AETHER

Atmospheric Electrochemical Transformation for Habitat and Environmental Regeneration

Embry-Riddle Aeronautical University – Prescott

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2026 Human Lander Challenge Forum, Huntsville, AL

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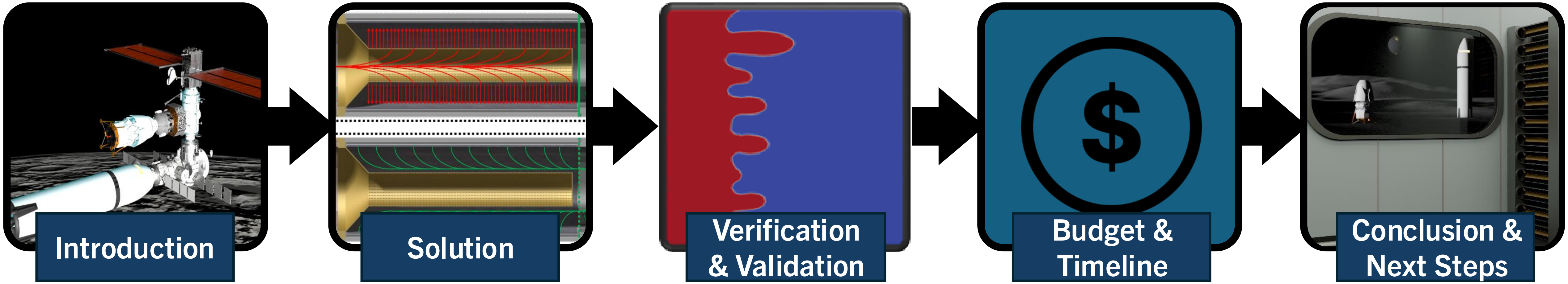
Agenda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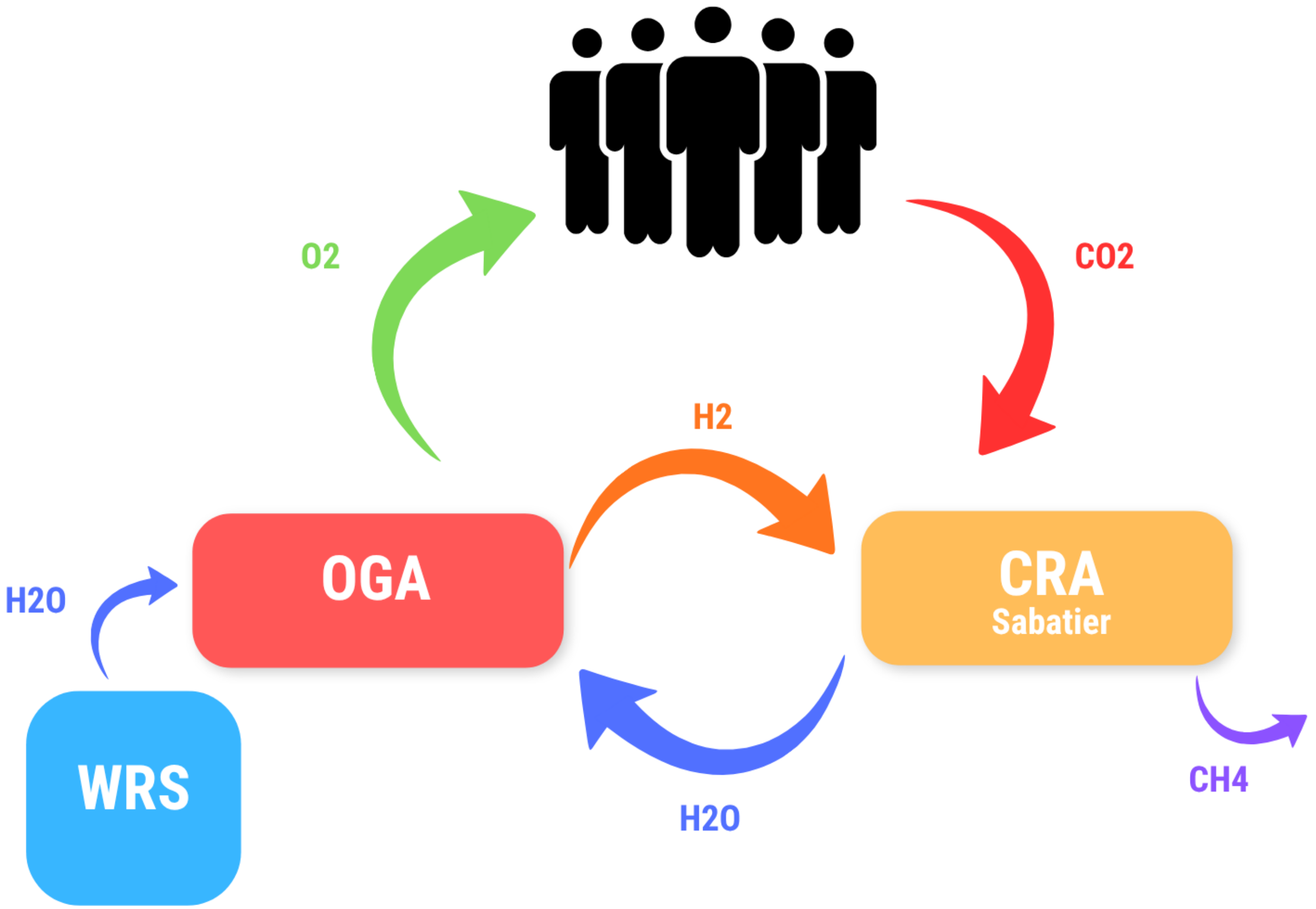
Background

- Current heritage oxygen reclamation architectures utilize electrolysis
- Electrolysis for short-term manned missions achieves 51% oxygen recovery yield

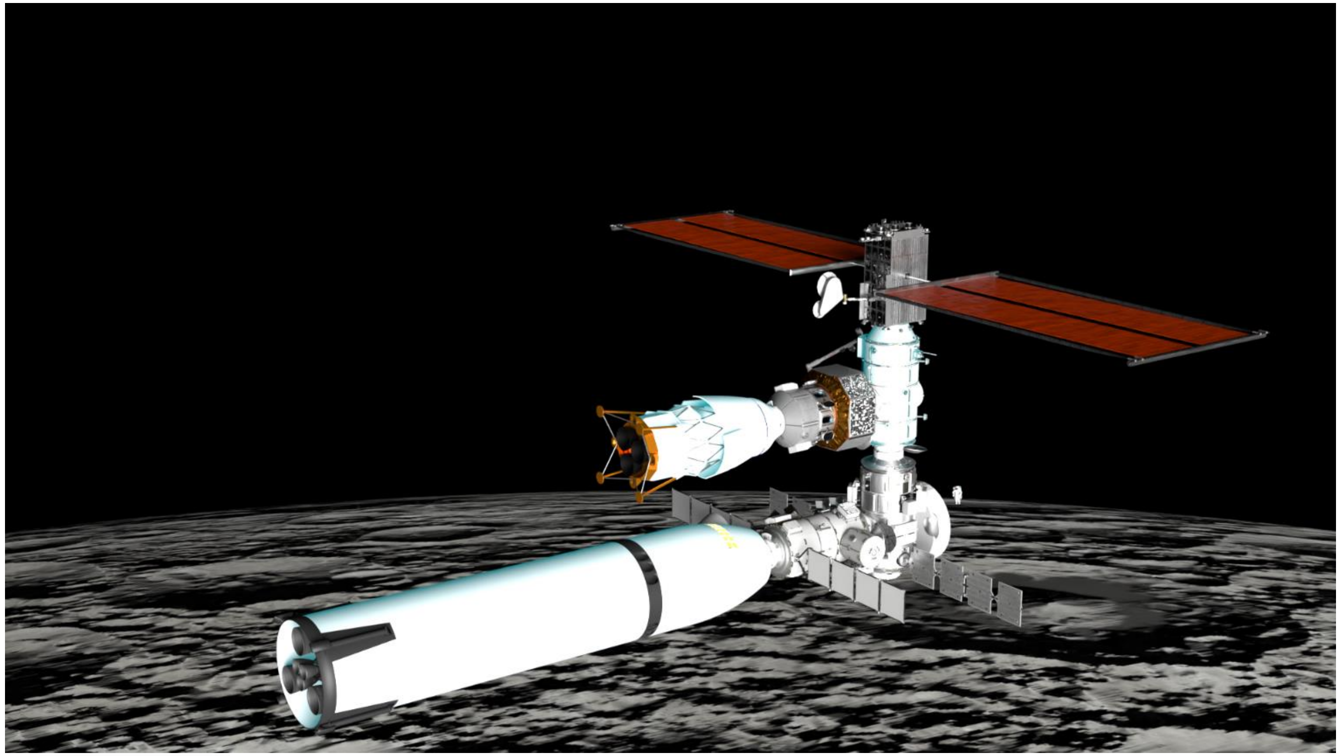


International Space Station (ISS) Oxygen Reclamation Visualization

[1]

Background

- Artemis program aims to establish a lunar base
  - 30-day mission length
  - Electrolysis requires water resupply
- Series-Bosch alternative is impractical
  - >500 °C operating temperature
  - Requires hydrogen



NASA Gateway AETHER Concept

[2],[3]

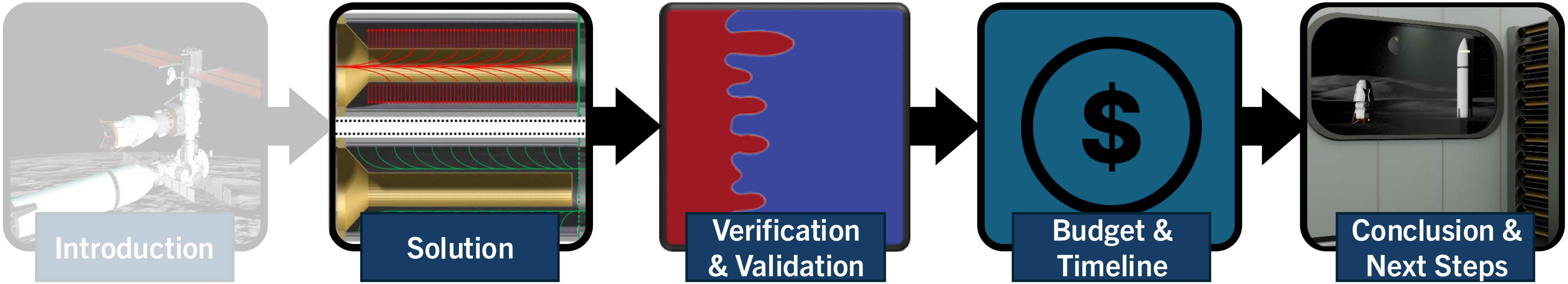
Problem

- Current oxygen reclamation methods are impractical for long-duration manned spaceflight
- Closed-loop, high-yield ECLSS oxygen recovery decoupled from water is required to facilitate extended lunar operations

NASA Moon Base Concept

[4]

Agenda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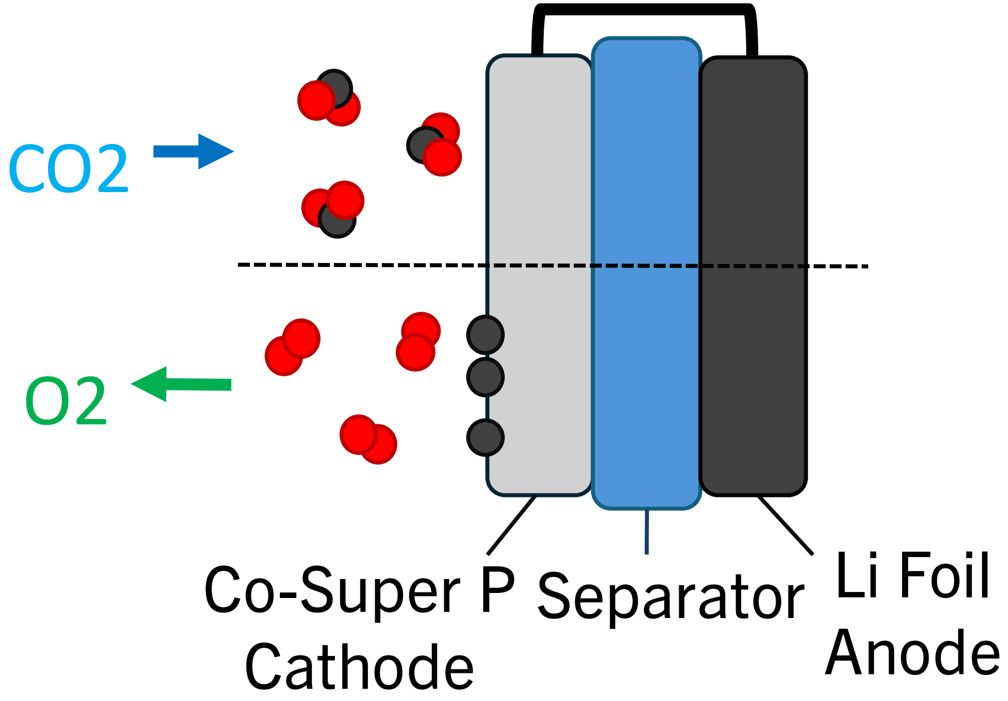
AETHER Overview

Atmospheric Electrochemical Transformation for Habitat and Environmental Regeneration

- Oxygen recovery system
- O_2 recovery yield of 94.7%
- Recovers oxygen by splitting $CO_2 \rightarrow O_2$
- Three electrochemical layers



[5]

AETHER Reactions

$$3CO_2 + 4Li^+ + 4e^- \longrightarrow 2Li_2CO_3 + C \quad (2.80\ V)$$

$$Li_2CO_3 + 4Li^+ + 4e^- \longrightarrow 3Li_2O + C \quad (1.43\ V)$$

$$2Li_2O \longrightarrow 4Li^+ + O_2 + 4e^- \quad (2.91\ V)$$

[5]

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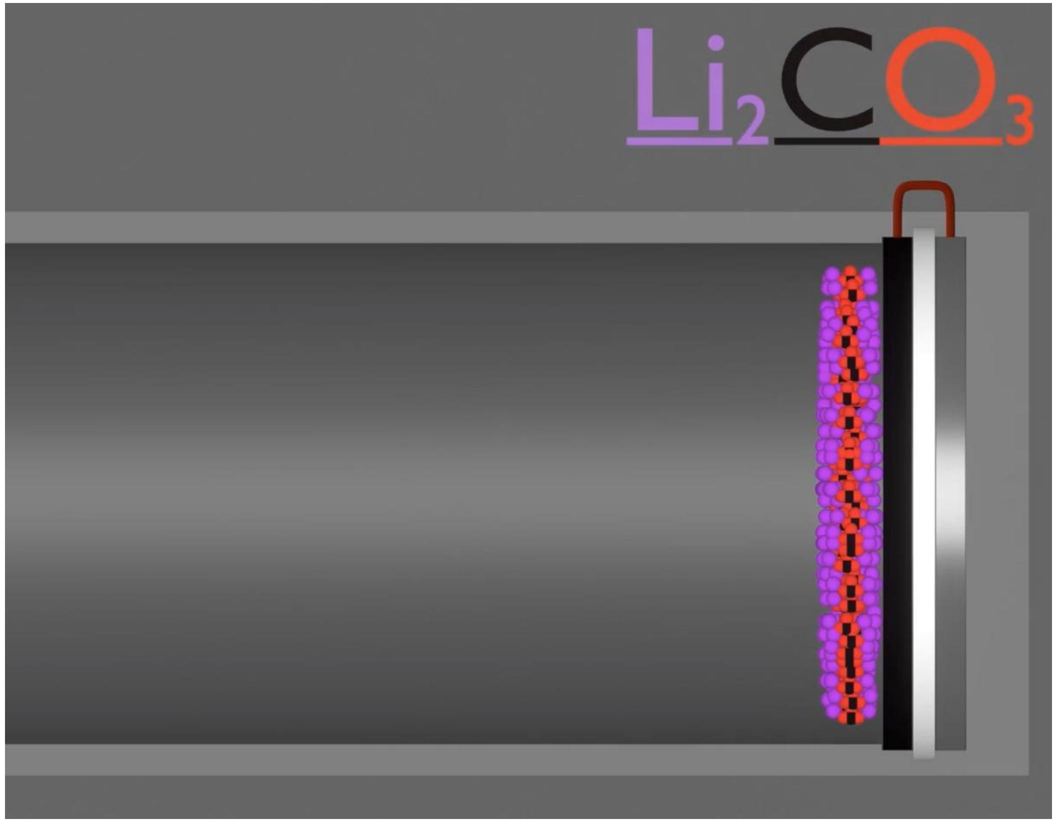

