Mass Economy Evaluation for Integrated ECLSS and Propulsion Architecture

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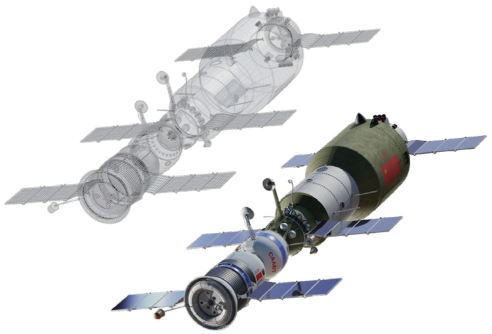
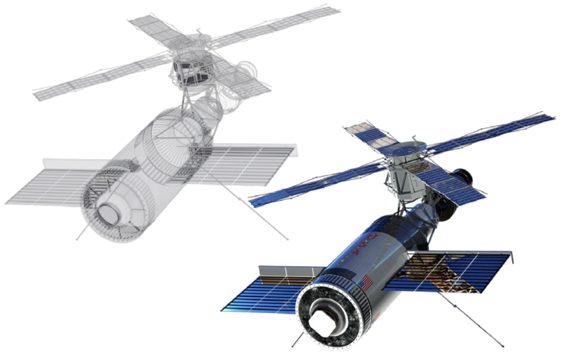
Importance of ECLSS to Human Spaceflight

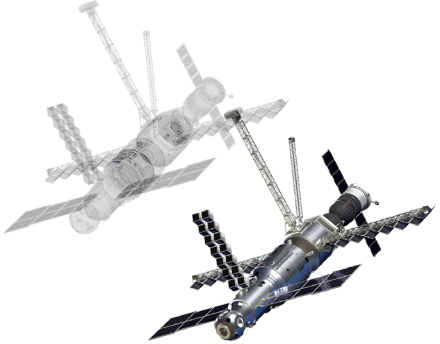
- Humans have a long history of spaceflight aboard various spacecraft
- One of the key systems that keeps astronauts alive is the ECLSS
- ECLSS is essential for sustaining human presence
  - Without it, human space exploration would not be possible
- Life support systems are also essential for enabling long-duration space missions, such as those that involve crewed missions to the Moon, Mars, or beyond
  - These missions require systems that can generate and recycle resources, such as air, water, and food, as resupply missions may not be possible or feasible



