ADVANCEMENT OF ISRU TECHNOLOGIES AND SYSTEMS:

WATER COLLECTION, PURIFICATION, AND ELECTROLYSIS

Presented by: **Jordan Holquist, Ph.D.**

for the 2023 Space Resources Roundtable, Golden CO, USA

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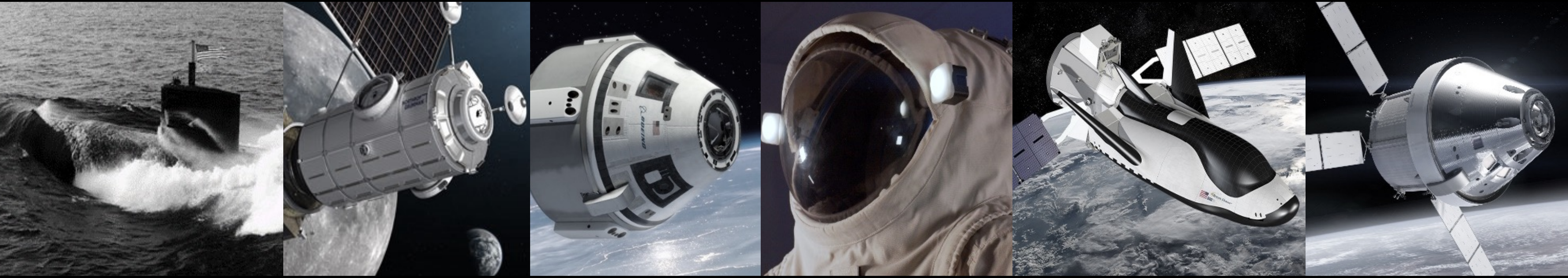


Company Overview

Paragon Space Development

An Innovative, Agile, World-Class Aerospace Corporation

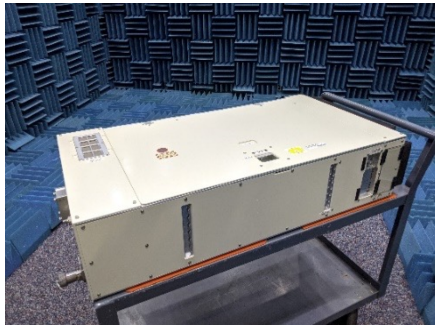
- U.S. Based, Privately Owned
- Leading **life support** & **thermal control** company
- Entrepreneurial Spirit of a Start-up
- Stability and Heritage of a 30-year-old company
- Three locations across the U.S.
  - Tucson, Denver, Houston
- First spinoff: World View in 2014
- Trusted Supplier / AS9100 Certified

NORTHROP GRUMMAN
BOEING
LOCKHEED MARTIN
NASA
SIERRA SPACE
Nanoracks
Dynetics A Leidos Company
SPACEX
AXIOM SPACE
NAVSEA NAVAL SEA SYSTEMS COMMAND
DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA
BLUE ORIGIN
OCEANEERING®

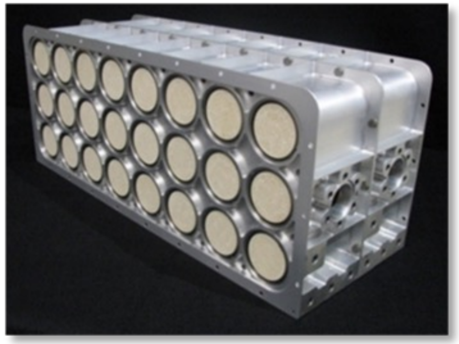
Select Programs

Northrop Grumman HALO ECLSS

ISS Brine Processor Assembly (BPA)

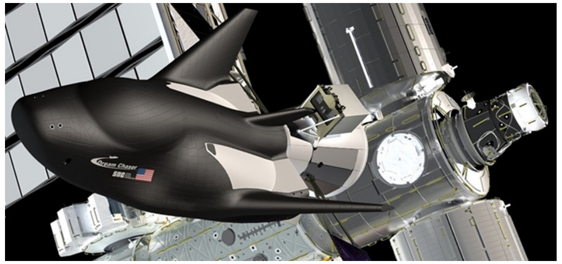


Boeing CST-100 Humidity Control Subassembly



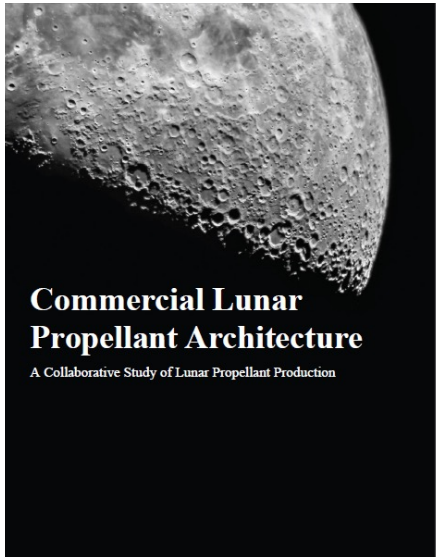
Lockheed Martin Orion

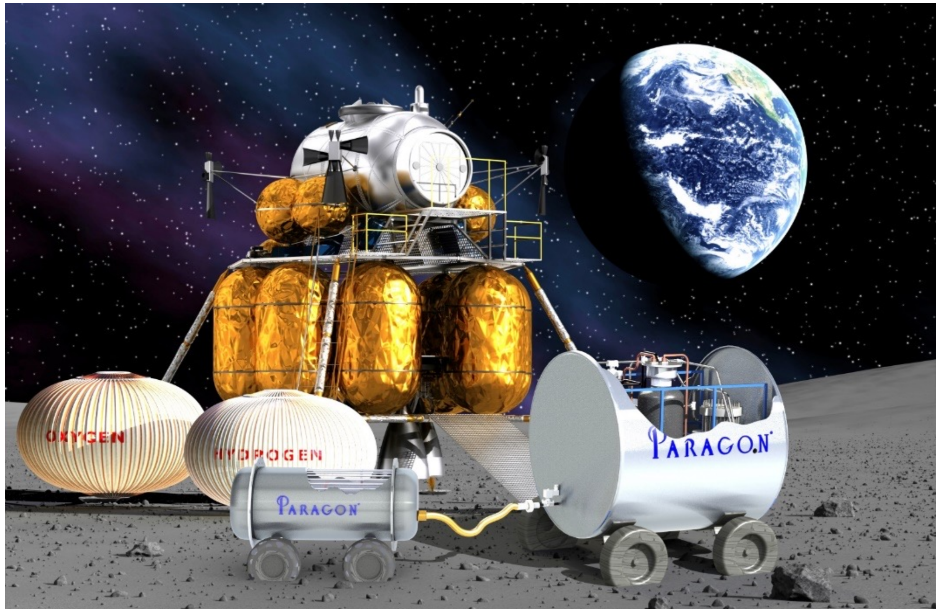
Sierra Space Dream Chaser Cargo Module Radiators

