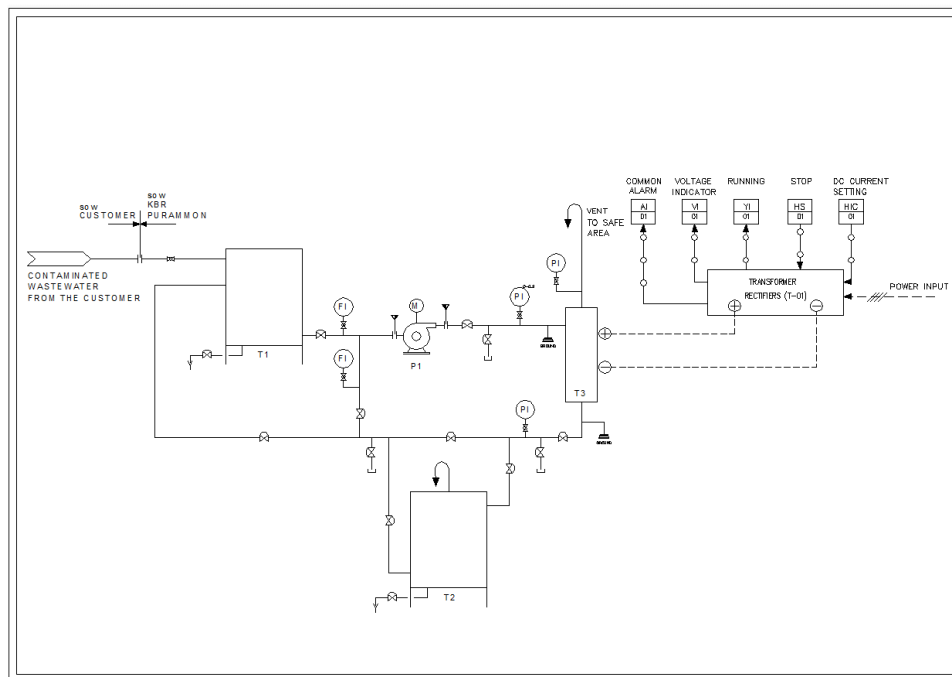


Figure 3. Laboratory system schematic.

### C. Analytical methods

Analytical inspection of the system performances was performed using Purammon's labs and an authorized laboratory (Environmental Services Company, Ltd., Israel). Methods of analysis were Ammonia: Salicylate Method

and SM 4500NH3C; Urea: Urease method and Total Kjeldahl Nitrogen (TN) SM 4500 NorgC; Total organic carbon: SM 5310B; Nitrite and nitrate: ISO 10304-1.

**Table 1. Customizing Simulated (Ersatz) Urine for Experimentation in the Current Phase of Testing.**

Chemical	Concentration, ppm	Component	Formula	M.W., g/mol	TOC, ppm	TN, ppm
Urea	1000	Urine Organic	CO(NH <sub>2</sub> ) <sub>2</sub>	60.06	199.8	466.2
Creatinine	1000	Urine Organic	C <sub>4</sub> H <sub>7</sub> N <sub>3</sub> O	113.12	424.3	371.3
Sodium chloride	5069	Urine Inorganic	NaCl	58.44	0.0	0.0
Potassium chloride	1930	Urine Inorganic	KCl	74.56	0.0	0.0
Potassium sulfate	0	Urine Inorganic	K <sub>2</sub> SO <sub>4</sub>	174.26	0.0	0.0
Potassium monobasic phosphate	1319	Urine Inorganic	KH <sub>2</sub> PO <sub>4</sub>	136.09	0.0	0.0
Magnesium chloride hexahydrate	719	Urine Inorganic	MgCl <sub>2</sub> *6H <sub>2</sub> O	203.31	0.0	0.0
Calcium chloride dihydrate	478	Urine Inorganic	CaCl <sub>2</sub> *2H <sub>2</sub> O	147.00	0.0	0.0
Ammonium bicarbonate	1000	Urine Inorganic	NH <sub>4</sub> HCO <sub>3</sub>	79.06	0.0	177.1
Chloride	4474		Cl <sup>-</sup>	35.45	0.0	0.0

