VDO Lunar Water Purification System

Aqualunar Challenge - Final Prototype Architecture and Key Experimental Results

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1. Purpose and scope

778 Labs developed and integrated a Vaporization-Distillation-Oxidation (VDO) water purification prototype during the Canadian Space Agency Aqualunar Challenge. This note provides a concise record of the as-built Stage 3 architecture and selected experimental results. The hardware was a terrestrial laboratory prototype developed to validate process physics and subsystem integration. This document is limited to hardware and tests actually implemented during the Challenge; later architectural extensions are outside its scope.

2. As-built prototype architecture

The Stage 3 prototype used a sequential process: low-pressure vaporization with electrostatic precipitation of entrained regolith, condensation, packed-column distillation for volatile separation, and a recirculating UV/ozone oxidation loop for final polishing. The prototype used liquid feedstock and integrated these stages into a common fluid system.

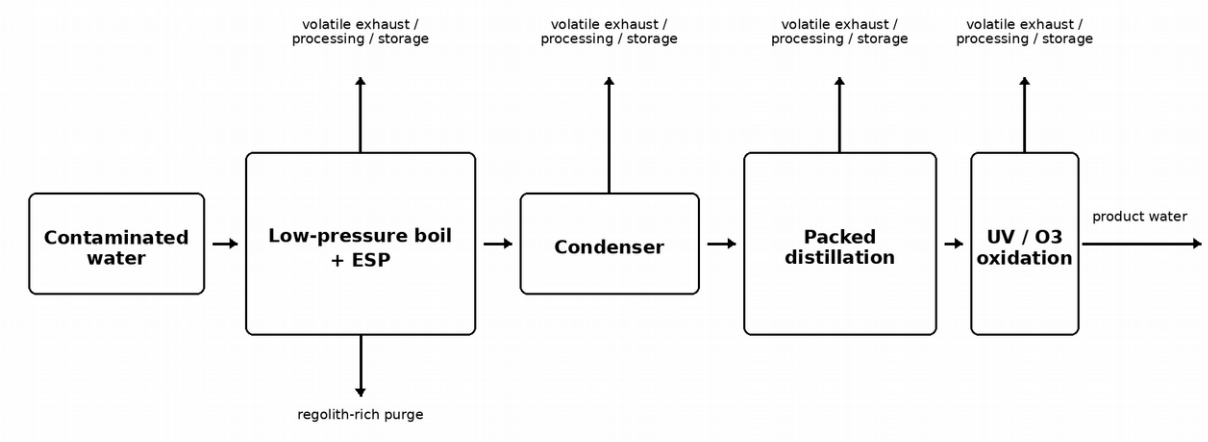


Figure 1. Simplified representation of the as-built Stage 3 VDO process.

2.1 Autonomous process control and feedstock adaptability

The Stage 3 prototype implemented closed-loop control for variable feed composition without requiring a fixed contaminant inventory. Pressure regulation automatically controlled volatile and non-condensable-gas exhaust; electrical conductivity and other sensors informed process-state decisions. Measured conditions drove diversion and recirculation of off-spec material for further processing. Long-duration autonomous solids management, regeneration, and fault recovery were not demonstrated.

3. Representative integrated operating point and mass allocation

Metric	Representative value	Interpretation
Water processing rate	2.2 kg/h	Integrated prototype operating point
Electrical input	~1 kW	Approx. total prototype electrical demand at the stated operating point
Specific electrical use	~0.45 kWh/kg	Calculated from 1 kW / 2.2 kg/h; test-rig value
As-built Stage 3 prototype mass allocation - 121 kg total (terrestrial test hardware)		
Vaporization: 24 kg	Distillation: 26 kg	Oxidation: 15 kg
Thermal circulation: 34 kg	Heat pump: 22 kg	Total: 121 kg

4. Experimental results

4.1 Regolith carryover suppression

Particulate performance was tested with distilled water containing 1 wt% LSP-2 lunar regolith simulant. Condensate samples were deposited on silicon wafers and analyzed by helium ion microscopy (HIM), with image analysis used to estimate particle-size distributions and volumetric loading.

Condition	Condensate loading	Result
ESP disabled	~11,000 ppbv	Baseline vapor-entrained regolith carryover
ESP at 15 W	~840 ppbv	~92% reduction relative to ESP-disabled condensate
1 wt% feed -> 840 ppbv	Derived overall rejection	~99.97% volumetric feed-to-condensate rejection*

*The ~99.97% figure is a derived overall feed-to-condensate rejection value, using the 1 wt% feed and an approximate regolith density of 3.1 g/cm3. It is not the incremental efficiency of the ESP itself. HIM analysis showed that the ESP strongly suppressed the dominant ~85 nm fraction and shifted the residual distribution toward smaller particles, with a residual peak near ~60 nm.