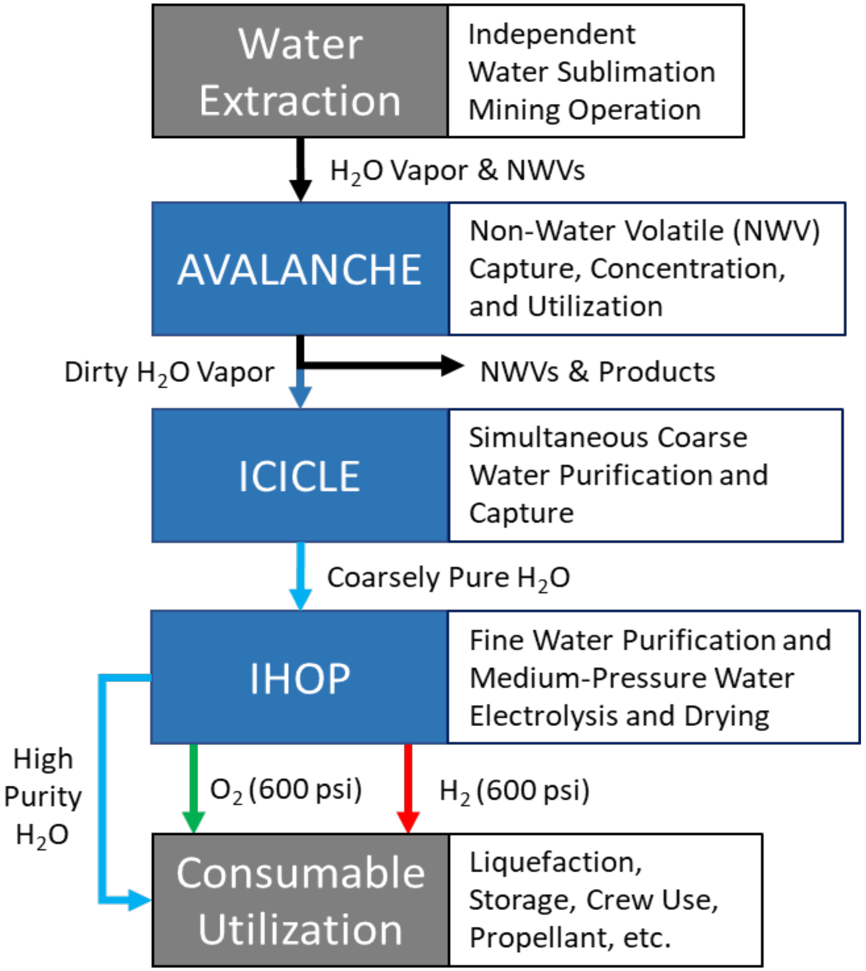


Paragon's ISRU Architecture Overview

- Paragon has been working on ISRU since 2018 Commercial Lunar Propellant Architecture community-wide study
- Paragon's approach to ISRU is **modular**, **expandable**, and **sustainable**
- System design and development has been done with **relevant environments** and **realistic contaminants** as design constraints
- Focused primarily on water-based ISRU, but technology is applicable to non-water based ISRU architectures (e.g., oxygen from regolith)







PARAGON SPACE DEVELOPMENT CORPORATION

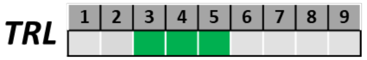
ICICLE – Water Collection & Purification

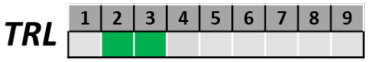
ICICLE: **I**SRU **C**ollector of **I**ce in a **C**old **L**unar **E**nvironment

Status: TRL 4 demonstrated, design for TRL 5 underway

Contracts

- SBIR Phase II – TRL 4 and TRL 5 Goals
- SBIR Phase I – Concept Development
- IR&D Cold Trap Experiment to TRL 3





Description

- Lunar water collection Cold Trap designed for coarse water purification during collection through freeze distillation
- Designed to be compatible with **any** upstream interface that sublimates water vapor from lunar regolith

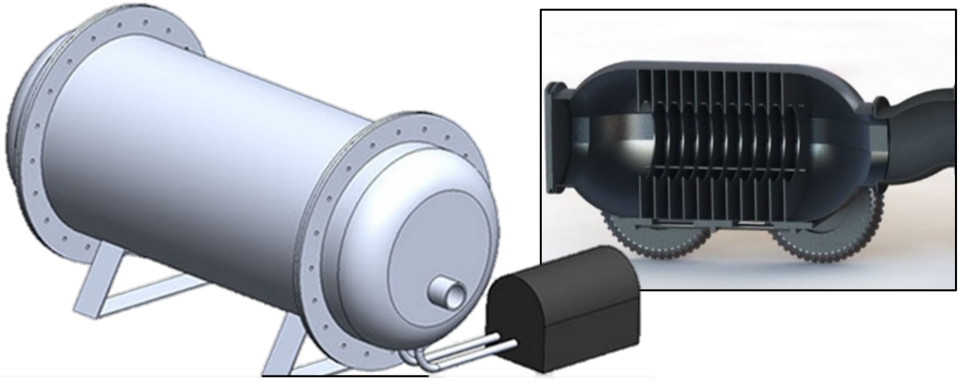
Summary

Buy-down ISRU technology development risk

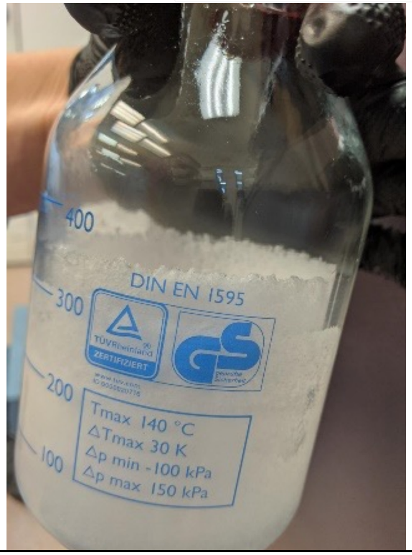
- Volatile contaminant species and conc. are still highly uncertain
- Controlled freeze distillation design is insensitive to volatiles "to the left" of water on a phase equilibrium diagram

Overall ISRU operating energy reduction

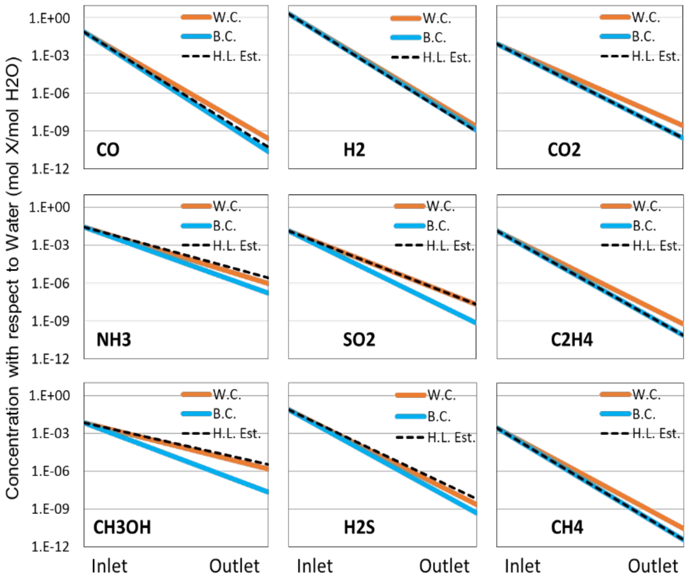
- Water sublimation is happening in ~all ISRU architectures
- Water condensation happening in ~all ISRU architectures
- **Gain significant water purification with minimal additional energy expenditure**