#### D. Simulative wastewater

Urine is a complex mixture of metabolites and inorganic salts, primarily urea and various protein breakdown products such as amino acids and creatinine. Urine is also highly variable from person to person and is affected by many factors, including individual dietary choice differences and medicines that may be consumed. Table 1 above outlines the properties of the simulative urine that was used for the tests. For engineering purposes, the urine ersatz was prepared with nine major inorganic components due to budgetary and timeline limits. The urea concentration was prepared at a dilution of 17 from a previously reported urea median value to shorten processing timelines<sup>7</sup>. The inorganic salt concentrations were prepared based on values reported from “Composition and Concentrative Properties of Human Urine<sup>7</sup>” and “Generation Rates and Chemical Compositions of Waste Streams in a Typical Crewed Space Habitat<sup>8</sup>.” These values are based on real data extracted from space life support systems. In future testing, high fidelity urine ersatz with elevated chemical concentrations will be used.

### III. Results

#### A. Electrodes testing

Representative results of testing the novel electrodes are given in Figure 3a and 3b below. In Figure 3, ammonia, urea, and total dissolved solids (TDS) are plotted versus time. Initial urea and ammonia concentrations of 490 mgN/L and 180 mgN/L were reduced to 0.03 and 0.88 mgN/L respectively. The TDS concentration provided an indication that the molecules were removed from the solution. Figure 3b presents the decline in conductivity and pH during the experiment due to ammonia removal.

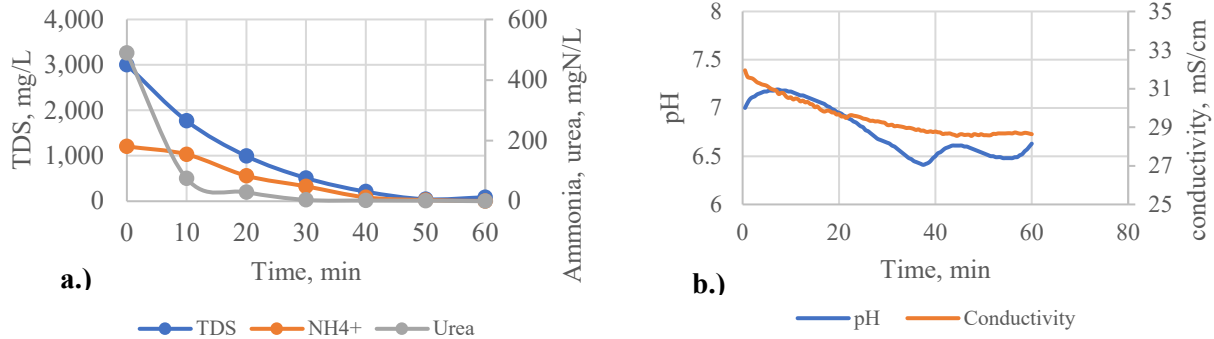


Figure 3. a.) Ammonia, urea, and TDS concentration versus time b.) Conductivity and pH versus time in a urine electrolytic treatment experiment.

#### B. CFD computing results

Reactor development with the ANSYS tool was done in stages. First, a module was configured. Then, fluid management and electrode positioning were optimized to secure strong drag forces to remove the gas bubbles. Figure 4 shows phases separation for the reactor. The water volume fraction approached one at the color red. A blue color indicated the presence of gas. Effective separation was achieved, while some gas was trapped below the baffle plate.

#### C. Complete system testing

Complete system testing was conducted in a batch mode. Wastewater was sent from the storage tank to the reactor and back

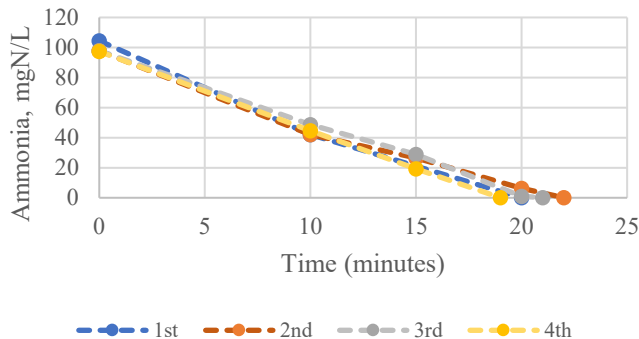


Figure 5. Ammonia concentration versus time in four urine experiments.