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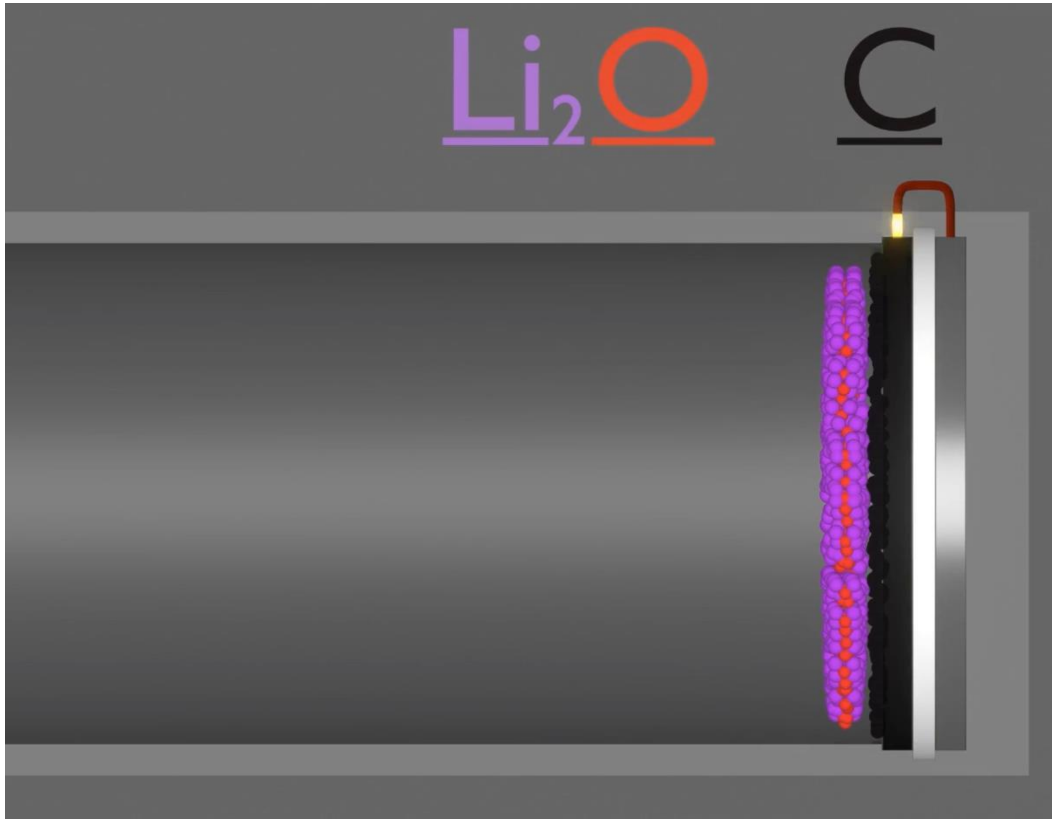
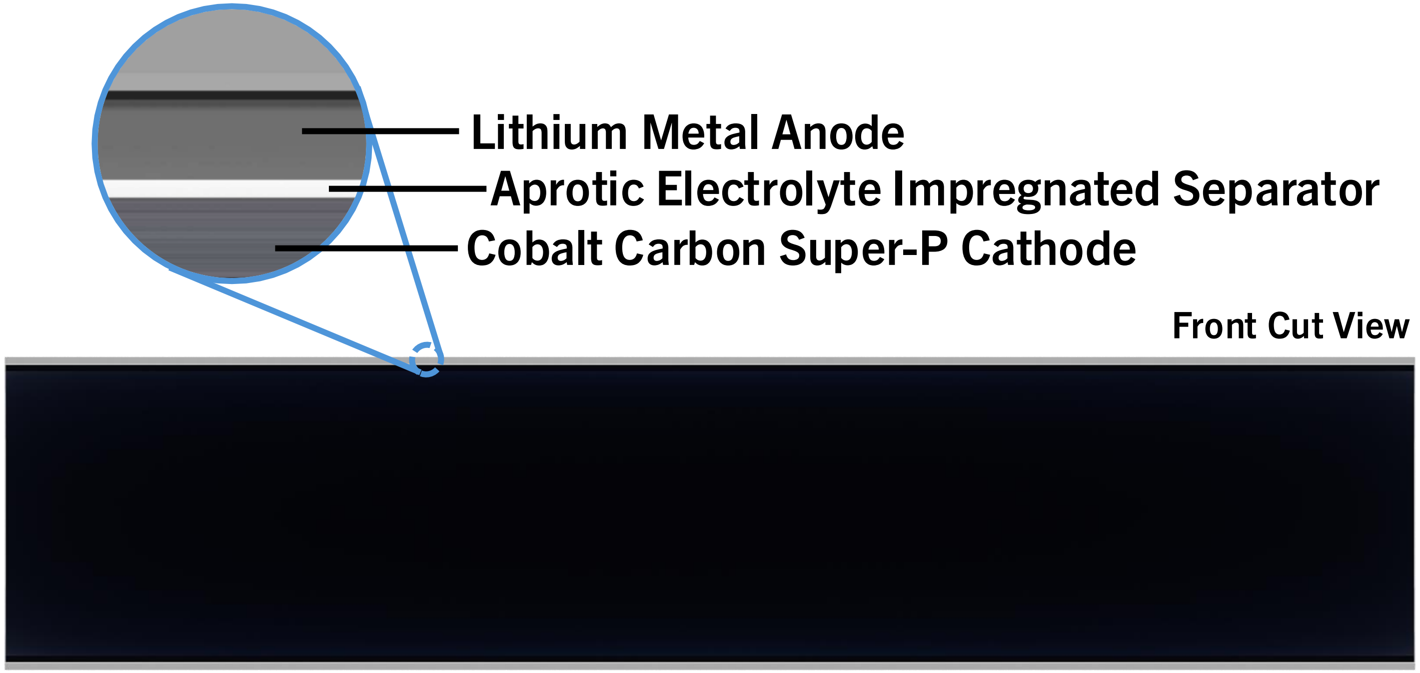
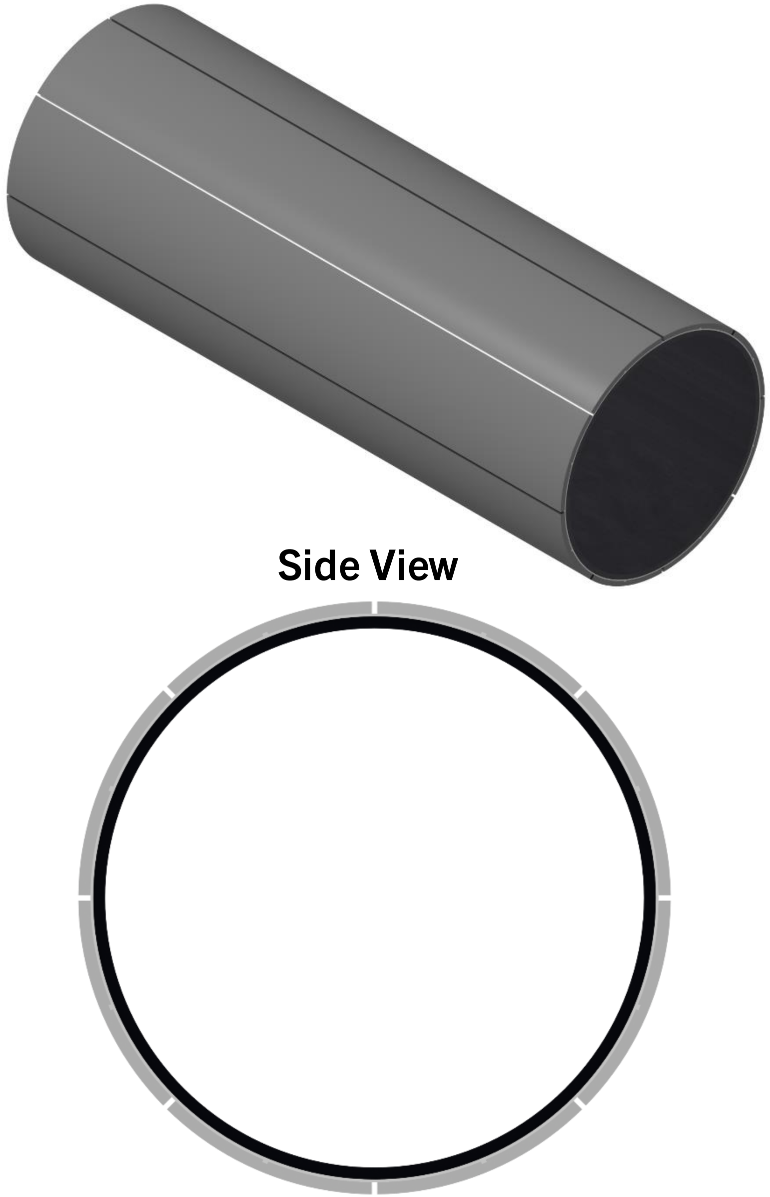


[5]

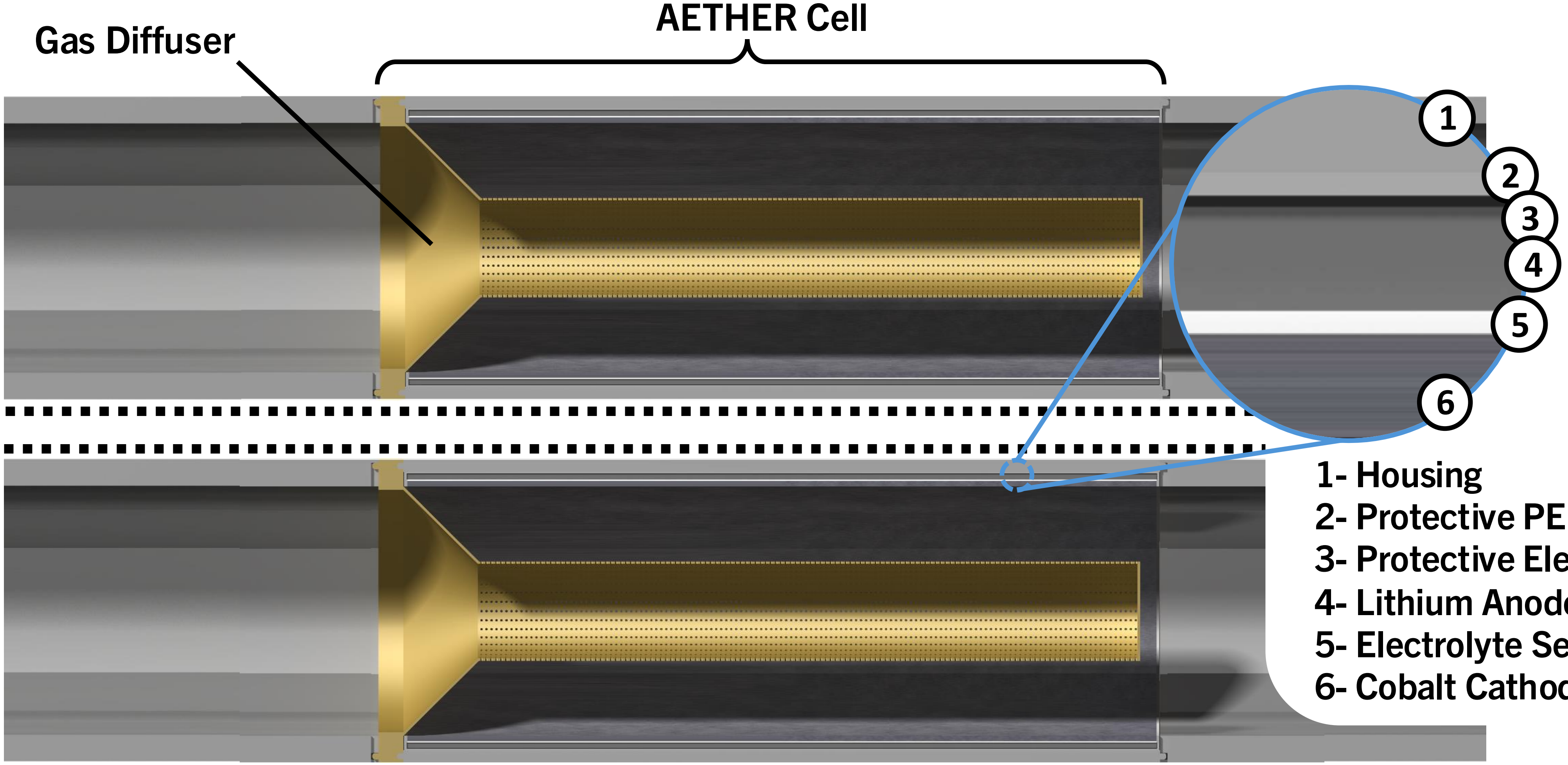
AETHER Layer Geometry

- Electrochemical layers in a cylindrical shape
  - Maximized reaction surface area