Notional ICICLE cold trap concept art
https://www.paragonsdc.com/what-we-do/in-situ-resource-utilization-isru/icicle/



TRL 3 Proof of Concept
"Ice in a bottle" Cold Trap Experiment
Holquist et al. (2021), ICES-2021-292



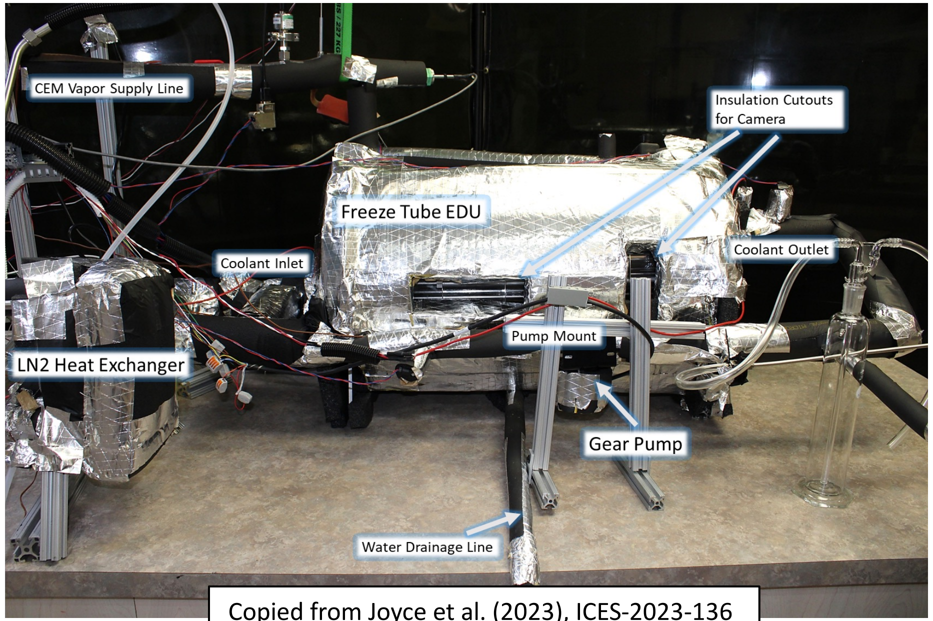
Copied from Holquist et al. (2020), ICES-2020-71

ICICLE – Water Collection & Purification

Case B, nominal conditions

Case C, nominal at half flow rate

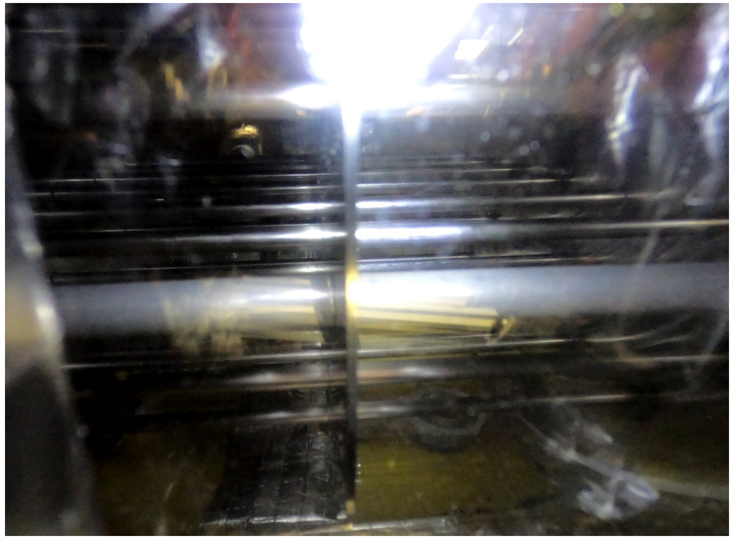
Freeze Tube TRL 4 Demonstrator Test Set Up



Copied from Joyce et al. (2023), ICES-2023-136

Case D, reduced humidity ratio

Case E, higher coolant temp.



Test Case	A		B		C		D		E		F	
Runtime (minutes)	63		171		211		154		241		544	
Test Parameter	Mean Value	Var. (+/-)	Mean Value	Var. (+/-)	Mean Value	Var. (+/-)	Mean Value	Var. (+/-)	Mean Value	Var. (+/-)	Mean Value	Var. (+/-)
$\dot{m}_{wv,inlet}$ (gH_2O/hr)	100	0.28	100	2.00E-09	49.9	6.40E-03	100	5.00E-09	99.9	7.00E-03	99.8	1.60E-02
w_{inlet} (kgH_2O/kgN_2)	3.23	0.29	3.23	3.10E-06	3.23	2.70E-02	0.64	2.60E-06	3.23	1.00E-06	3.23	1.70E-02
$T_{vapor,inlet}$ (°C)	17.0	11.8	13.2	2.4	11.8	1.5	21.4	0.53	22.3	0.93	23.6	1.97
P_{shell} (Pa)	539	24	699	22	465	19	2011	110	683	19	650	28
$T_{coolant,avg}$* (°C)	-38.8	1.74	-39.3	4.71	-36.4	1.63	-37.6	3.67	-28.2	4.86	-40.2	5.61
$\Delta T_{coolant}$* (°C)	2.22	0.02	3.08	0.36	2.72	0.25	3.15	0.31	3.08	1.06	2.80	0.73