4.2 Vaporization-distillation ammonia and methanol removal

Challenge input and output samples were analyzed independently by the Centre Regional de Spectrometrie de Masse at Universite de Montreal using headspace GC-MS. The submitted output had passed through vaporization and distillation, but not oxidation; the GC-MS values therefore characterize the vaporization-distillation (VD) output.

Analyte	Median measured input	Final VD output	Derived removal
Ammonia	~112,000 ppm	<15 ppm (GC-MS LOD)	>99.986%
Methanol	~29,700 ppm	~100 ppm	~99.66%

4.3 Distillation ammonia validation

During Stage 3 ammonia testing, electrical conductivity (EC) was monitored in process at the distillation-column bottoms. For this controlled test matrix, the feed entering the column after primary vaporization and condensation consisted of water, methanol, and ammonia; regolith remained upstream in the primary boiler. Because methanol is nonionic under these conditions, the EC signal provided a species-specific estimate of residual ammonia. The column-bottoms reading was essentially indistinguishable from the distilled-water baseline, corresponding to approximately 1 ppm NH3 or less. Relative to the ~112,000 ppm median measured ammonia input reported in Section 4.2, this corresponds to at least ~99.9991% ammonia removal. The observation was congruent with Non-Random Two-Liquid (NRTL) vapor-liquid-equilibrium model predictions.

5. Oxidation subsystem: configuration and evidence

The Stage 3 prototype incorporated a closed gas-loop UV/ozone advanced oxidation system for downstream polishing of residual organics. An oxygen concentrator was used to supply the recirculating gas loop with nominally ~95% O2. The loop used a 20 W electrical ozone generator and a 55 W electrical, 254 nm Hg UV-C lamp. An SCD41 sensor monitored CO2, temperature, and relative humidity in the gas loop.

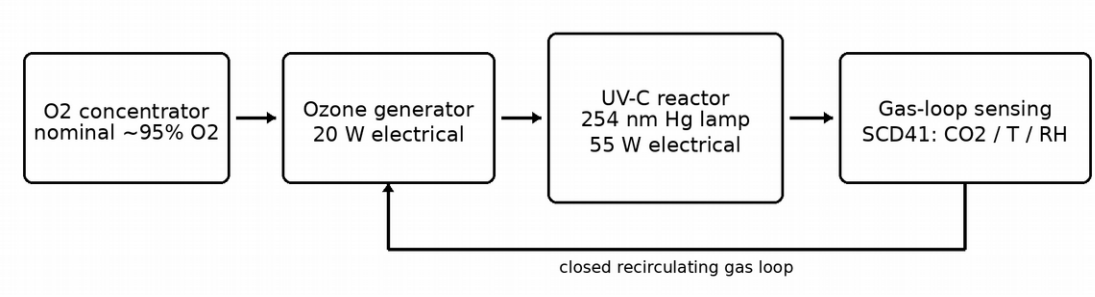


Figure 2. Functional oxidation test loop; power values are electrical ratings, not UV fluence or ozone dose.

5.1 Oxidation observations and model comparison

During development testing, the SCD41 reported CO_2 values exceeding 25,000 ppm and a rise-and-plateau trajectory broadly consistent with the reactor kinetics model. The SCD41 is specified for quantitative CO_2 performance over approximately 400-5,000 ppm; accordingly, readings above that range are treated here only as qualitative indicators of strong CO_2 evolution, not as calibrated concentration measurements.

Methanol oxidation proceeds through multiple oxygenated intermediates. At the 100 ppm methanol concentration used above to represent the VD output, the model predicts formic acid to be the most persistent residual, remaining at approximately 1-10 ppm after 60 minutes. Methanol and formaldehyde are predicted to be present at trace-ppb concentrations after the same reactor exposure. These species were not directly quantified experimentally during the development tests; oxidation progress was inferred from CO_2 evolution and comparison with the model rather than established by direct chemical analysis.

6. Interpretation and limitations

- The reported Stage 3 results establish an experimental baseline for integrated phase-change processing, nanoscale regolith carryover suppression, volatile separation, and operation of a UV/ozone polishing loop.
- The 2.2 kg/h and ~1 kW values describe the terrestrial test hardware at a representative operating point and are not flight-system SWAP predictions.
- No extended-duration regolith-loading campaign was performed; long-term fouling, solids accumulation, autonomous cleaning/regeneration, and multi-year fault recovery remain open research questions.
- The prototype was not operated in lunar gravity, lunar vacuum, or the cryogenic thermal environment of a permanently shadowed region.
- This public note intentionally describes only the as-built Stage 3 prototype. Later design variants and implementation details are not part of the disclosed architecture.