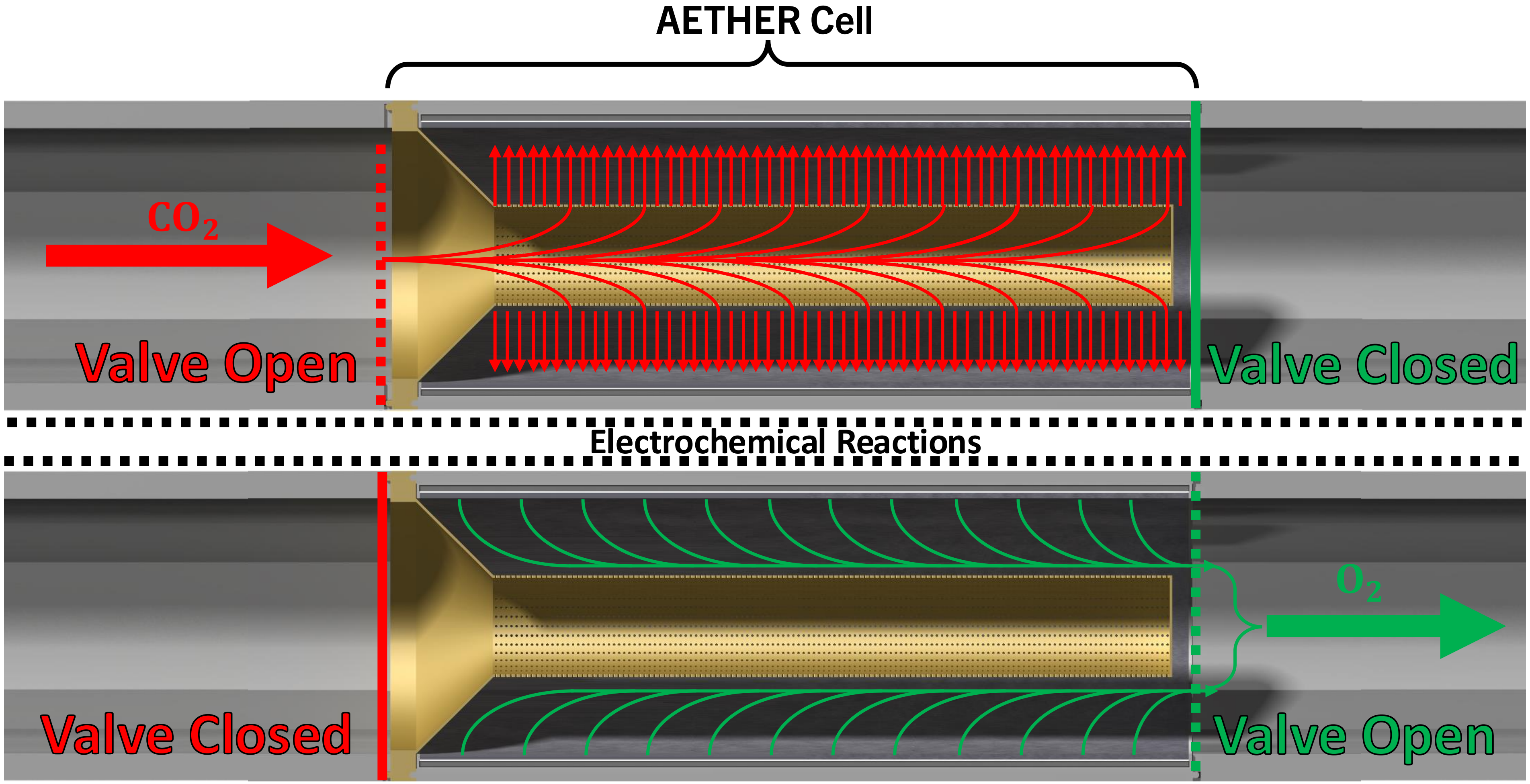


AETHER Layer Geometry: Implemented



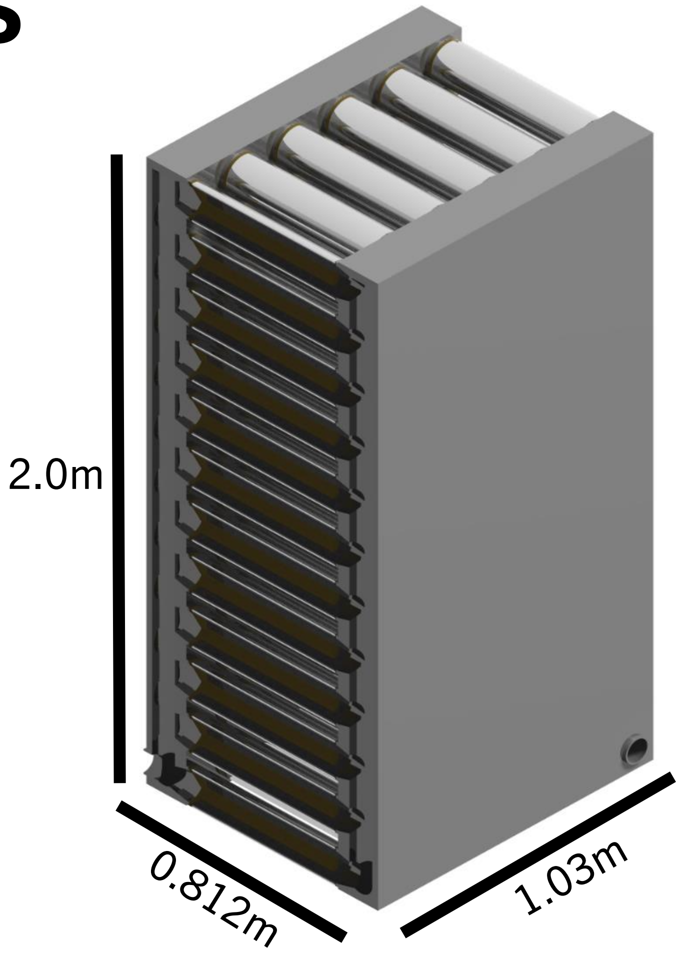
1- Housing
2- Protective PEEK
3- Protective Electrolyte
4- Lithium Anode
5- Electrolyte Separator
6- Cobalt Cathode

AETHER Cell Flow: Implemented



AETHER Analysis Assumptions

- AETHER system consists of 72 cells
  - Total system mass of 514.48 kg with 50% margin
  - Average reaction voltage of 2.38 V
  - Uniform current density of $75.0\,\frac{mA}{cm^2}$
- Crew of 4 astronauts each requiring 0.89 kg of O_2
  - O_2 production margin of 18%
- Bruggeman-Percolation simulations model carbon buildup

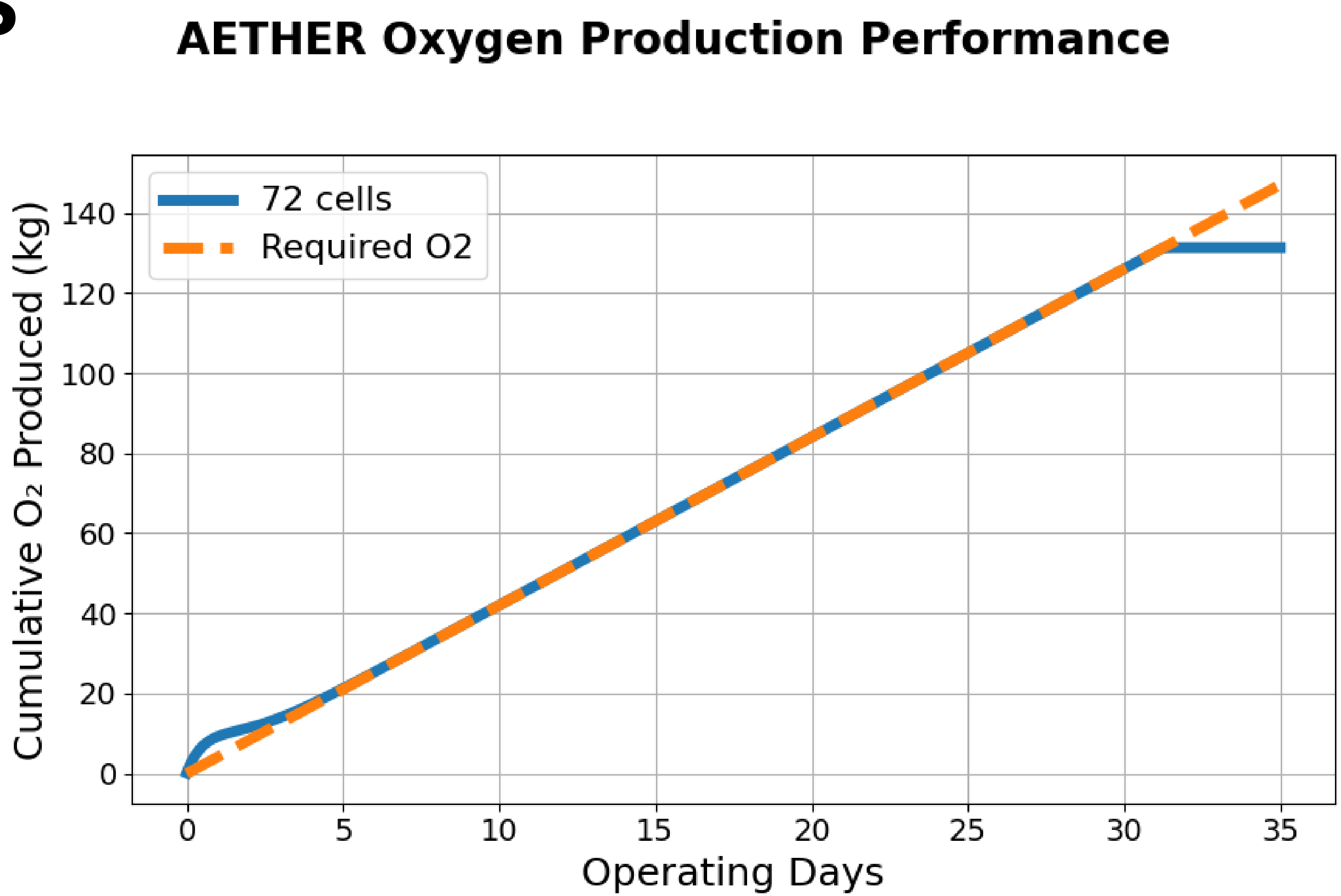


AETHER Rack Dimensions

[2],[5],[6],[7],[8]

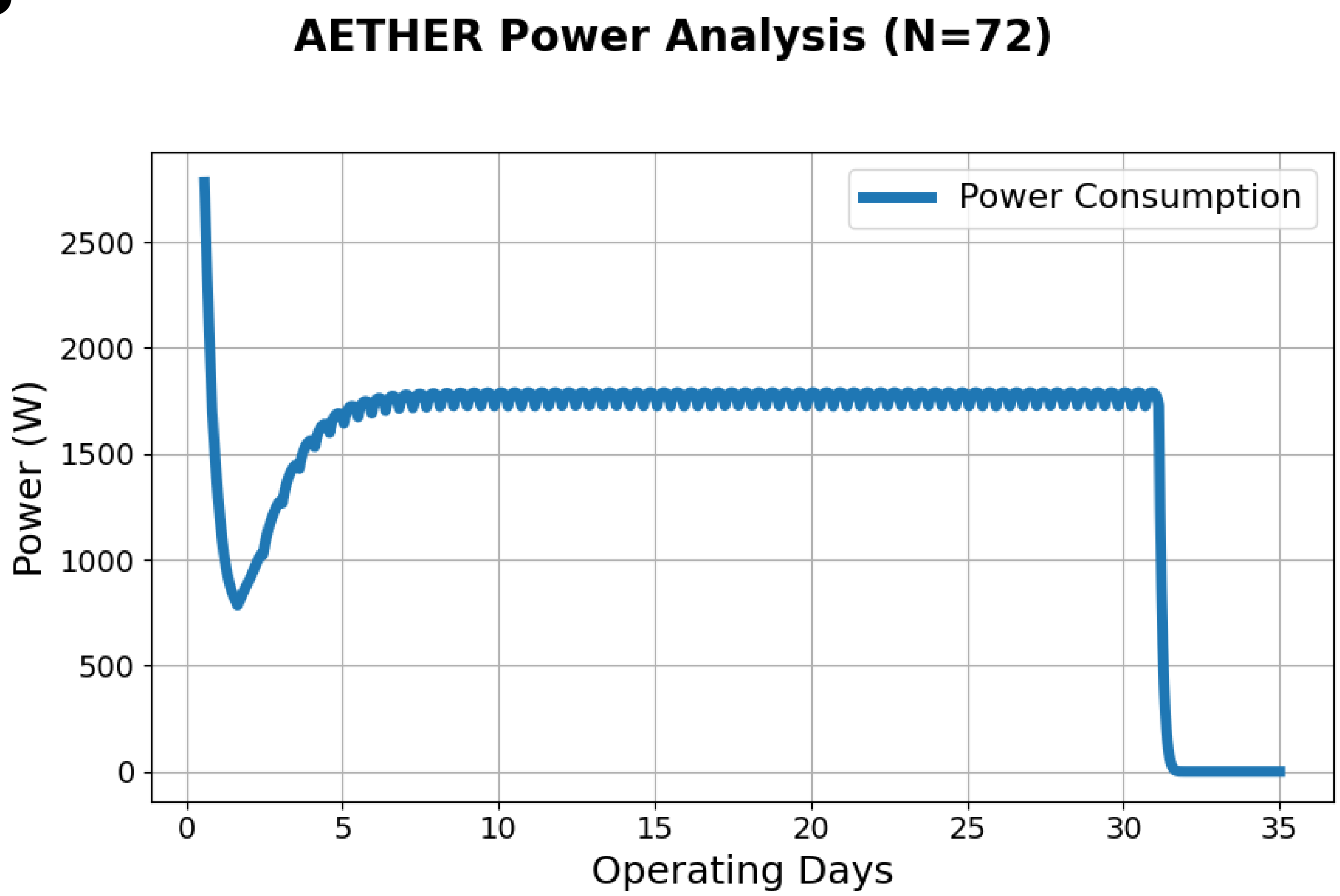
AETHER Analysis

- AETHER meets O_2 production requirement for 4 astronauts
- System loses operational capacity at day 31.32 due to carbon buildup



AETHER Analysis

- AETHER
  - 1.773 kW operational
  - 34.55 kWh over a day
- ISS OGA
  - 3.573 kW operational
  - 0.382 kW idle
  - 36 kWh over a day



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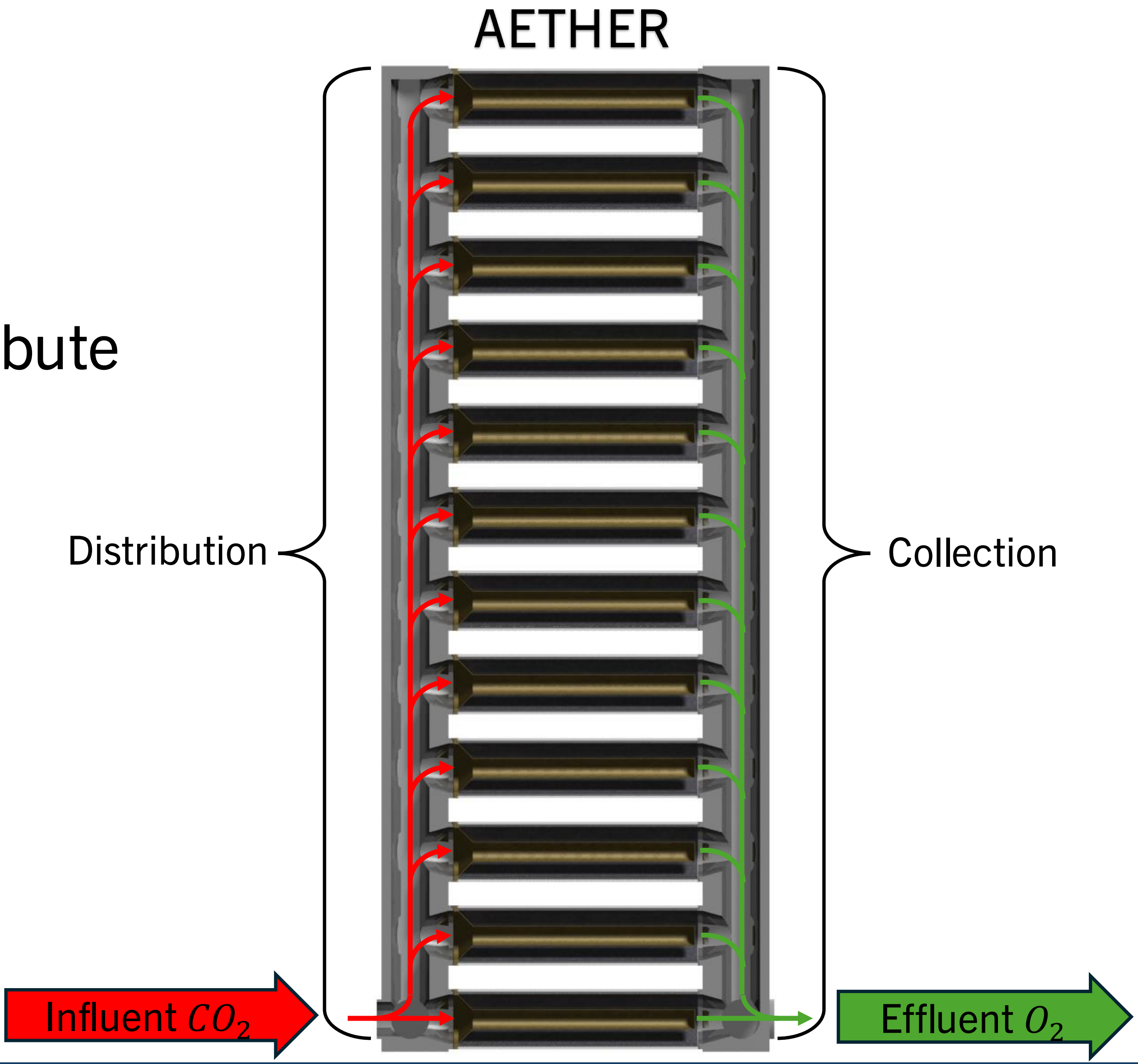
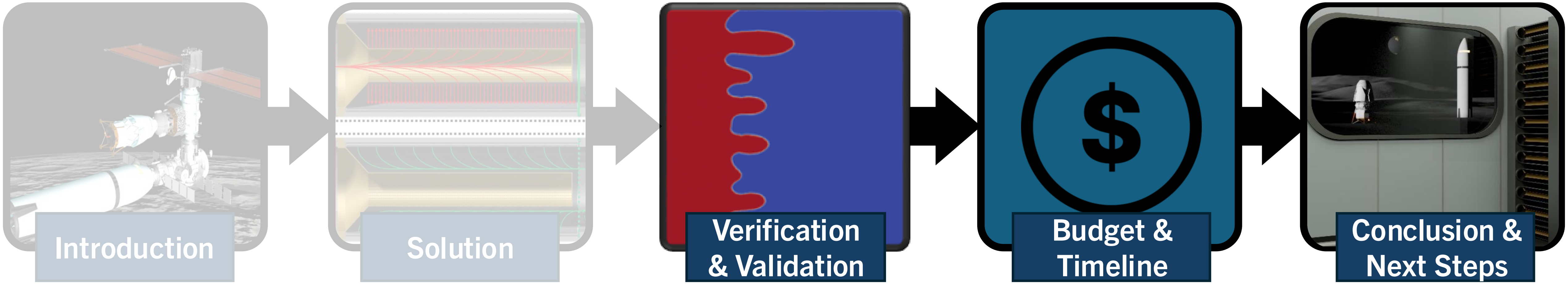
AETHER Design