ICICLE – Water Collection & Purification

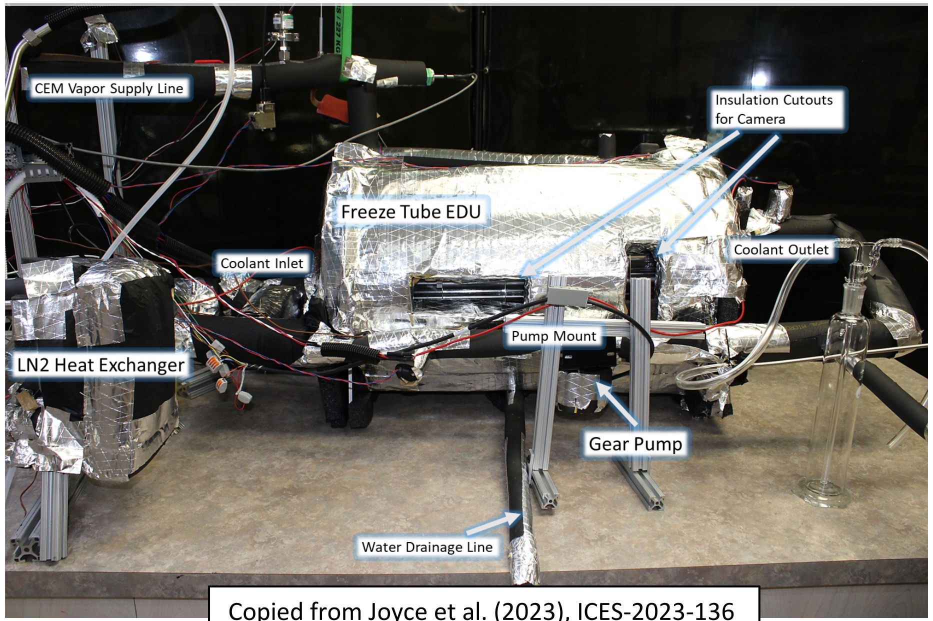
Case F, 1st Quarter of Test

Case F, 2nd Quarter of Test

Case F, 3rd Quarter of Test

Case F, 4th Quarter of Test

Freeze Tube TRL 4 Demonstrator Test Set Up



Copied from Joyce et al. (2023), ICES-2023-136

Test Case:	A	B	C	D	E	F	
Method	Collection Efficiency (%)						Uncertainty (+/-)
η_{freeze} (Eq. 1)	97.1	97.6	94.9	97.0	92.0	97.7	2.5%
Method 1 (Eq. 4)	96.8	154	113	146	145	107	See Section IV.A
Method 2 (Eq. 5)	99.6	99.6	99.6	99.2	98.6	99.2	4.9%
Method 3 (Eq. 6)	81.0	89.5	79.5	63.3	72.3	85.7	See Section IV.A

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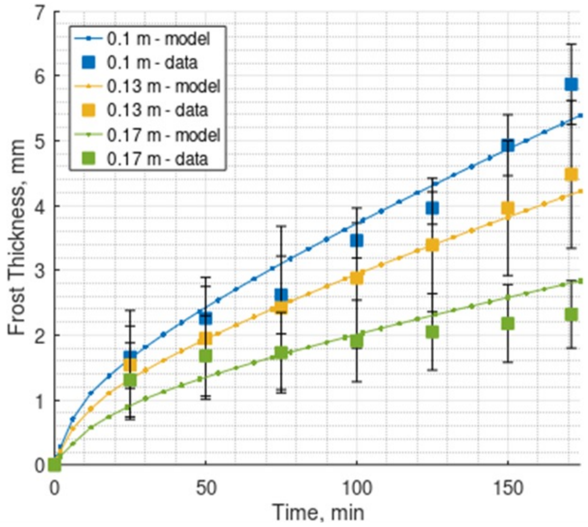
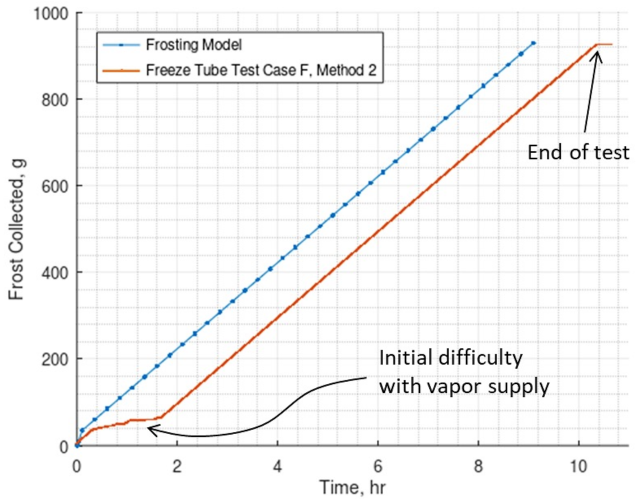
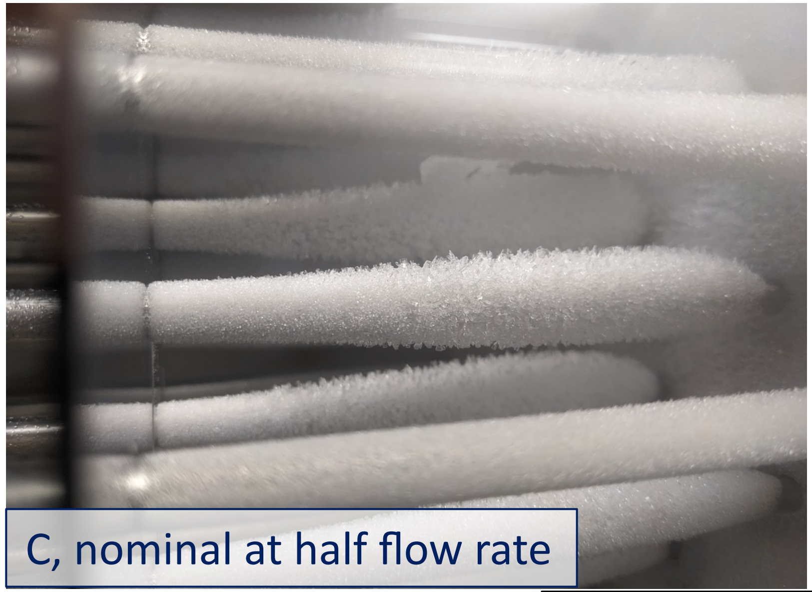
ICICLE – Model and Data Comparisons



Above: Frost growth over time for Case B, data compared to model for select positions.

Below: Total frost collected over time, model versus data for Test Case F

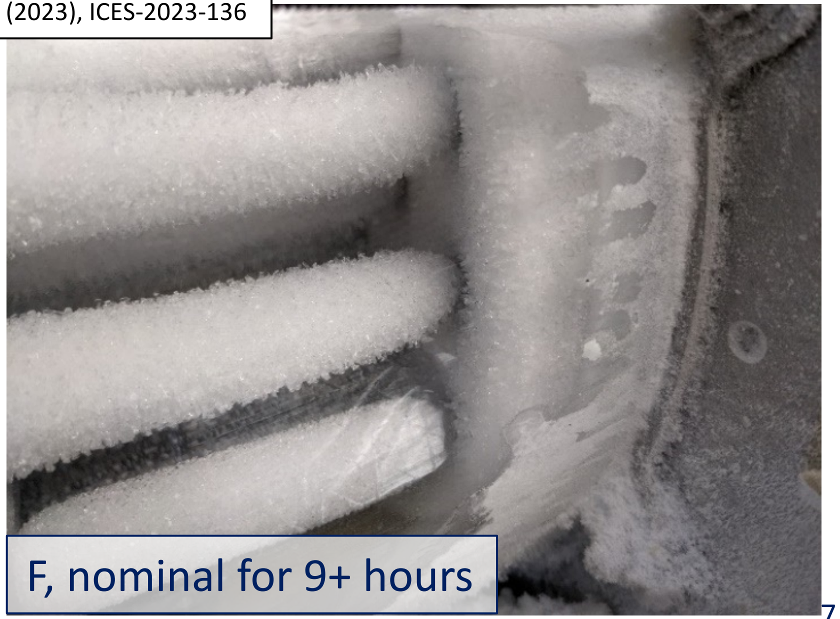



C, nominal at half flow rate


D, nominal at reduced humidity ratio

Copied from Joyce et al. (2023), ICES-2023-136


E, nominal with higher coolant temp.