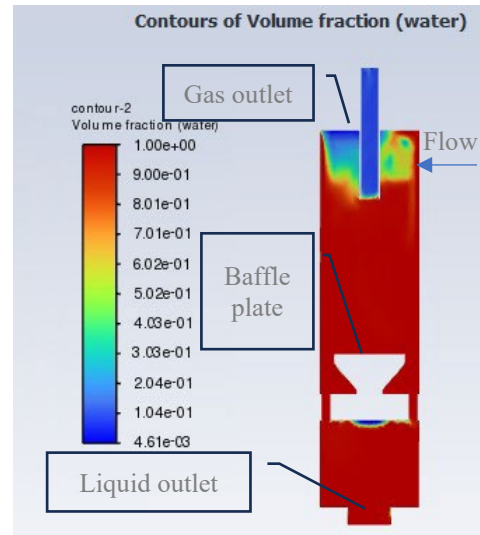


Figure 4. Water – gas separation of the reactor.

without passing through the additional tank. Results of the first four tests are plotted in Figure 5. All four tests resulted with complete removal and provided an insight to the system robustness, purifying the sample closely to zero-order reaction (almost linear concentration reduction versus time).

#### **IV. Conclusion**

The development of the technology tested in this paper began with laboratory bench-scale experiments that were preceded by the development of process specifications, design work, and system analysis that, when considered together with the results, confirmed the selected process potential.

This paper outlines the development and optimization process of the initial phase of an electrolytic system. The iterations made in the early investigation effort, as information from both laboratory testing and analysis runs were obtained, assisted in updating performance targets as well as further advancing and validating predictive tools and models for continued process optimization. The developed system has achieved its process goals, reducing initial ammonia and urea concentrations from several hundred mgN/L to below 1 mgN/L. TDS and conductivity were used as immediate indications for the removal and may be considered for real application sensors. Model optimization resulted in complete gas-liquid separation which supports implementing the electrolytic reactions inside a hydrocyclone.

From these results described in this article, we are confident that this technology is well suited for long-term missions. The system lower equivalent system mass, the potential of recovering nutrients, and trading power consumption in place of requiring mass quantities of chemicals to process wastewater are all factors that enhance the validity of the ES. For use in cases where austere remote conditions are assumed, these are major advantages.

KBR and Purammon will now move to the next phase, operating a full-scale system in the KBR laboratories. Future work will include longer operation cycles, electrode accelerated life tests, gas utilization investigation, sensitivity analyses for ground application and then a zero-G flight test.

#### **Acknowledgments**

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## References

- <sup>1</sup>Volpin, F. U. et. al, "Urine Treatment on the International Space Station: Current Practice and Novel Approaches," *Membranes* [online journal], Vol. 10, No. 11, Paper 327, URL: <https://doi.org/10.3390/membranes10110327> [cited 9 April 2024].
- <sup>2</sup>Boyce, Stephanie, et al. "Closing the Water Loop for Exploration: 2022 Status of the Brine Processor Assembly," 51st International Conference on Environmental Systems, 2022.
- <sup>3</sup>Yahia, M.B., Wjihi, S., "Study of the hydrogen physisorption on adsorbents based on activated carbon by means of statistical physics formalism: modeling analysis and thermodynamics investigation," *Scientific Reports* [online journal], Vol. 10, 16118, URL: <https://doi.org/10.1038/s41598-020-73268-w> [cited 25 April 2024].
- <sup>4</sup>Xin, Hu., Maohong, Fan., Brian, F., Towler., Maciej, Radosz., David, A., Bell., Ovid, A., Plumb. (2010), "Hydrogen Adsorption and Storage," *Coal Gasification and Its Applications*, Ch. 8, pp 157-245.
- <sup>5</sup>Klaus, Christmann. "Hydrogen Adsorption on Metal Surfaces" *Atomistics of Fracture*, Springer, Boston, MA, 1983, pp 363-389.
- <sup>6</sup>Gregory, Jerkiewicz., Alireza, Zolfaghari, "Comparison of Hydrogen Electroadsorption from the Electrolyte with Hydrogen Adsorption from the Gas Phase," *Journal of The Electrochemical Society* [online journal], Vol. 143, pp. 1240-1248, URL: doi: 10.1149/1.1836623 [cited 26 April 2024].
- <sup>7</sup>Putnam, David F., "Composition and Concentrative Properties of Human Urine," NASA CR-1802, July 1971.
- <sup>8</sup>Wydeven, Theodore, Golub, Morton A., "Generation Rates and Chemical Compositions of Waste Streams in a Typical Crewed Space Habitat," NASA Technical Memorandum 102799, August 1990.