- Low footprint method to distribute and collect influent/effluent
- Lithium anode surrounded by electrolyte to protect from environment
- Ease of cell replacement
- Scalable to support larger missions



Agenda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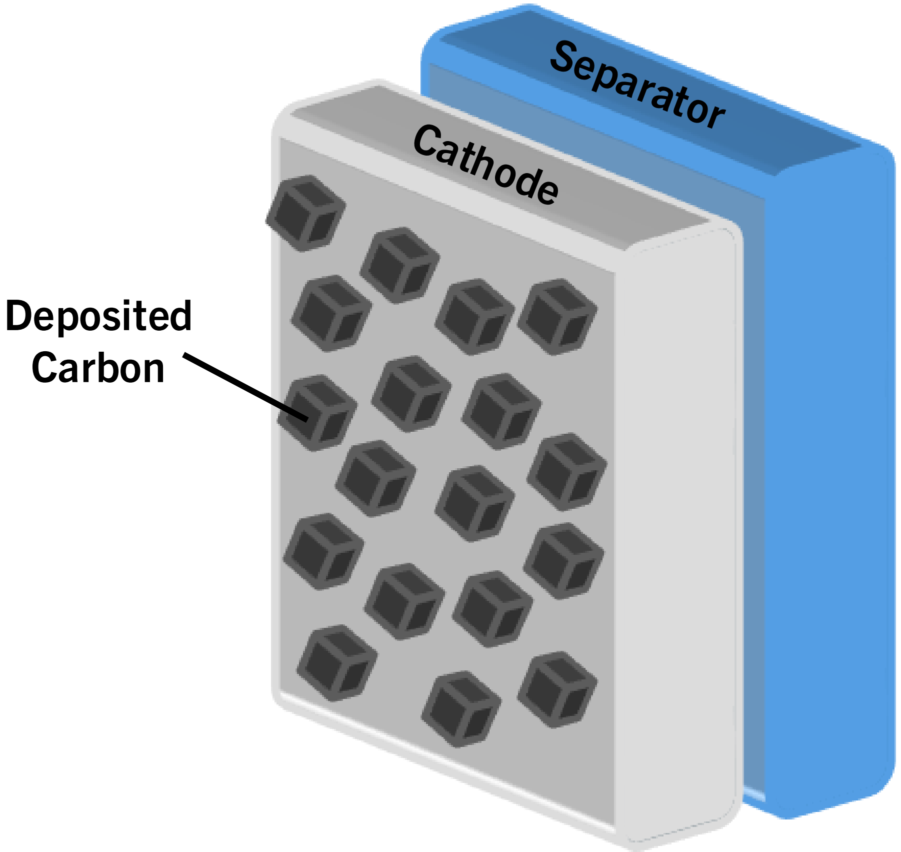
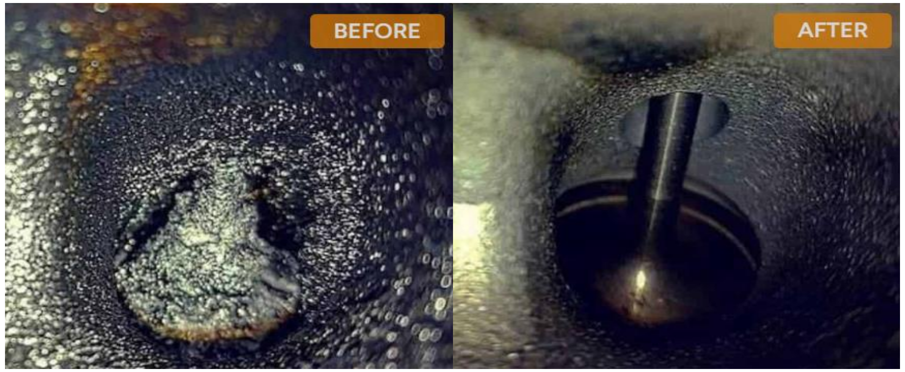
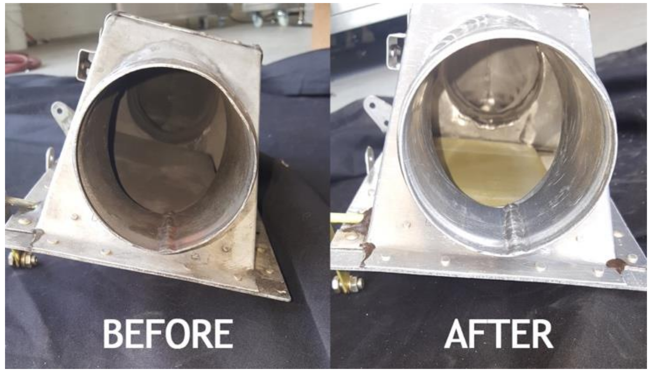
Operational Constraint: Carbon Buildup





Automotive Air Intake Valve With Walnut Blasting

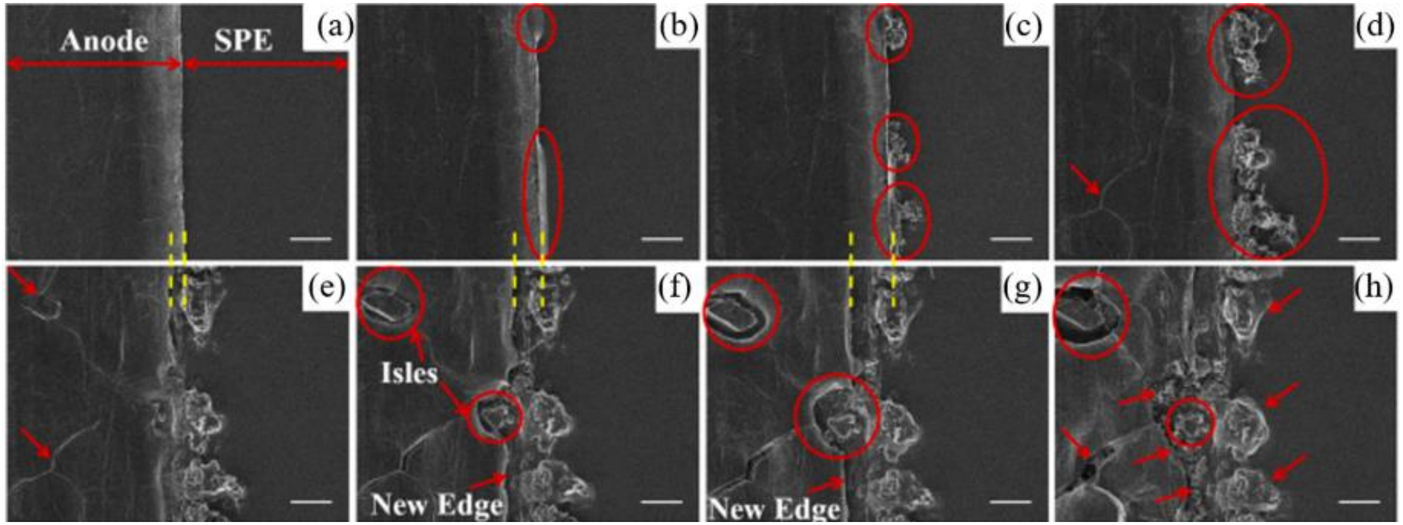


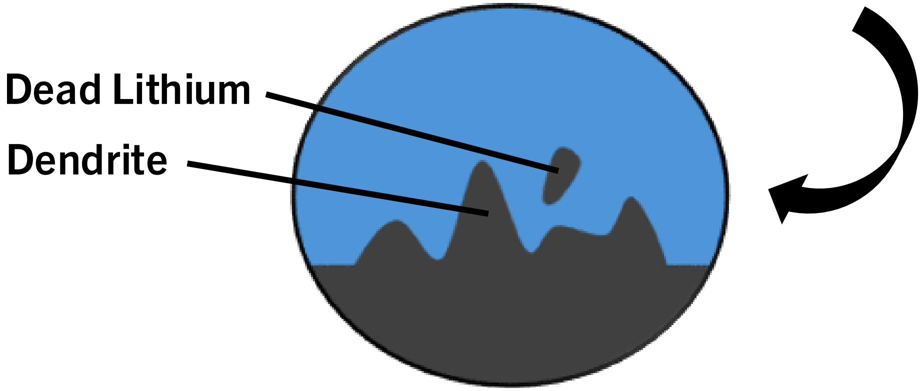
Air Duct With Ultrasonic Cleaning

[9],[10]

Operational Constraint: Dendrite Formation

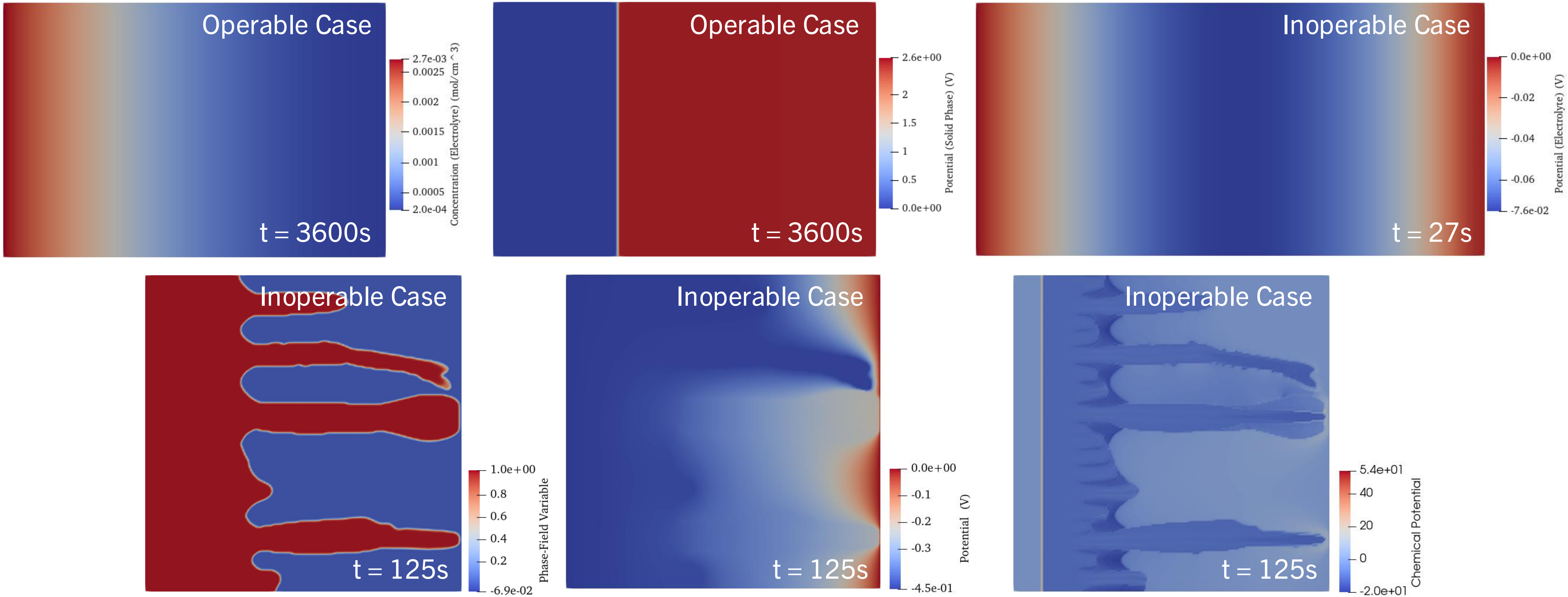
- Lithium crystal growths propagated due to uneven current distribution
- Risk of puncturing the separator
- Risk of losing lithium inventory





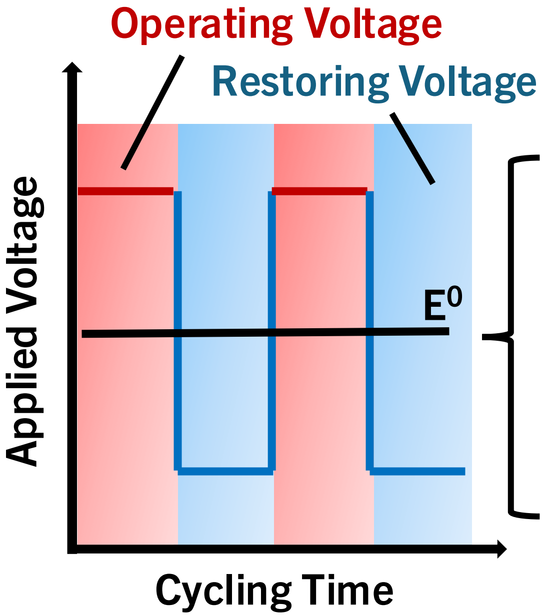
[11]