F, nominal for 9+ hours

IHOP – Water Purification & Electrolysis

IHOP: **I**SRU-derived water purification and **H**ydrogen **O**xygen **P**roduction Subsystem

TRL

1	2	3	4	5	6	7	8	9

Status: Component TRL 4 demonstrated, TRL 5 partially complete

Contracts

- NASA NextSTEP-2 Track 2 (Component Advancement)
    - Component TRL 5, Subsystem TRL 4

Description

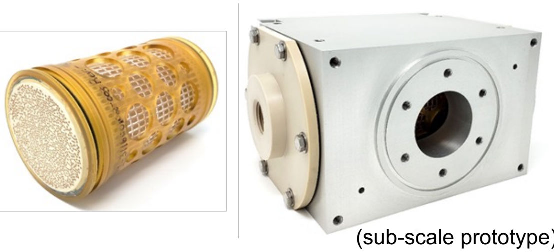
- Integrated multi-stage water purification and electrolysis
- Full-scale lunar system design iteratively advancing in tandem with full-scale prototype & integrated testing
- IHOP is projected to require **no regeneration or resupply** while producing H_2 and O_2 propellant for two years.

Summary

Robust, continuous, and integrated water purification and electrolysis

- Minimizes uncertainties associated with volatile species and concentrations
- The Paragon Ionomer-membrane Water Processing (IWP) Technology removes a broad range of contaminants through membrane distillation without consumables or cycled regeneration
- The aerospace water electrolyzer has been demonstrated for >6,000 hours
- The lunar system design is easily scalable and intended for multi-system parallel string operation

Paragon IWP Technology



(sub-scale prototype)

TRL

1	2	3	4	5	6	7	8	9

Copied from Holquist et al. (2021), ICES-2021-295

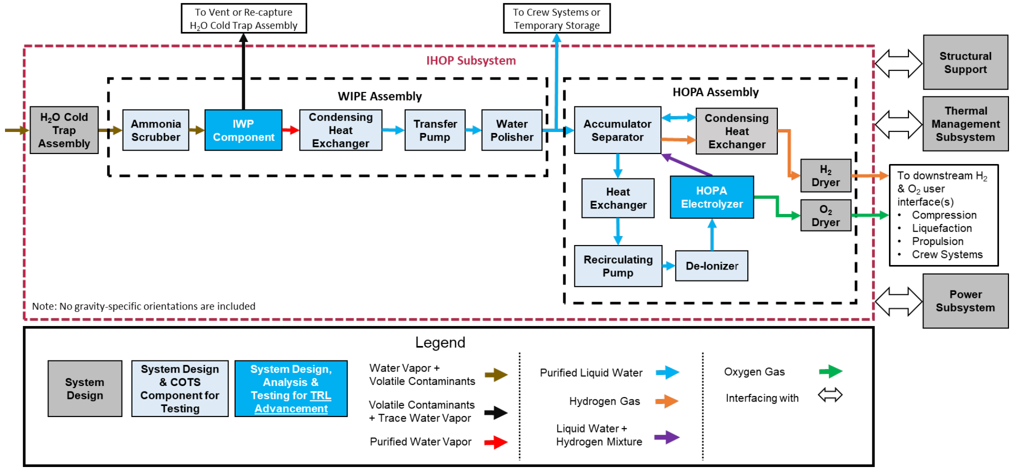
Notional IHOP subsystem concept art
https://www.paragonsdc.com/what-we-do/in-situ-resource-utilization-isru/ihop/

Aerospace Electrolyzer

(reference image)

TRL

1	2	3	4	5	6	7	8	9



Copied from Holquist et al. (2021), ICES-2021-295

IHOP – Water Purification & Electrolysis

IHOP Assumptions and Requirements

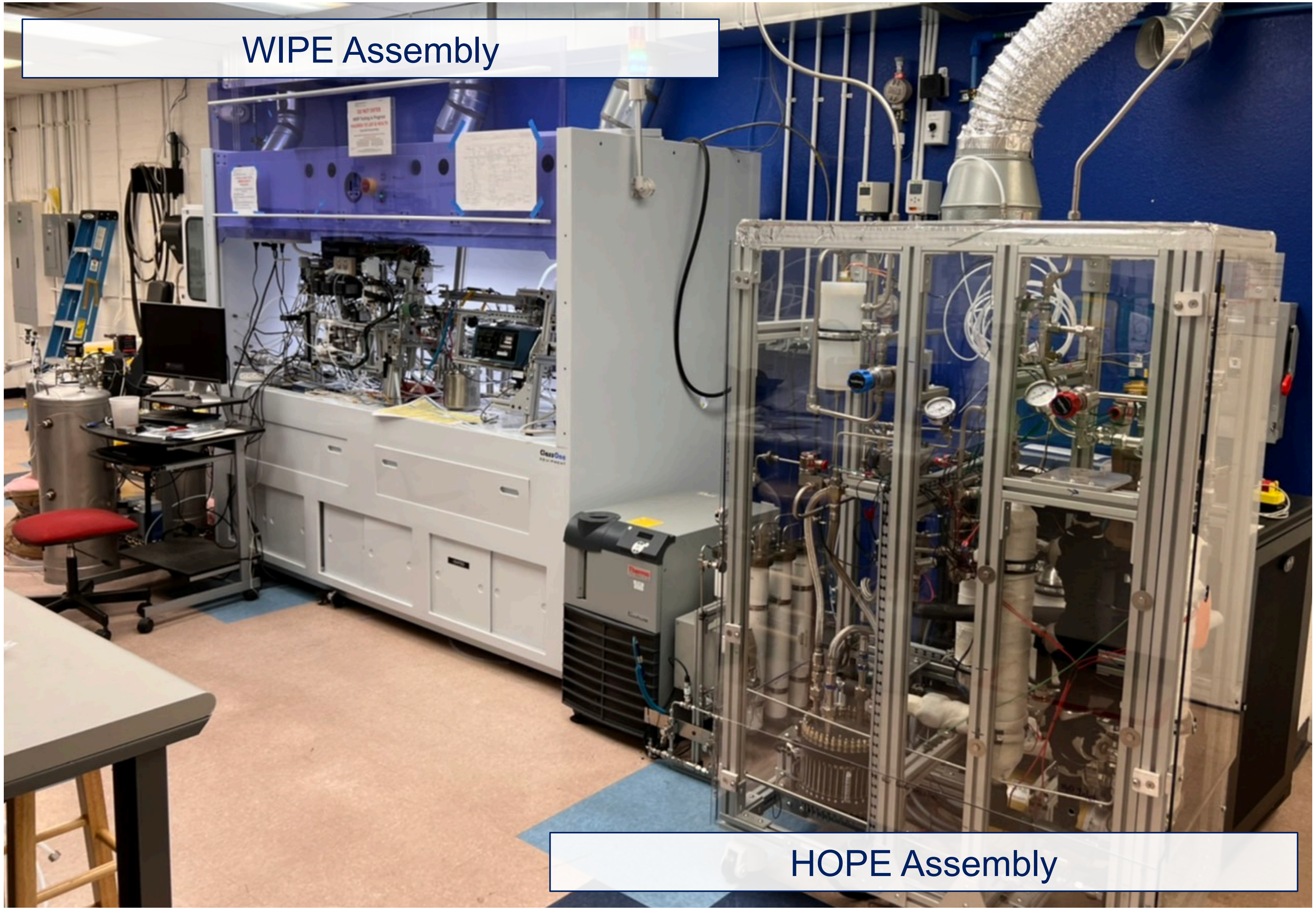
- WIPE Assembly: Designed to process 1.34 kg/h of H_2O
- HOPE Assembly: Designed to electrolyze 1.3 kg/h of H_2O yielding 0.14 kg/h H_2 & 1.16 kg/h O_2
- Design for scalability, assume operation on a sunlit crater rim, and design for 2 years (225 d/y) of operation