7. Data provenance

Regolith results were generated by 778 Labs during Stage 3 using HIM-based particle analysis. Vaporization-distillation (VD) ammonia and methanol output concentrations were measured independently by the Centre Regional de Spectrometrie de Masse at Universite de Montreal using headspace GC-MS; those analytical samples were not processed through oxidation. In-process distillation ammonia estimates were derived by 778 Labs from electrical-conductivity measurements in the controlled water/methanol/ammonia test matrix and compared with NRTL vapor-liquid-equilibrium predictions. Prototype mass allocations, oxidation-loop component ratings, sensor observations, and reactor-model results are 778 Labs development records.

References

[1] 778 Labs, Stage 3 Final Report, Canadian Space Agency Aqualunar Challenge, January 2026.

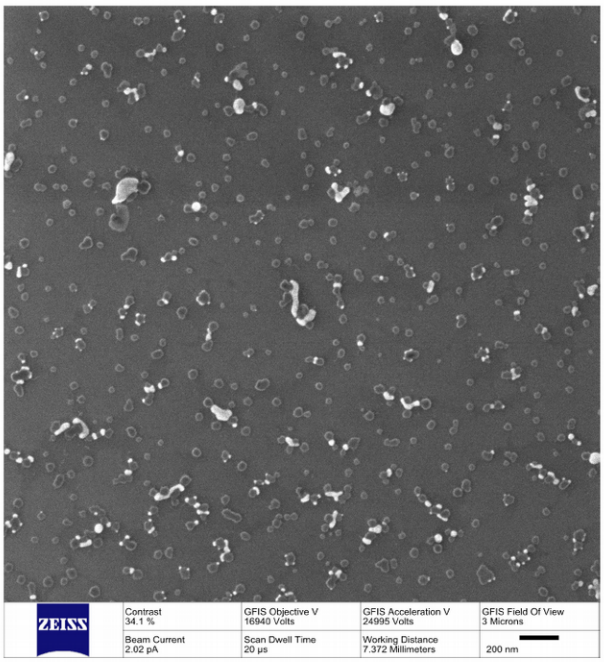
[2] 778 Labs, ESP Effectiveness Study Summary, Aqualunar Stage 3 supplemental test record, 2026. Reproduced on the following page.

[3] Centre Regional de Spectrometrie de Masse, Universite de Montreal, Aqualunar Challenge Sample Testing - 778 Labs Team, February 27, 2026.

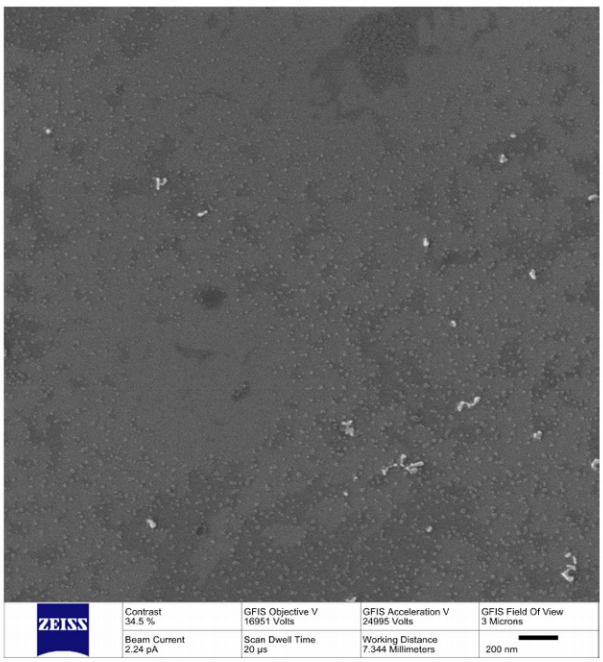
[4] Sensirion AG, SCD4x / SCD41 carbon-dioxide sensor product documentation and datasheet, accessed 2026.

ESP Effectiveness study summary

778 Labs - Aqualunar Stage 3



ESP Off, typical view



ESP 15W, typical view

We tested the prototype primary boiler and condenser with the ESP at various settings. The boiling rate was much faster than required to make this a challenging test for the system. 1% by mass regolith was added to distilled water, and we collected the outputs. Using a micropipette, three spots of 50µL of each sample were dispensed on a clean silicon wafer in a laminar flow hood. The wafer was heated to 50°C to evaporate the drops. The hydrophobic substrate meant that the drops shrank and deposited a relatively uniform regolith film at each location. This sample was then loaded into a helium ion microscope (HIM) for high resolution imaging.

Five locations were chosen at random for each ESP sample, and 3um x 3um images were taken at each location. These were analyzed using ImageJ to identify the particle size distribution, the particle surface density was then calculated for each sample, and using the average patch area for each sample we determined the dust concentration in ppbv.