Simulation: P2D & Dendrite Growth

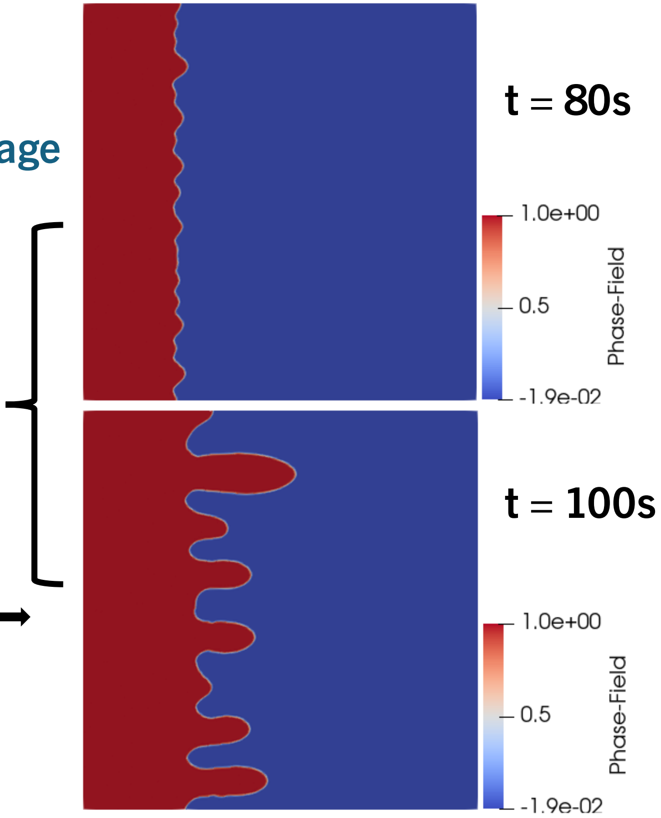


Mitigation Method: Pulsed Voltage

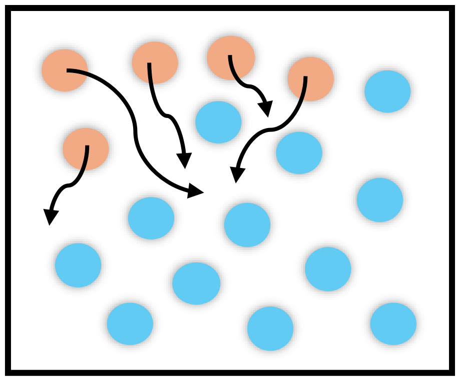
- Pulse above E^0 to resume chemical processes
- Pulse below E^0 to halt chemical processes
- Pulsing promotes self-diffusion of Li^+



Pulsed Voltage Effect On Dendrite Growth



Pulsed Voltage Premise For Clogging Distribution



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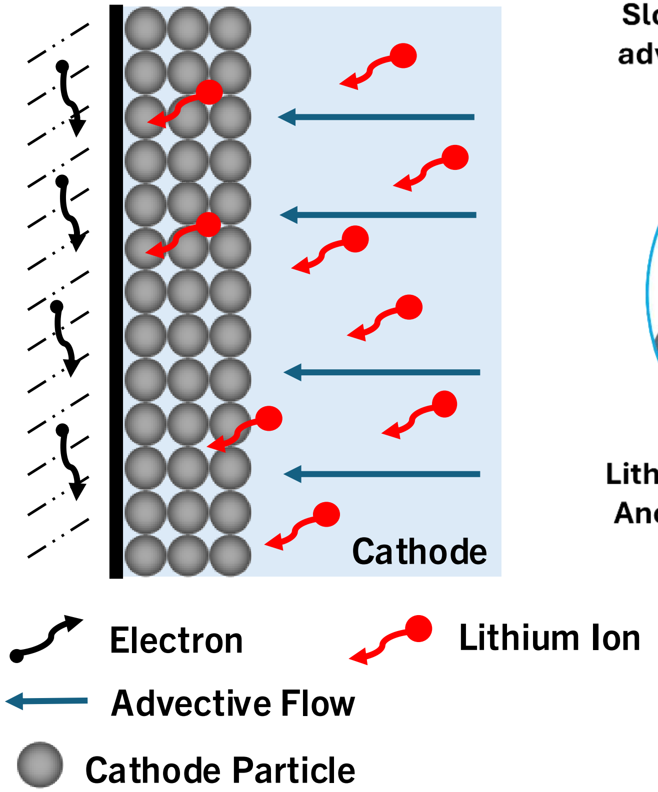
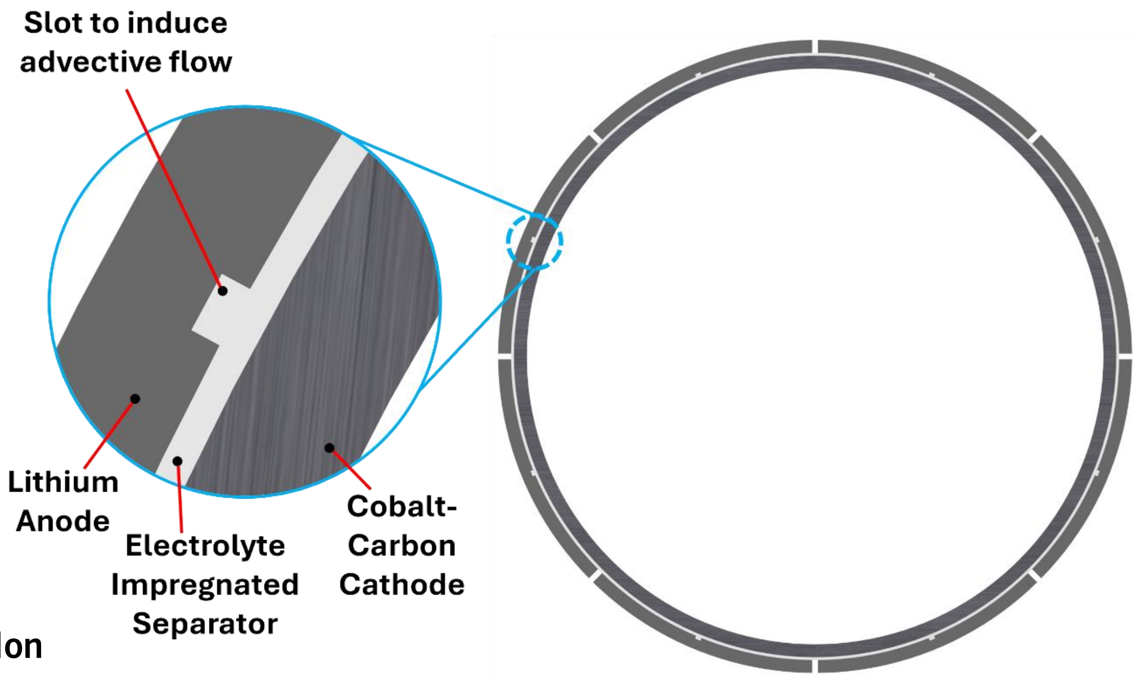
Mitigation Method: Advective Flow

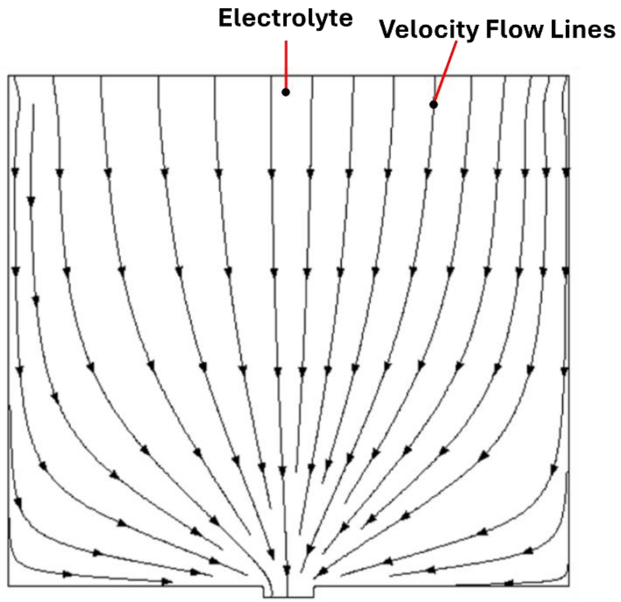
Advective Flow Premise



Advective Flow Full-Scale Implementation



Advection Streamlines



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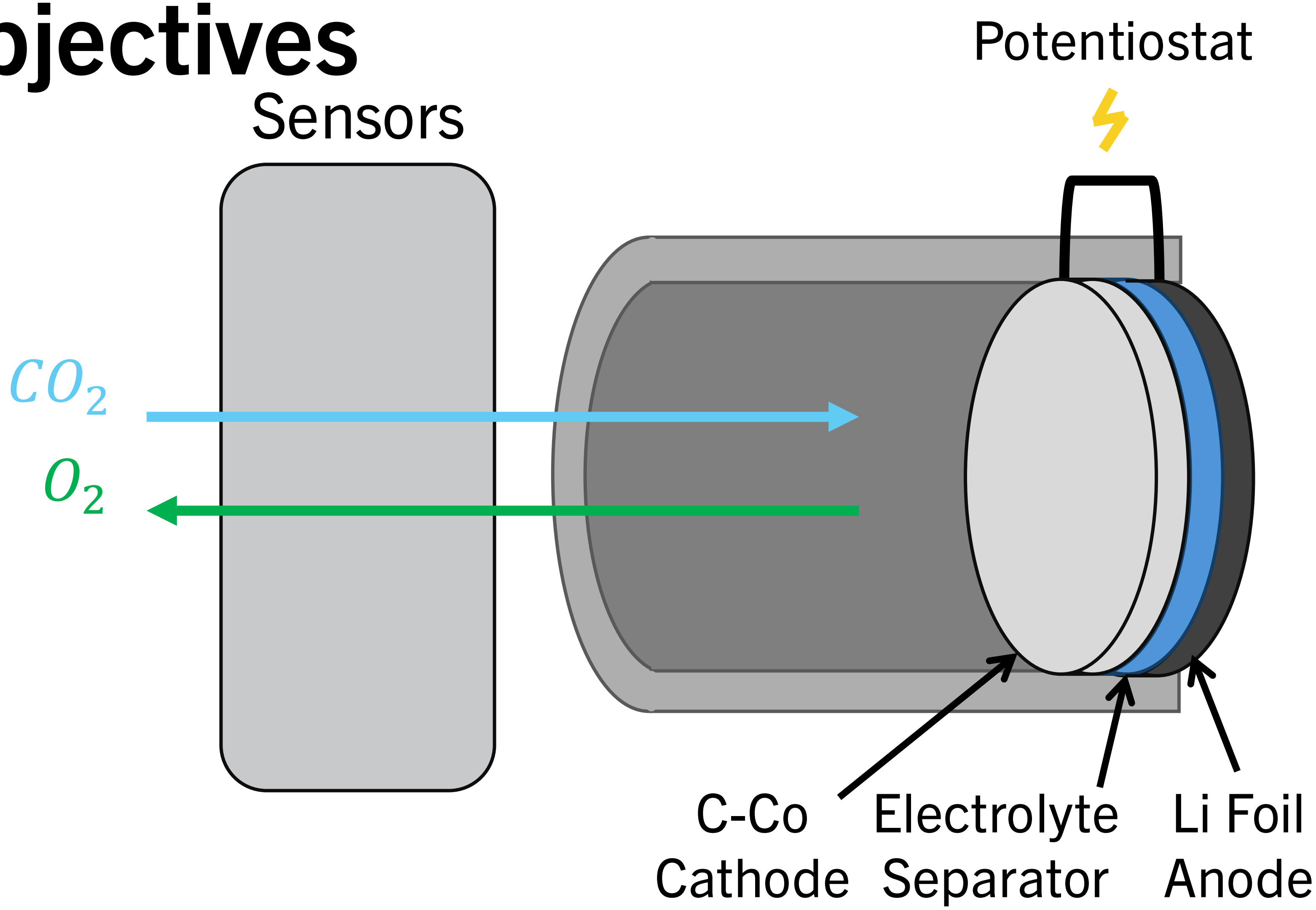
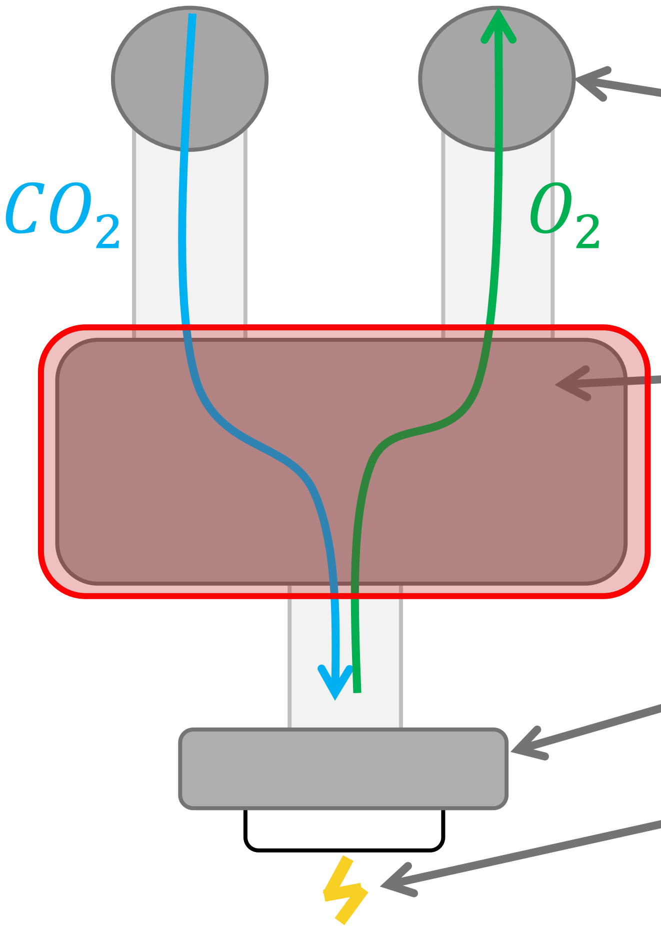
AETHER Test Objectives

- Prove oxygen production in a series of three **consecutive** reactions
- Determine reaction efficiency and system lifespan in practice
- Prove requirements



AETHER Test Design

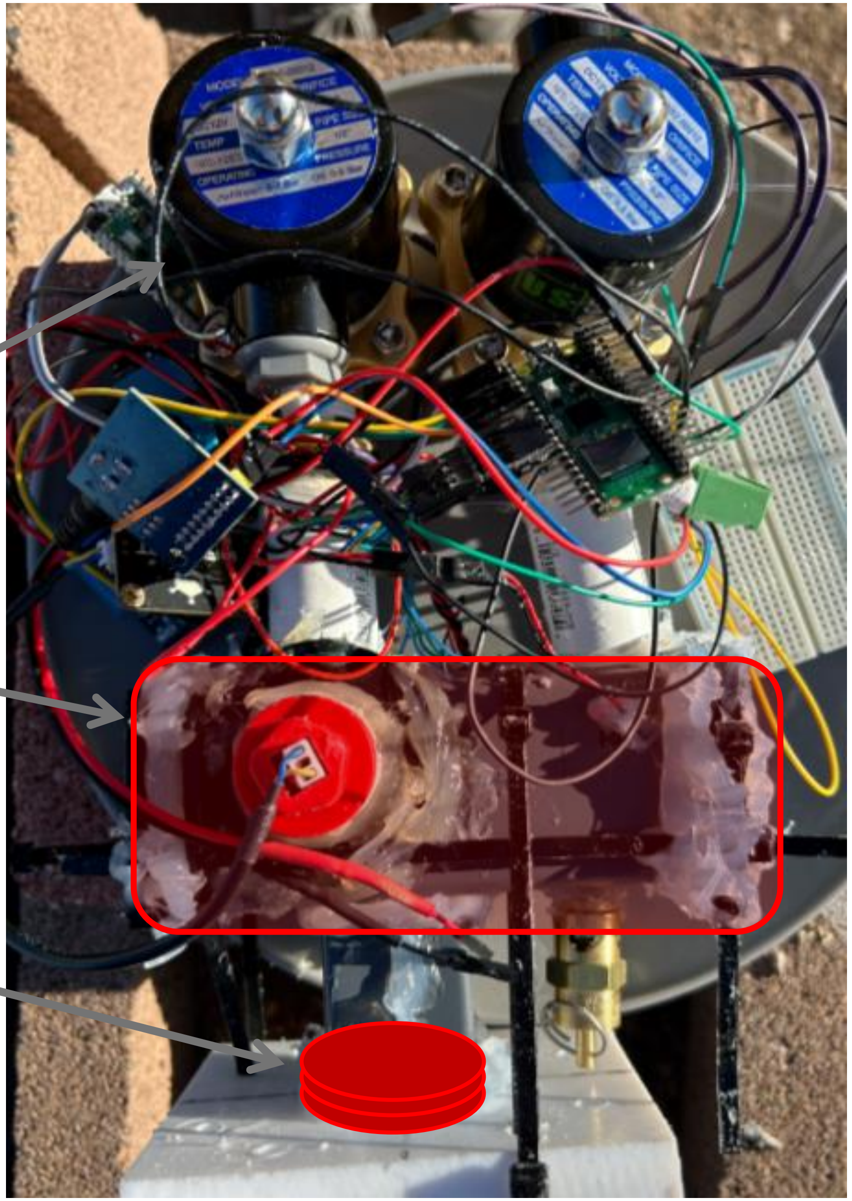


Solenoid Valves (in/out)