WIPE Output Water / HOPA Input Water Targets

- Resistivity: 10 MΩ-cm (0.1 µS/cm)
- Total Organic Carbon (TOC): < 30 ppb (30 µg/L)
- Total Sulfur: < 1 ppm (1 mg/L)

HOPE H_2/O_2 Output Targets

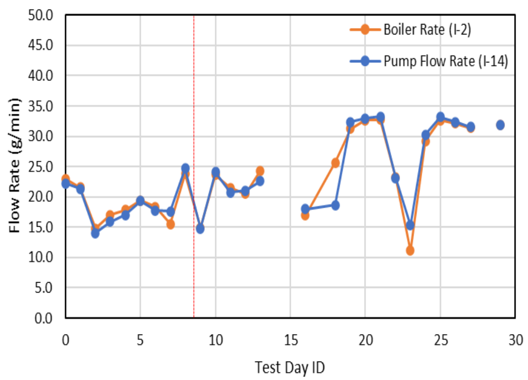
- Pressure: 600 psia (~41 bar, ~4100 kPa)
- Temperature: 60°C



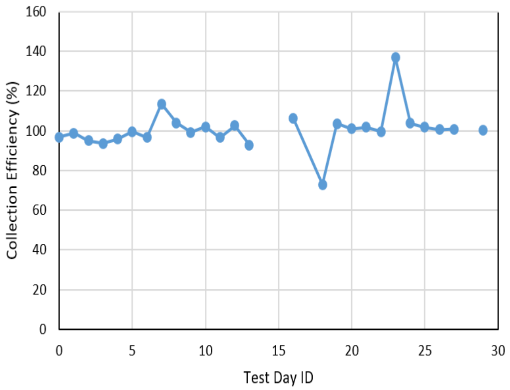
WIPE Assembly Testing Results

- Processing rates and collection efficiencies are hitting targets of 1.34 kg/hr and >90%
- Initial WIPE testing was to characterize performance and allow for re-designs to meet targets on second revision
- WIPE testing lessons-learned and design deltas have been reported to NASA and implemented for the next round of upcoming testing
- **Next Steps**: Further testing with WIPE 2.0 will reveal if additional measures are necessary for the overall subsystem performance goals

Flow Rate



Collection Efficiency



Copied from Holquist et al. (2022), ICES-2022-105

Lunar Inputs to Cold Trap			Model	Worst Case Lunar Est. out of Cold Trap		Best Case Lunar Est. out of Cold Trap	
Formula	Conc. w.r.t. H_2O (mol%)	Conc. w.r.t H_2O (ppm)	H-Law 273K Conc. Est. (ppb)	Exp.-to-Model (ratio)	Lunar Cold Trap Outlet Est. (ppb)	Exp.-to-Model (ratio)	Lunar Cold Trap Outlet Est. (ppb)
CO	100	80900	0.05	5.09	0.3	0.43	0.02
H_2	225	22500*	1	2.73	2.7	1.35	1.3
H_2S	8.09	73000	7	0.34	2.2	0.07	0.5
NH_3	7.30	26600	2677	0.35	929	0.07	176
SO_2	2.66	14000	21	1.07	22	0.03	0.7
C_2H_4	1.40	13700	0.1	8.22	0.6	1.00	0.1
CH_4	1.37	2800	0.003	8.22	0.03	1.00	0.003
CH_3OH	0.94	6700	3512	0.43	1495	0.01	21
CO_2	0.67	9400	0.3	9.45	3	1.00	0.3

Copied from Holquist et al. (2021), ICES-2021-295

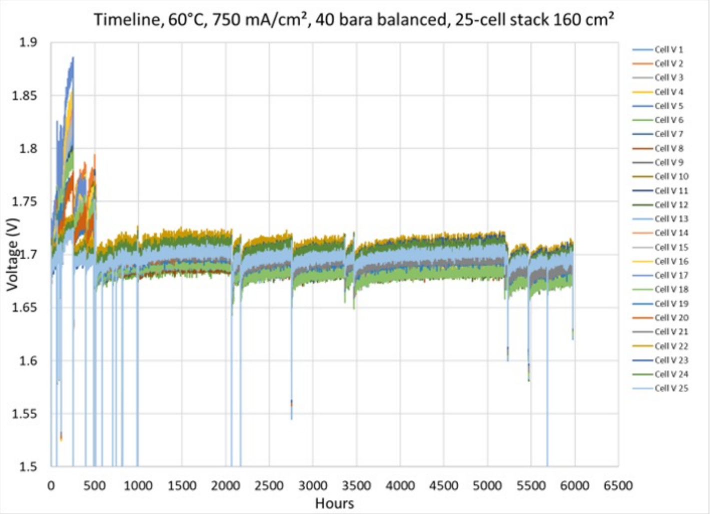
Table: WIPE 1.0 Test Data

Parameter	Target	Actual
Run time	4 weeks continuous	3 weeks cumulative (8 days cont.)
Processing rate	22 g/min (1.34 kg/hr)	10 – 33 g/min (0.6 – 1.98 kg/hr)
Collection efficiency	> 90%	102% ± 11% (sensor noise)
Water Resistivity (conductivity)	10 MΩ-cm (0.1 μS/cm)	1 – 0.20 MΩ-cm (1 – 5 μS/cm)
Water Total Organic Carbon (TOC)	< 30 ppb (30 μg/L)	180 – 400 ppb (180 – 400 μg/L)
Total Sulfur	< 1 ppm (1 mg/L)	< 0.4 ppm (0.4 mg/L)*

IHOP – Water Electrolysis

HOPE Electrolyzer & Assembly Testing Results

- Endurance testing was completed with Electrolyzer Stack Build 1 in an early version of the HOPA Assembly
- Freeze-Thaw cycles demonstrated in 1,200 h operation over 4 cycles
- Lessons-learned worked with NASA SME support and materials updated
- HOPA design updated, built, and checked out – ready for integrated testing with Electrolyzer Stack Build 3 (Build 2 was used for freeze-thaw cycle testing)
- **Next Steps**: Testing with realistic contaminant loading using water directly output from WIPE Assembly



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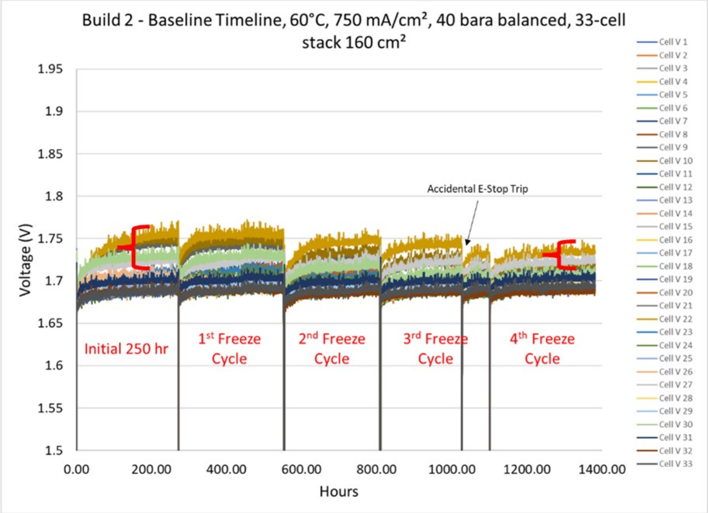
Parameter	Units	Predicted	Actual
Run time	Hours	5,000	5,978
Current Density	mA/cm²	750	750
Water Inlet Temperature	°C	60	60
Stack Pressure	Psia	600	600
Water Consumption	kg/h	1.0	1.0
Stack Voltage	V	42.4	42.3
Power Consumption	kW	5.1	5.1
Energy Requirement	kWh/kg H2	46.3	46.3



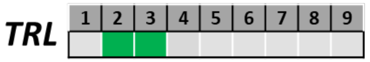
AVALANCHE – Non-Water Volatiles

AVALANCHE: Ammonia and Volatiles Accumulation in Lunar Architectures for non-Water Capabilities furthering Human Exploration

Status: TRL 2+, seeking development & integration opportunities

Contracts

- SBIR Phase I – Concept Development



Description

- Lunar non-water volatiles (NWV) separation, capture, and utilization
- Designed to be compatible with **any** upstream gaseous interface from heated volatiles or lunar regolith

Summary

Improve ISRU system lifetime through risk reduction

- Volatile contaminant species and conc. are still highly uncertain
- Design to capture known particulates and volatiles with higher phase transition temperatures than water
- **Protect downstream equipment by designing for the most consequential and hardest to separate contaminants**

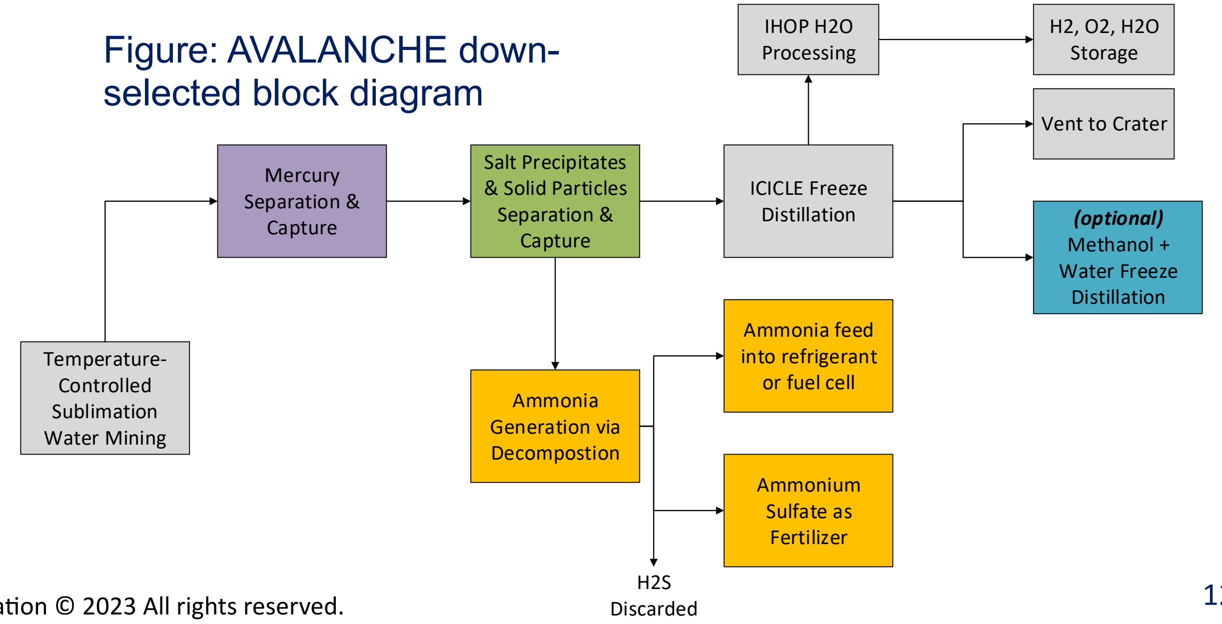
Add value through alternative consumables generation

- NWVs, particularly ammonia, have potential use in fuel cells, plant growth fertilizer, and even hydrazine propellant

Table: AVALANCHE process collection efficiency summary

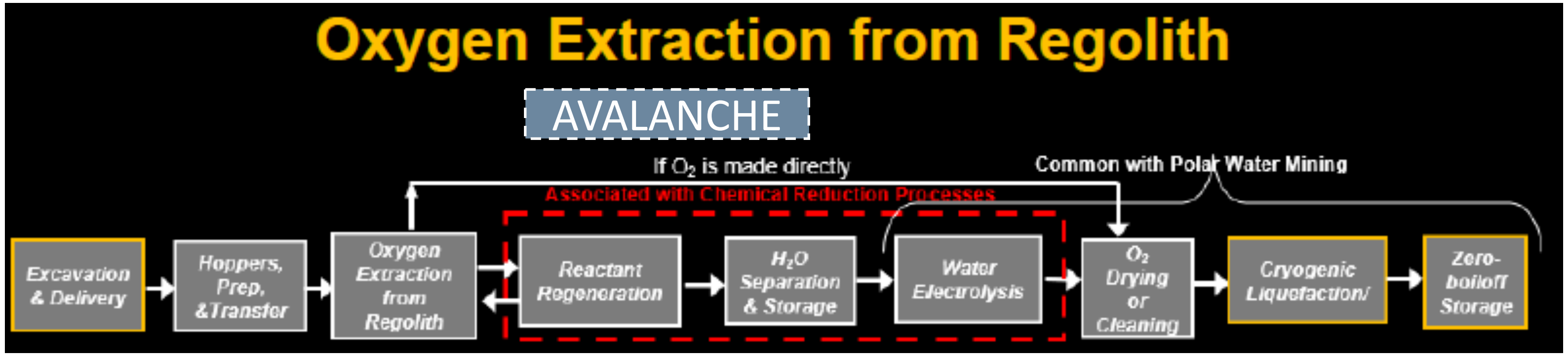
Temperature:	283 K	283 K	240 K	170 K
Collection Efficiencies at each Stage:	Mercury Separator	Salt Separator	ICICLE	Exhaust Cold Trap
Carbon monoxide	0%	0%	0%	0%
Hydrogen	0%	0%	0%	0%
Hydrogen sulfide	0%	0%	0%	0.51%
Ammonia	0%	**91.72%**	0%	0.33%
Sulfur dioxide	0%	**87.13%**	0%	**1.64%**
Ethylene	0%	0%	0%	0%
Methane	0%	0%	0%	0%
Methanol	0%	0%	0%	**99.13%**
Carbon dioxide	0%	0%	0%	0%
Mercury	**99.47%**	**0.52%**	0%	0%
Water	0%	**1.22%**	**94.98%**	**3.65%**