Measurement Chamber

AETHER Disks

Potentiostat
(not pictured)



AETHER Technology Validation

Spring 2026

- Housing & pressure structure
- Anode synthesis complete

Fall 2026

- Complete disks
- Integrate disks into housing
- Fully integrated, consecutive reaction

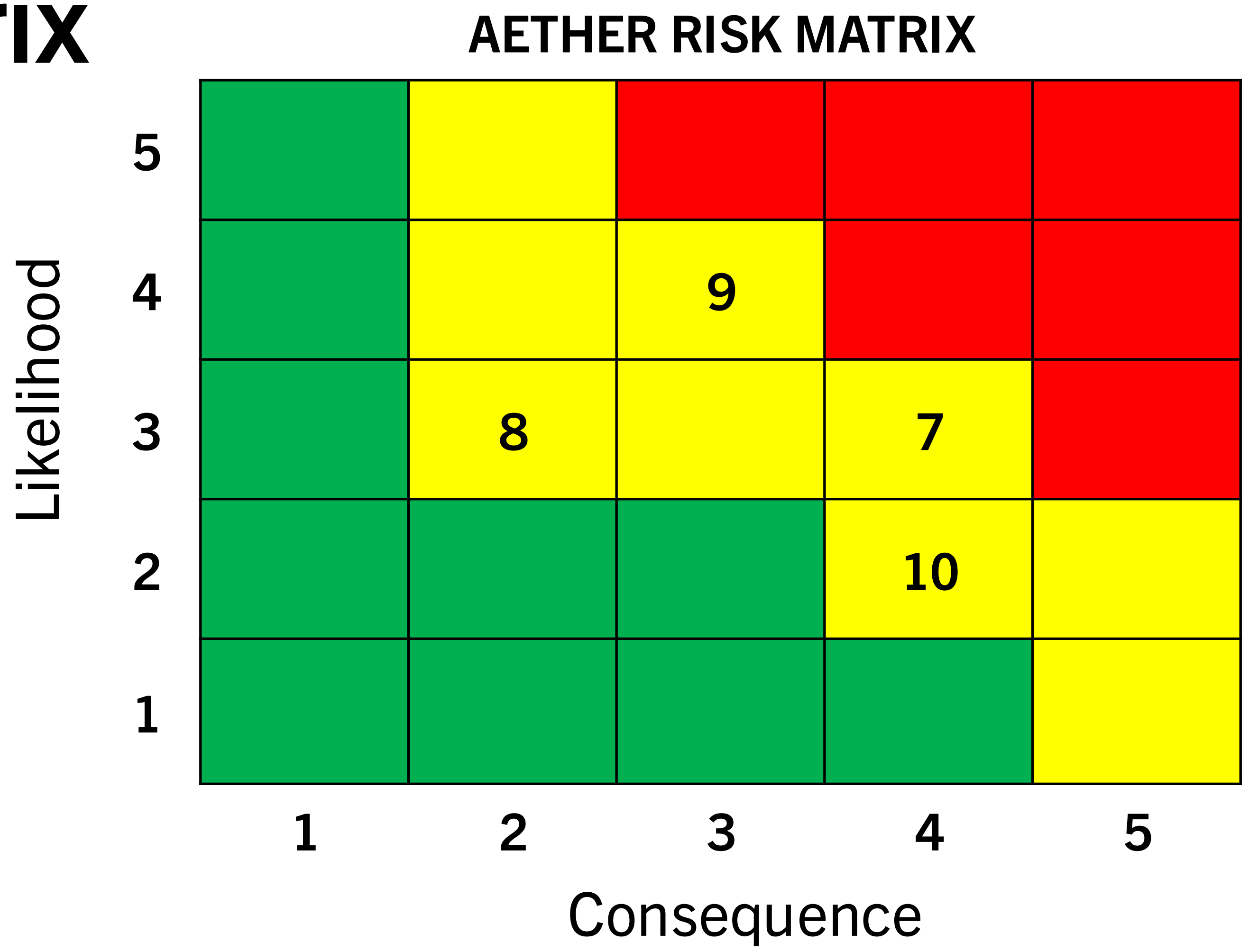
Spring 2027

- Long duration prototype tests to determine maximum lifespan
- Limiting factor mitigation

AETHER Prototype Test Setup

Risk Priority Matrix

9. Carbon Build-Up
10. Dendrite Formation
7. Contaminated Outflow
8. Particulate Build-Up



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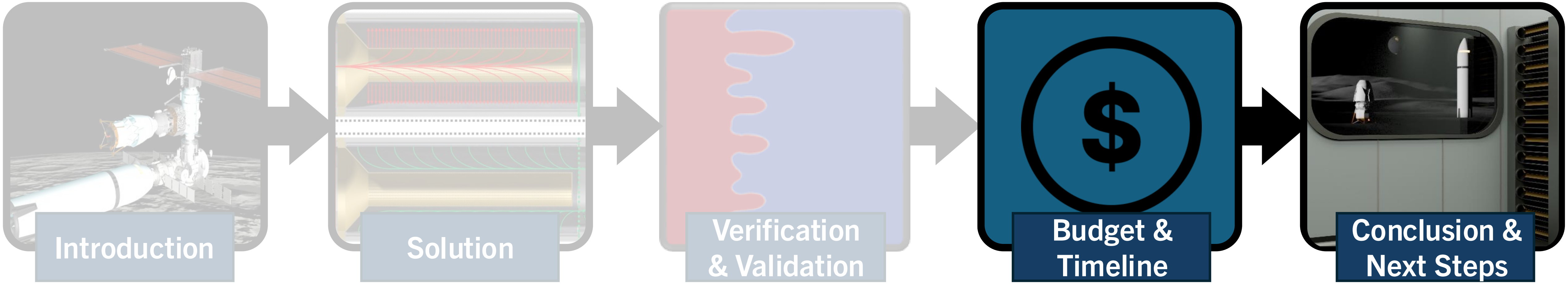
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Budget

- System cost was estimated using PCEC for a 6-month mission with 4 crew members
- CER formula based on ECLSS subsystems for historical launch vehicles
- Assumes an initial weight of 1,137 lb and a resupply weight of 992 lb
- Total Non-Recurring: **$294.7M**; Recurring: **$21.2M**

Cost Phase	FY2015 $M	FY2028 $M
Non-Recurring	223.7	294.7
Design & Development	202.8	267.2
System Test Hardware	20.9	27.6
Flight Unit (Recurring)	16.1	21.2
TOTAL	**239.8**	**315.9**

Budget

- Total Project: **$655.2M**
- 10 employees
- 50% manufacturing margin
- 30% total cost margin

Mission Phase	Phase C	Phase C	Phase D	Phase D	Phase D	
Year	FY 1 (2028)	FY2 (2029)	FY3 (2030)	FY4 (2031)	FY5 (2032)	Total ($K)
PERSONNEL						
Science Personnel	80	82	84	86	88	421
Engineering Personnel	320	328	337	345	353	1,683
Technicians	60	62	63	65	66	316
Administration Personnel	120	123	126	129	132	631
Project Management	240	246	252	259	265	1,262
Total Salaries	820	841	863	884	905	**4,313**
Total ERE	229	235	241	247	253	**1,204**
TOTAL PERSONNEL	1,049	1,076	1,103	1,131	1,158	**5,517**
DIRECT COSTS						
System Cost (from CER)	63,180	64,823	66,465	68,108	69,751	332,327
Manufacturing Margin (50%)	31,590	32,411	33,233	34,054	34,875	166,163
Total Direct Costs	94,770	97,234	99,698	102,162	104,626	**498,490**
FINAL COST CALCULATIONS						
Total Projected Cost	95,819	98,310	100,801	103,293	105,784	**504,007**
Total Cost Margin (30%)	28,746	29,493	30,240	30,988	31,735	**151,202**
Total Project Cost	124,565	127,803	131,042	134,281	137,519	**655,209**

Timeline – 7 Year Plan

- 14 months for additional tests and preliminary design
- 28 months for detailed design and system integration
- 38 months for integrated and environmental testing
  - Conducted with the rest of the spacecraft

May 2027
- Technology Completion

Dec 2027
- PDR
- Detailed Design

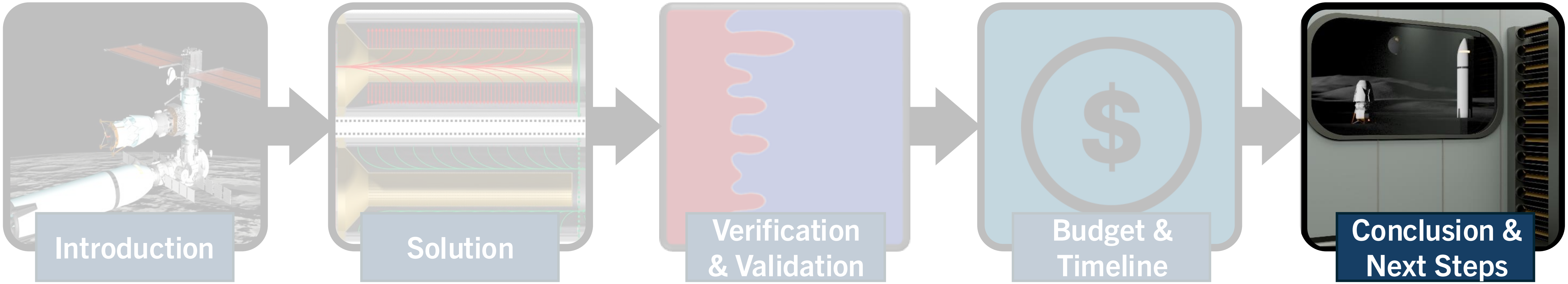
Sept 2028
- CDR
- Fabrication

Nov 2029
- Develop System Confidence

Nov 2029
- SIR
- System Integration

Aug 2032
- ORR
- Prepare for Operations

Agenda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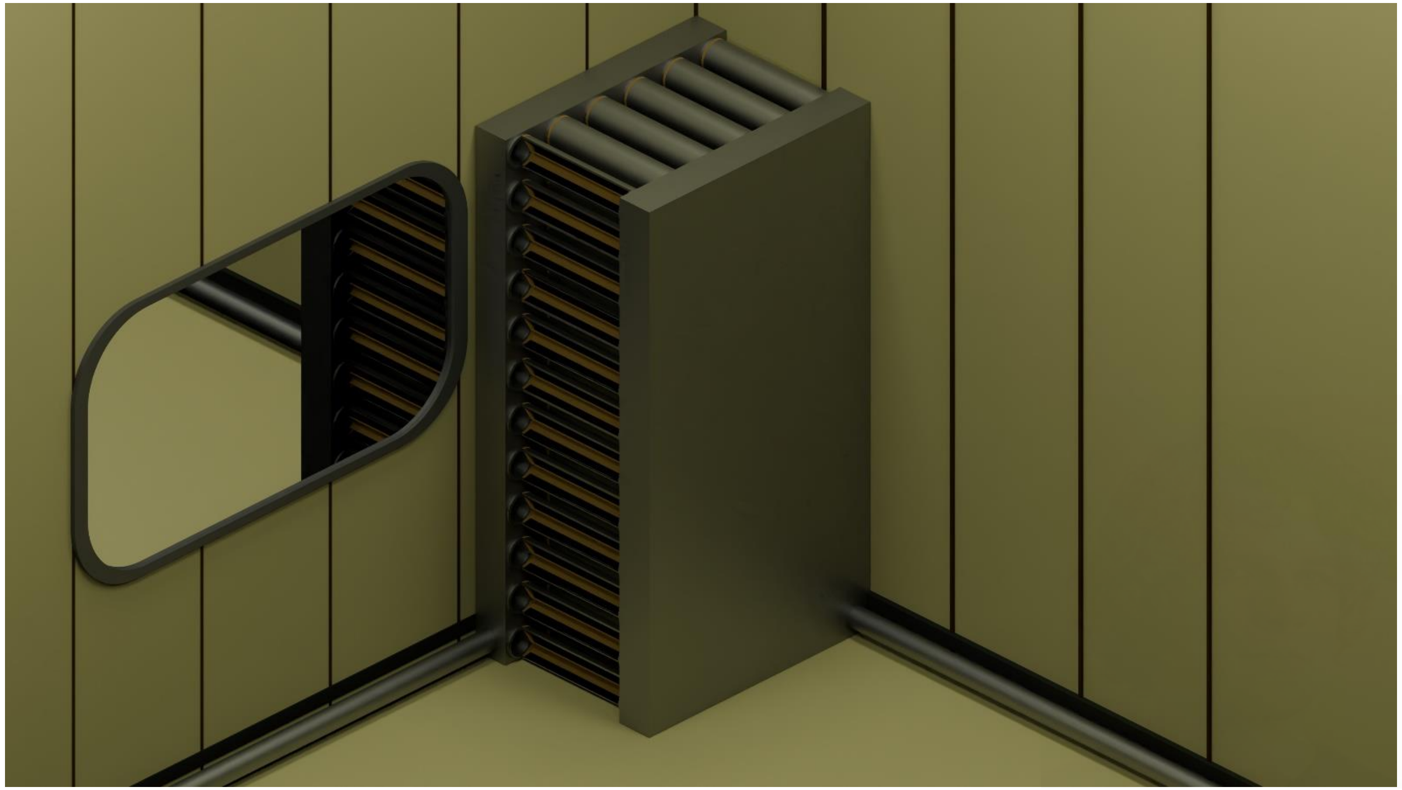
Conclusion

- AETHER fulfills all key mission requirements
- Advantages of AETHER Architecture
  - Theoretical yield of 94.7%
  - Less reliance on ECLSS infrastructure
  - Closing the loop



Full-Scale AETHER Concept Render

[5],[13]

Future Work

- Verify oxygen production
- Test efficiency in relevant environment
- Analyze dendrite formation and product clogging more deeply

AETHER for Lunar Surface Operations Concept

AETHER

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2026 Human Lander Challenge Forum, Huntsville, AL

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Appendix

HLR Req #	High Level Requirements	Verification Method	Status
1-0	System shall be able to withstand Lunar regolith	Analysis	NO DATA
2-0	System shall be able to withstand Martian regolith	Analysis	NO DATA
3-0	System shall yield >50% oxygen reclamation for the duration of a mission	Analysis	MET
3-1	System shall be capable of providing O2 to 4 astronauts per day	Analysis	MET
4-0	System shall use less than 36kWh over 24 hours	Test	MET
4-1	System shall be electronically grounded	Inspection	MET
5-0	Systems' replaceable components must be accessible	Demonstration	MET
6-0	System shall form an electrolyzer cell	Test	MET
7-0	System shall remain in a controlled environment	Test	MET
8-0	System shall have a mass at launch of less than 664.5kg	Inspection	MET
9-0	System shall be scalable	Analysis	MET
10-0	System shall be able to consecutively run all AETHER reactions for a minimum of two-day periods without human interaction	Test	MET

CCR Req #	Critical Level Requirements	Verification Method	Status
1-0	System shall meet NASA standards	Analysis	ON TRACK
1-1	System shall have minimal barriers to NASA adoption	Analysis	ON TRACK
1-2	System shall be cost effective with justified estimates	Analysis	MET
1-3	System shall pose no additional risk to the crew	Analysis	MET
1-4	System shall be targeted for operational use within 5-8 years	Test	MET
2-0	System shall withstand operational environments	Inspection	ON TRACK
2-1	System shall withstand Launch Loads	Demonstration	NO DATA
2-2	System shall last the duration of an average Lunar Mission - 30 Days	Test	ON TRACK
2-3	System shall last the duration of an average Martian mission - 1200 Days	Test	ON TRACK
2-4	System shall be able to withstand radiation exposure	Inspection	NO DATA
3-0	System shall be simple to implement, operate and understand	Test	ON TRACK
4-0	System shall be capable of improving current NASA ECLSS systems	Test	MET

Current Testing Status

Test	Objective	Status
Power and Electronics Integration Test	Verify sustainable power and accurate sensor readings	**Successful**
Glovebox Pressure Test	Ensure glovebox integrity	**Successful**
Planetary Ball Mill Cathode Synthesis	Prepare carbon cobalt for synthesis	**Successful**
Lithium Anode Synthesis	Construct lithium anode	**Successful**
Cathode and Electrolyte Synthesis	Fully construct cathode and electrolyte separator	**In Progress**
Final AETHER Testing	Test fully integrated AETHER system	**Not Complete**

Requirement Compliance Review

HLR Req #	Required Value	Value	Compliance Type	Related Slide	Compliance Status
1-0	-	-	Simulation Test		NO DATA
2-0	-	-	Integration & Simulation Test		NO DATA
3-0	>50%	94.6%	Literature Review		MET
3-1	4	4	Analysis		MET
4-0	<36 kWh	34.55 kWh	Analysis		MET
4-1	-	-	Design		MET
5-0	-	-	Design		MET
6-0	-	-	Design		MET
7-0	-	-	Design & Test		MET
8-0	<664.5 kg	515.48 kg	Analysis		MET
9-0	-	-	Design		MET
10-0	<2 days	34.33 days	Analysis		MET

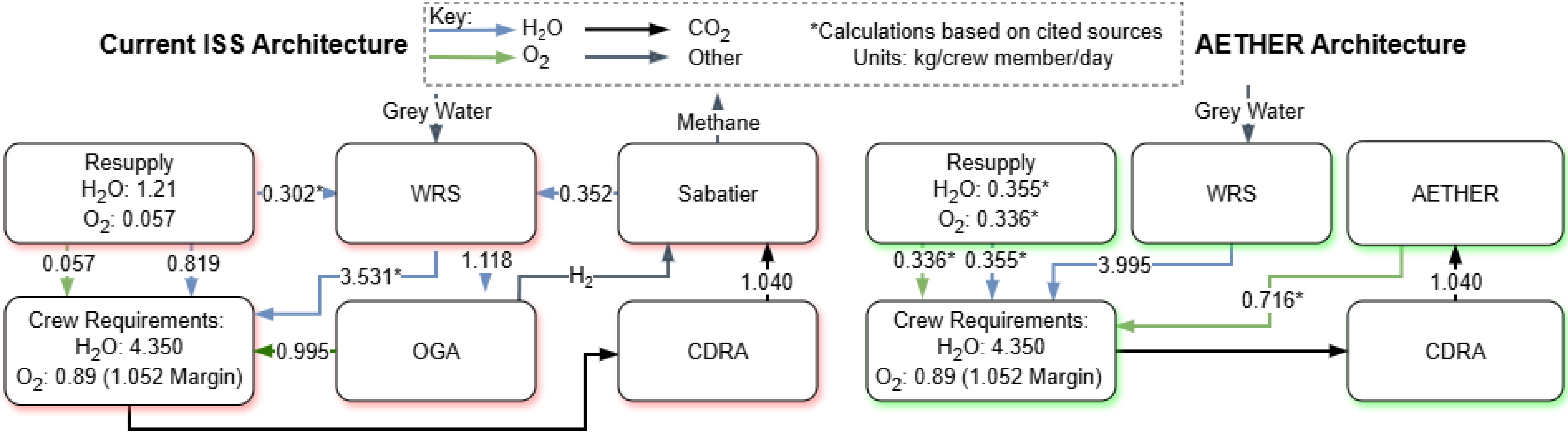
CC Requirement Compliance Review

CCR Req #	Required Value	Value	Compliance Type	Related Slide	Compliance Status
1-0	-	-	Design & Literature Review		ON TRACK
1-1	-	-	Design & Literature Review		ON TRACK
1-2	-	-	Budget		MET
1-3	-	-	Design		MET
1-4	5-8 years	6 years	Timeline		MET
2-0	-	-	Test & Design		ON TRACK
2-1	-	-	Test		NO DATA
2-2	<30 days	-	Test		ON TRACK
2-3	<1200 days	-	Test		ON TRACK
2-4	-	-	Test		NO DATA
3-0	-	-	Design		ON TRACK
4-0	-	-	Design & Literature Review		MET

Requirements Met Via Simulation & Testing

CCR Req #	Critical Level Requirements	Verification Method	Status
2-2	System shall last the duration of an average Lunar Mission - 30 Days	Simulation & Testing	MET
2-3	System shall last the duration of an average Martian mission - 1200 Days	Simulation & Testing	MET

- Forced advective flow complemented with pulsed voltage schemes alleviates dendritic growth
- Pulsed voltage schemes evenly distribute clogging products
- Increased system runtime and oxygen production


Current ISS Architecture
Key:
H_2O
O_2
CO_2
Other
*Calculations based on cited sources
Units: kg/crew member/day
AETHER Architecture
Grey Water
Methane
Resupply
H_2O: 1.21
O_2: 0.057
0.302*
WRS
0.352
Sabatier
0.057
0.819
3.531*
1.118
H_2
1.040
Crew Requirements:
H_2O: 4.350
O_2: 0.89 (1.052 Margin)
0.995
OGA
CDRA
Grey Water
Resupply
H_2O: 0.355*
O_2: 0.336*
WRS
AETHER
0.336*
0.355*
3.995
0.716*
1.040
Crew Requirements:
H_2O: 4.350
O_2: 0.89 (1.052 Margin)
CDRA

[6]

Full-Scale Implementation Risk Matrix

AETHER Implementation Risk Matrix

LIKELIHOOD	1	2	3	4	5
5					
4			9		
3		5, 8		7	
2		6	4	10	
1				11	1, 2, 3

CONSEQUENCES

Full-Scale Implementation Risks

ID	Risk Name	Description	Related Systems	L	C	Method	Plan
1	Cobalt Spontaneous Combustion	Cobalt may spontaneously ignite due to its pyrophoric nature, or due to shock, vibrations, or friction, potentially harming system functionality and or crewmembers.	Cathode, Reactants	1	5	M	Electrostatic, ultrafine, and nanoparticle filters will be employed to deny the possibility of uncontrolled cobalt powder exposure to a spacecraft environment.
2	Lithium Oxygenation	Lithium can violently combust when exposed to oxygen, potentially causing damage to personnel, testing materials, and the environment.	Cathode, Reactants	1	5	M	Lithium will only be handled while under an inert Argon atmosphere, and will be stored in an airtight container with an Argon atmosphere.
3	Lithium Hydrogenation	Lithium can violently combust when exposed to water and other hydrogen ions, potentially causing damage to personnel, testing materials, and the environment.	Anode, Reactants	1	5	M	Lithium will only be handled while under an inert Argon atmosphere, and will be stored in an airtight container with an Argon atmosphere.
4	Cathode/Anode Failure	Improper ionization seperator can compromise the capability of the system to reclaim carbon dioxide.	Cathode, Anode	2	3	M	By employing multiple cathode/anode modules a loss of one module can be mitigated. Following a singular module failure the crew must replace the failed module.
5	Lithium Degradation	Lithium has the potential to degrade over time when in contact with atmosphere decreasing efficiency in ion transfer as well as increasing volatility when exposed to hydrogen.	Anode, Reactants	3	2	A	Upon eventual degradation of Lithium anode, a replacement must be installed, ensuring proper disposal procedures in a humidity free environment.

Full-Scale Implementation Risks

6	Humidity Exposure	System exposure to humidity can degrade the cathode and anode leading to a loss in efficiency.	Cathode, Anode, Filtration	2	2	M	Filtration system will employ adequate humidity reduction filters and must be replaced following buildup leading to increase in humidity in the system. Any degraded Anodes or Cathodes should be promptly replaced by the crew.
7	Contaminated Out-flow	AETHER out-flow can be contaminated with Carbon, Cobalt, or PTFE dust which may pose a severe health and safety risk to crewmembers.	Filtration	3	4	M	Series of electrostatic, ultrafiltration and nanofilters will be employed to ensure no contaminants exist in AETHER's out flow. If such filters fail proper cleaning or replacement procedures must be conducted to ensure a restoration to full system functionality.
8	Particulate Buildup	AETHER in-flow may contain particulates, which can build-up on the surface of the cathode, leading to a loss in reaction efficiency	Filtration	3	2	M	Nanoscale and Electrostatic filters will be employed to ensure no particulates enter the AETHER reaction chamber. If such filters fail, proper cleaning or replacement procedures must be conducted to ensure a restoration to full system functionality.
9	Carbon Buildup	Carbon extracted from CO2 may deposit onto the cathode, reducing the efficiency of AETHER with a replacement module being required if the buildup hits a criticality point.	Filtration, Cathode, Reactants	4	3	M	Potential methods of mitigation include using walnut shell sand-blasting and supersonic vibrations to remove surface-level carbon.
10	Dendrite Formation	Lithium dendrites may occur along the surface of the anode, reducing the quality of the surface of the anode, thus reducing the reaction effectiveness. Large dendrites have the potential to cause the cathode-anode separator to fail.	Cathode, Reactants	2	4	M	Specialized geometry will be employed to ensure ions are able to move fast enough to reattach to the anode uniformly.

Full-Scale Implementation Risks

11	Electrical Failure	Loss of connectivity between the power source and the cathode/anode can lead to a decrease in system efficiency. Failure of the power source to deliver proper potential difference to the cathode/anode can lead to a decrease in efficiency	Circuitry, Power, Cathode, Anode	1	4	M	Ensure all AETHER modules are wired in parallel as well as redundant power sources. If any connection fails, the crew must follow proper repair procedures to ensure restoration to full system functionality.

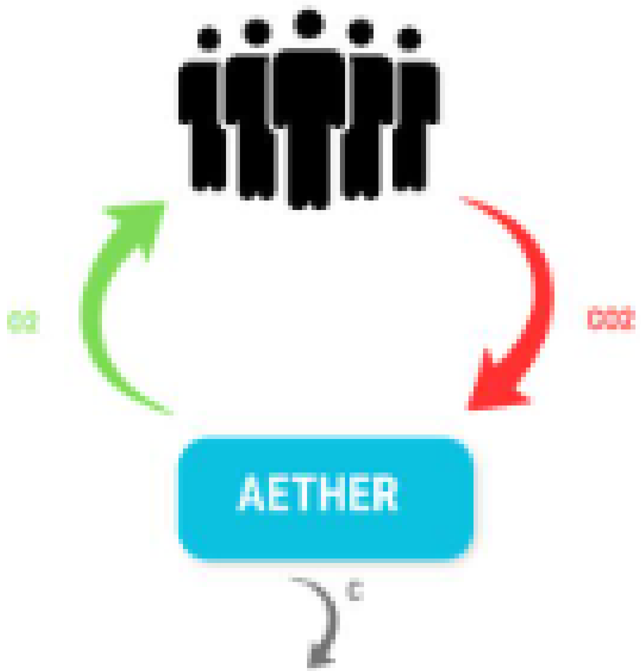
Future Work

CCR Req #	Required Value	Requirement	Compliance Type	Compliance Status
1-0	-	System shall meet NASA standards	Design & Literature Review	ON TRACK
1-1	-	System shall have minimal barriers to NASA adoption	Design & Literature Review	ON TRACK
2-0	-	System shall withstand operational environments	Test & Design	ON TRACK
2-1	-	System shall withstand Launch Loads	Test	NO DATA
2-2	<30 days	System shall last duration of average Lunar Mission	Test	ON TRACK
2-3	<1200 days	System shall last duration of average Martian Mission	Test	ON TRACK
2-4	-	System shall be able to withstand radiation exposure	Test	NO DATA
3-0	-	System shall be simple to implement and operate	Design	ON TRACK

Solution Trade Study

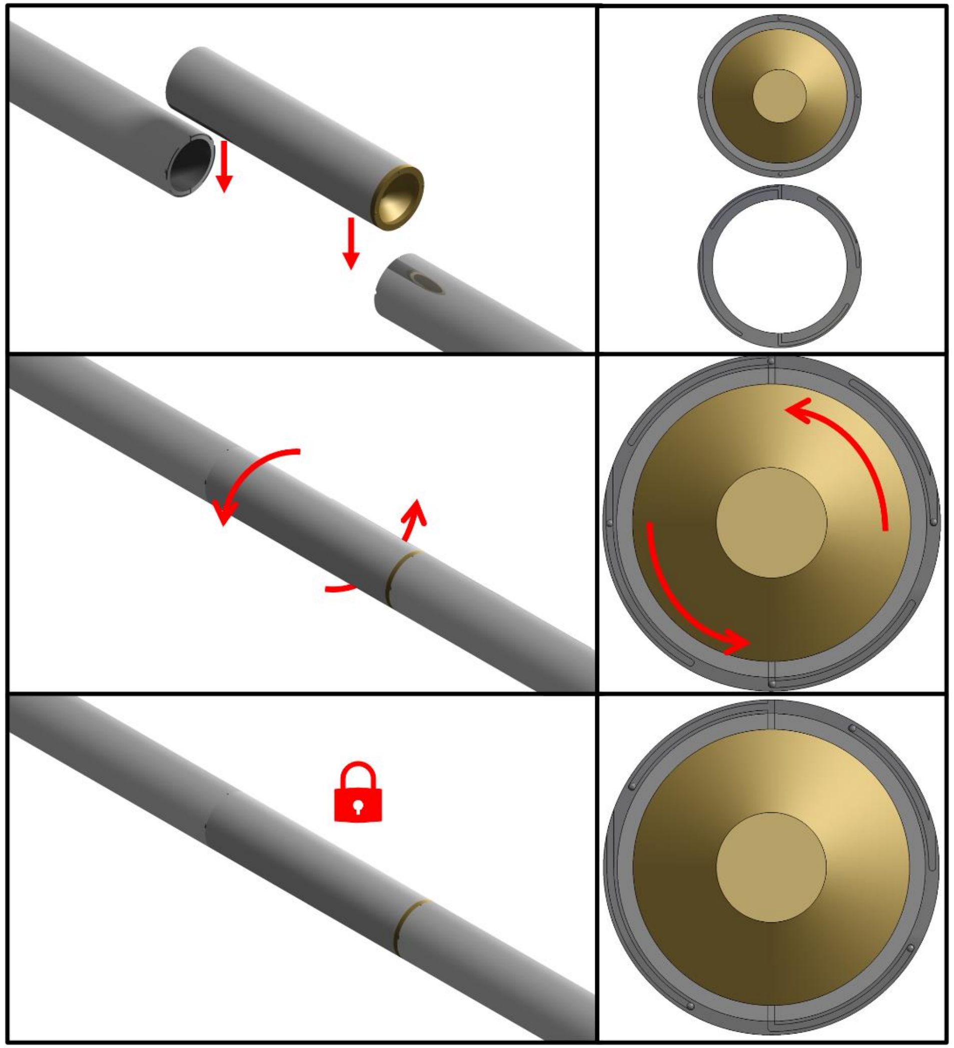
Category			Scores	Trades				
Criteria	y? ('	Weight	Scale	**SEAL**	**AETHER**	**SOMBR**	**ANMS**	**Vortex Filtration**
Past Research		10%	3	2.5	2	3	3	1.5
Fits Within Suggested Challenge Topics		0%	1	1	0	0	1	0
Difficulty within Competition Timeframe		20%	3	1.5	1.5	2.5	1.5	2
Opportunity Afterwards		5%	3	2	3	2.5	2	2.5
Risk to Implementation		10%	3	2.5	2	1.5	2	2.5
Improvement to ECLSS/Innovation		25%	3	2	3	2.5	1.5	2
Testability		15%	3	2.5	2	2.5	3	2.5
Ease-of-Integration into NASA Architecture		10%	3	2	2.5	1	3	2
Interest/Preference		5%	3	1.5	3	2	1.5	1.5
Weighted Total %		100%		68%	77%	76%	70%	69%