Figure: AVALANCHE down-selected block diagram



Related ISRU Applications & Technology

- ISRU system architecture commonality allows for technology advancement on separate “tracks”
- Utilizing demonstrated and in-development water processing technologies shortens the on-ramp for oxygen from regolith complete systems
- Continued development de-risks delayed water-based ISRU development due to near term shifting funding and priorities



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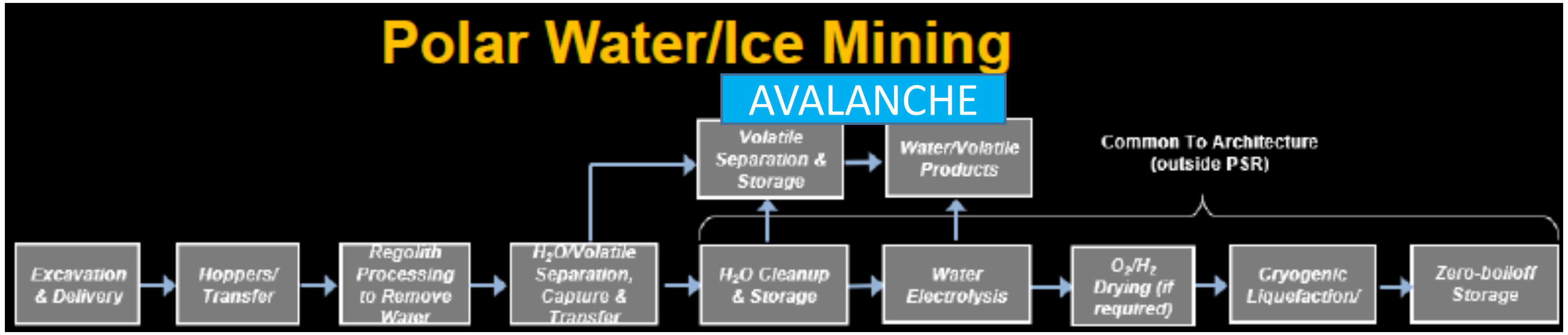
ICICLE IHOP



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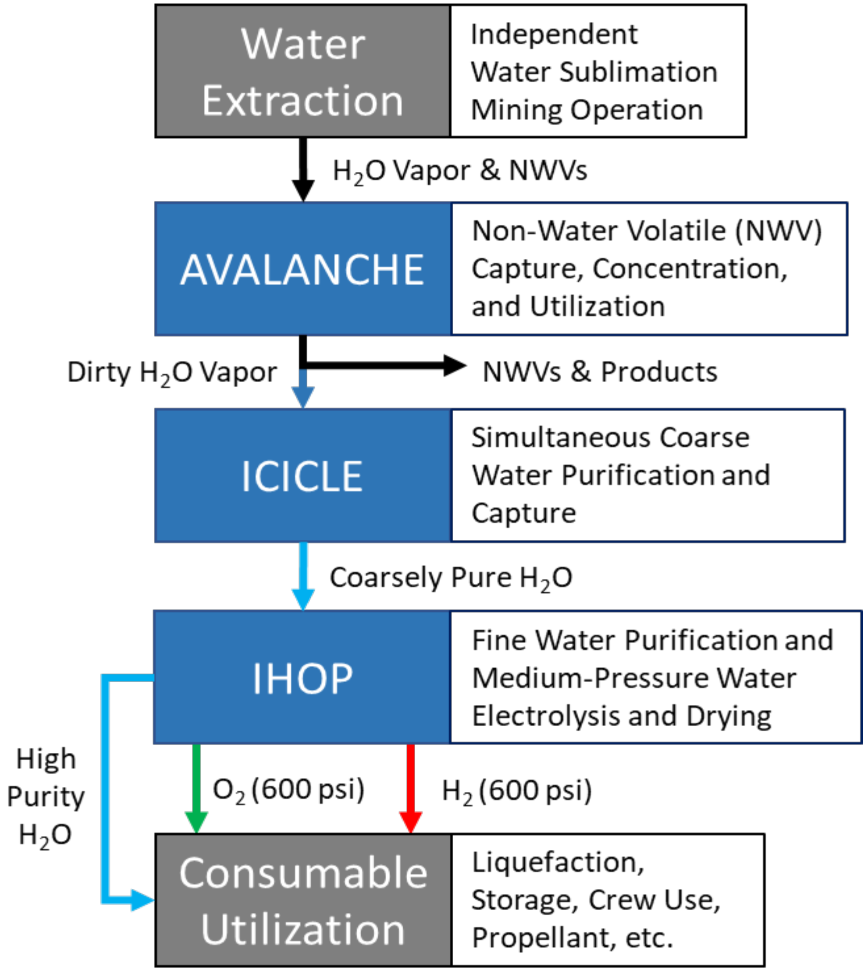
ICICLE IHOP



Acknowledgements & References

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- Holquist, J. B., Joyce, C. J., Rivera, R., Tewes, P., Myles, T., Markham, D., Ebaugh, T., Rich, M., and Willey, J., "Demonstration of Paragon's ISRU Propellant Production Subsystem Electrolyzer and Electrolysis Assembly," 52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, AB, Canada. [Accepted]
- Joyce, C. J., Holquist, J. B., Rivera, R., and Moeller, T., "Demonstration and Model Validation of Freeze Distillation as a Purification Step for Lunar Water Processing," 52nd International Conference on Environmental Systems, 16-20 July 2023, Calgary, AB, Canada. [Accepted]
- Holquist, J. B., Gellenbeck, S., Joyce, C. J., Rivera, R., Bower, C. E., Tewes, P., "Demonstration of Paragon's Water Purification Assembly for Lunar Water Processing," 51st International Conference on Environmental Systems, 10-14 July 2022, St. Paul, MN, USA
- Holquist, J. B., Gellenbeck, S., Bower, C. E., Tewes, P., "Experimental Proof of Concept of a Cold Trap as a Purification Step for Lunar Water Processing," 50th International Conference on Environmental Systems, 12-15 July 2021.
- Holquist, J. B., Gellenbeck, S., Bower, C. E., Tewes, P., "Demonstration of Paragon's Ionomer-membrane Water Processor (IWP) Technology as a Purification Step for Lunar Water Processing," 50th International Conference on Environmental Systems, 12-15 July 2021.
- Holquist, J. B., Pasadilla, P., Bower, C., Cognata, T., Tewes, P., and Kelsey, L., "Analysis of a Cold Trap as a Purification Step for Lunar Water Processing," International Conference on Environmental Systems 2020, 2020.

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