Simplified ECLSS System

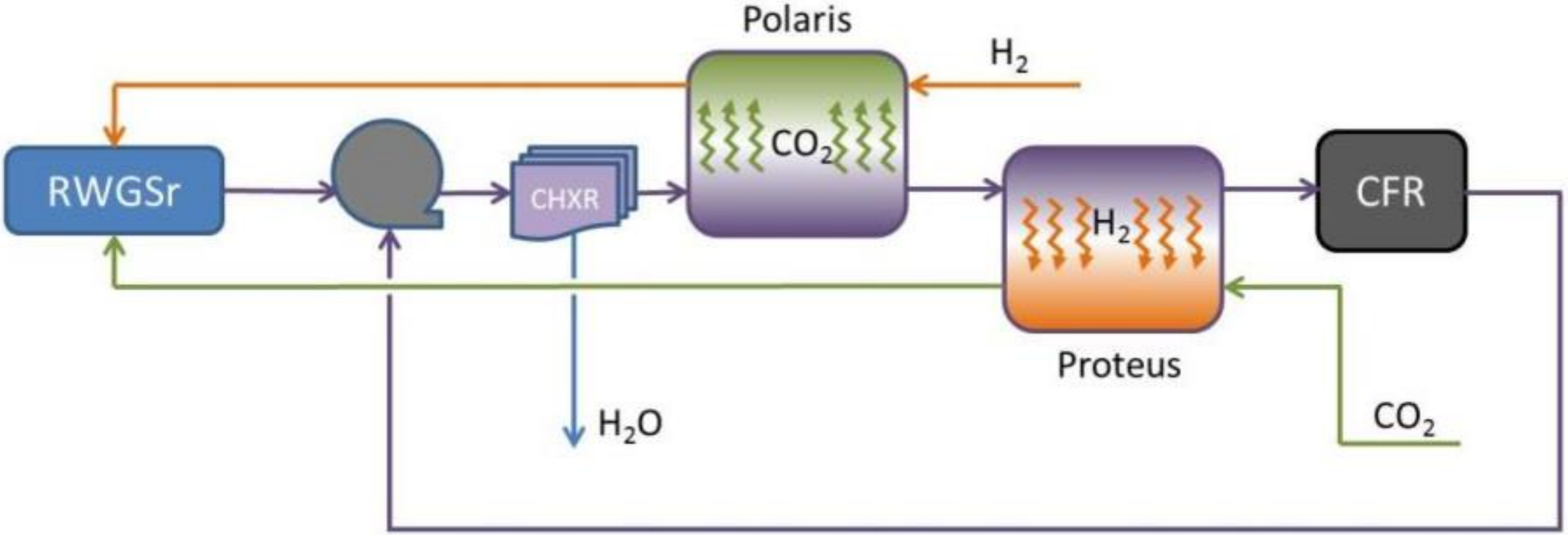


[6]

Ease of Replacement



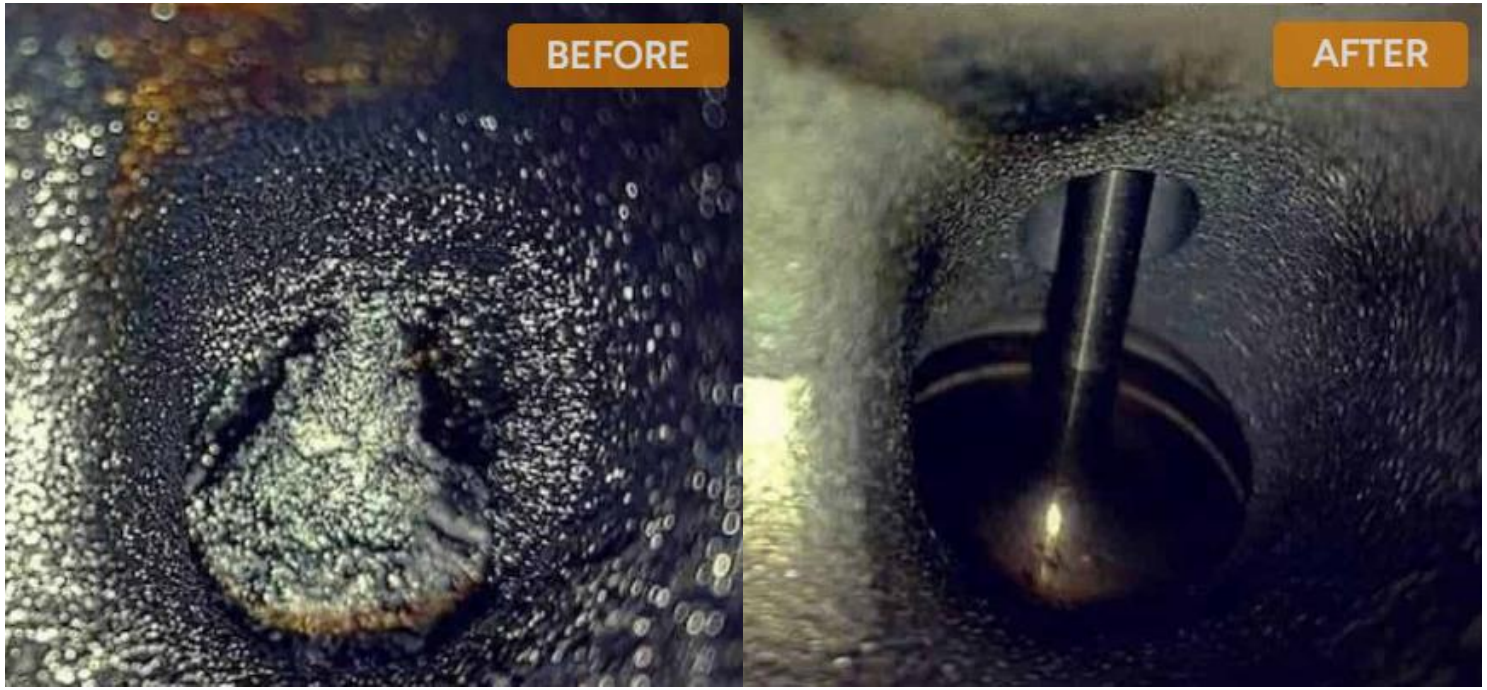
Series-Bosch System



[14]

Carbon Deposition Removal: Walnut Blasting

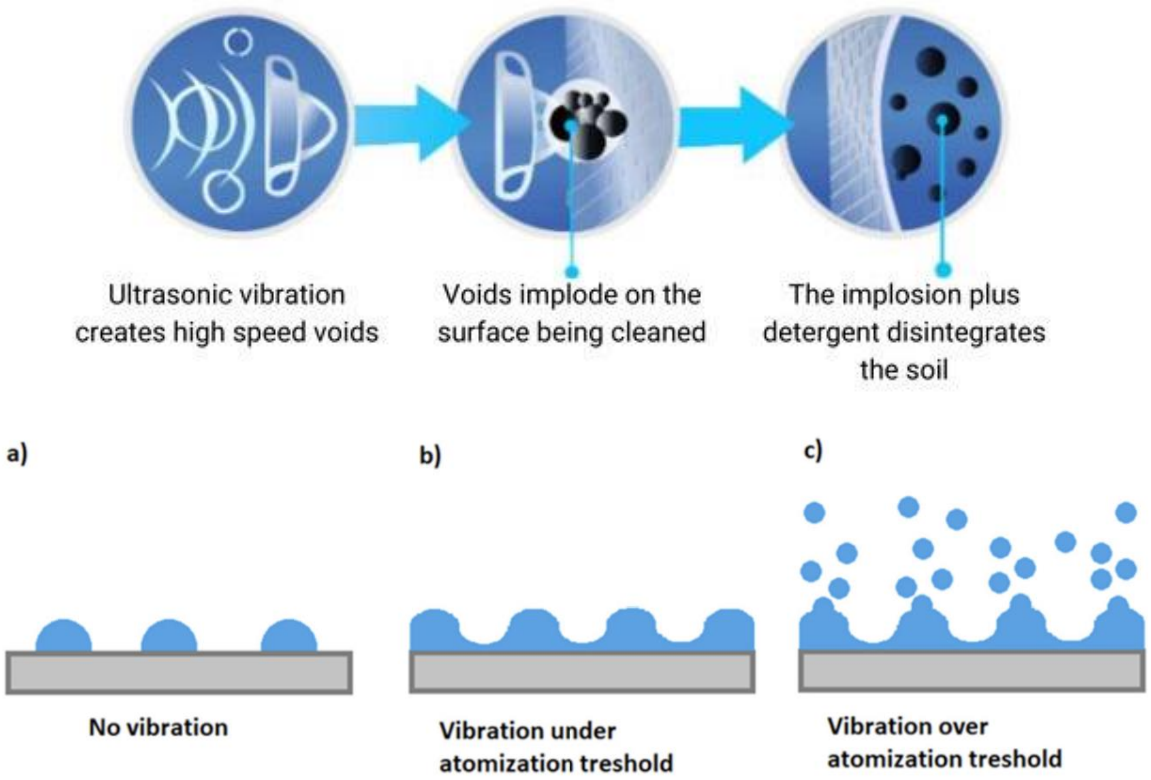
Series Bosch's Carbon

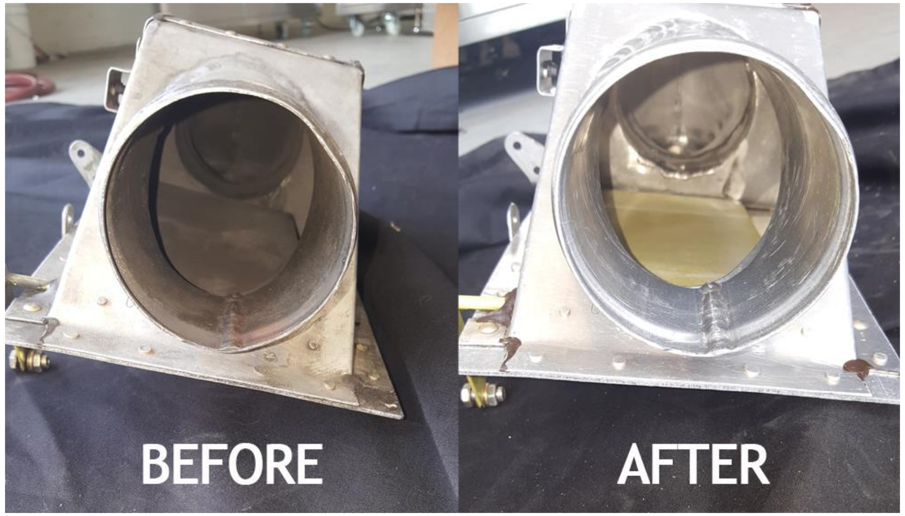


Automotive Air Intake Valve With Walnut Blasting

[9],[10]

Carbon Deposition Removal: Ultrasonic



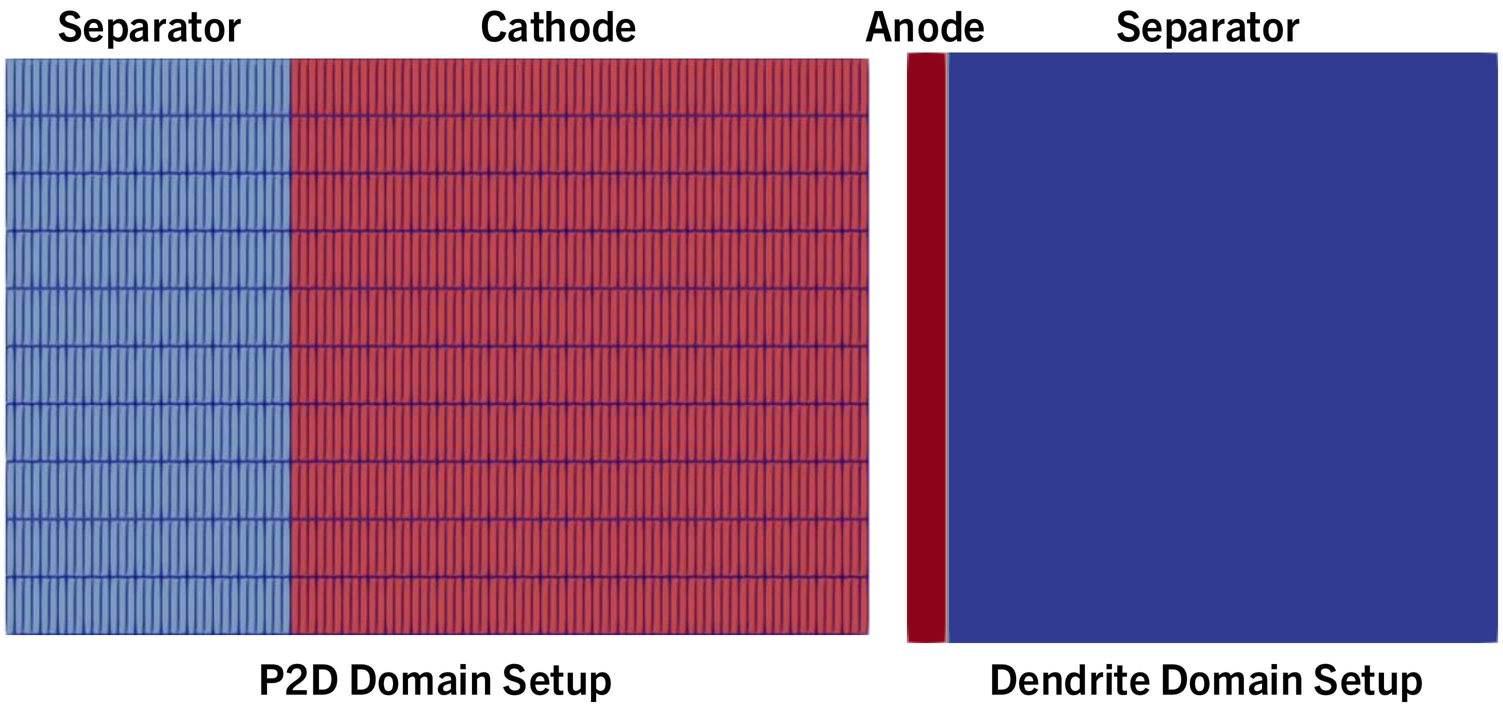


https://www.proultrasonics.com/

[15],[16],[17]

Model Formulation: Pseudo-2D & Dendrite

- **General Model**
  - Pseudo-2D Formulation
  - Assumes No Intercalation
- **Dendrite Growth Model**
  - Allen-Cahn Phase-Field & Cahn-Hilliard Formulation
  - Assumes Isotropy



Engineering Life Cycle

Pre-Phase A	Phase A	Phase B	Phase C	Phase D	Phase E
Requirements Trade Studies Mini-proposals	Feasibility Initial Design Proposal	Initial testing Technical Report	Final design Full-scale testing	Flight-ready AETHER	Operations and maintenance

[18]