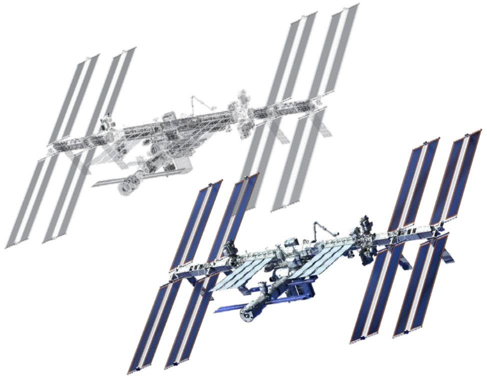
Salyut-1 [29]
April 1971 – October 1971



Skylab [29-32]
May 1973 – February 1974



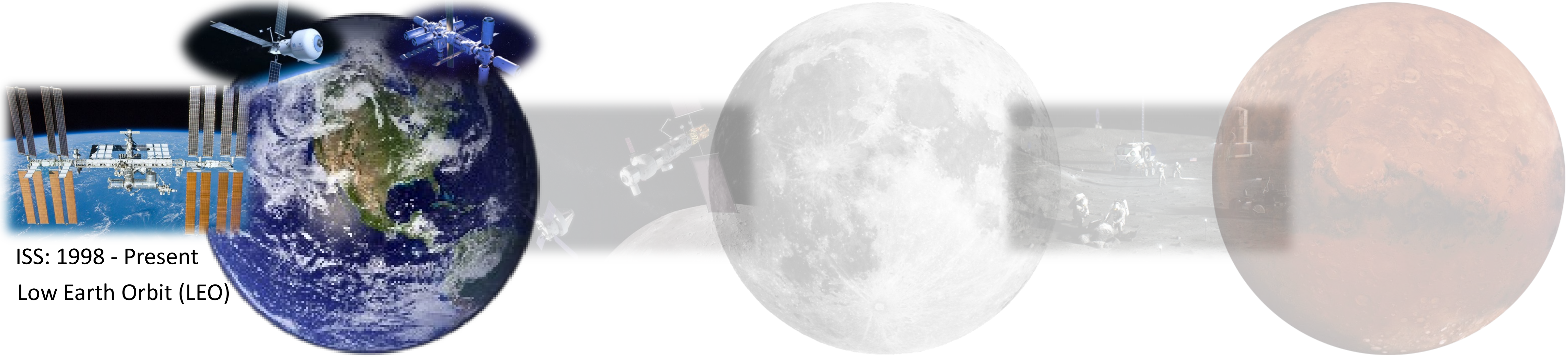
Mir [32]
February 1986 – March 2001



ISS [33]
Nov 1998 - Current

Low Earth Orbit Destination Development

- **International Space Station (ISS)** provides tremendous contributions to human spaceflight by being on orbit for over 22 years
- Joining the ISS, NASA initiated the Space Act Agreement (SAA) to support the development of **commercial space stations**
  - Blue Origin, Nanorack, and Northrop Grumman* were selected in 2021 under funded SAA-1
  - Additional new companies, such as Sierra Space, SpaceX, Vast Space were selected in 2023 for unfunded SAA-Collaborations for Commercial Space Capabilities-2 initiative (CCSC-2)

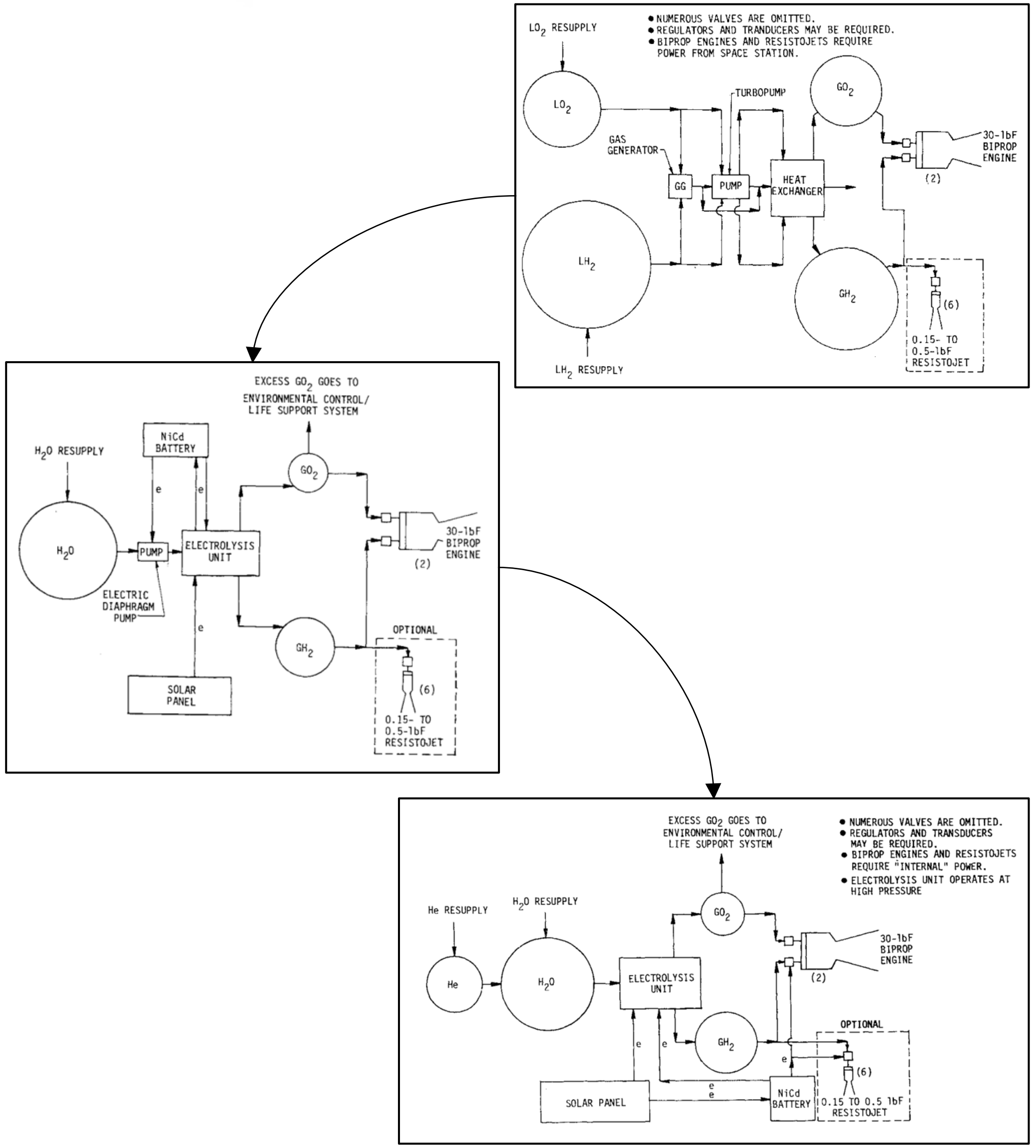


*Northrop Grumman withdrew in 2023

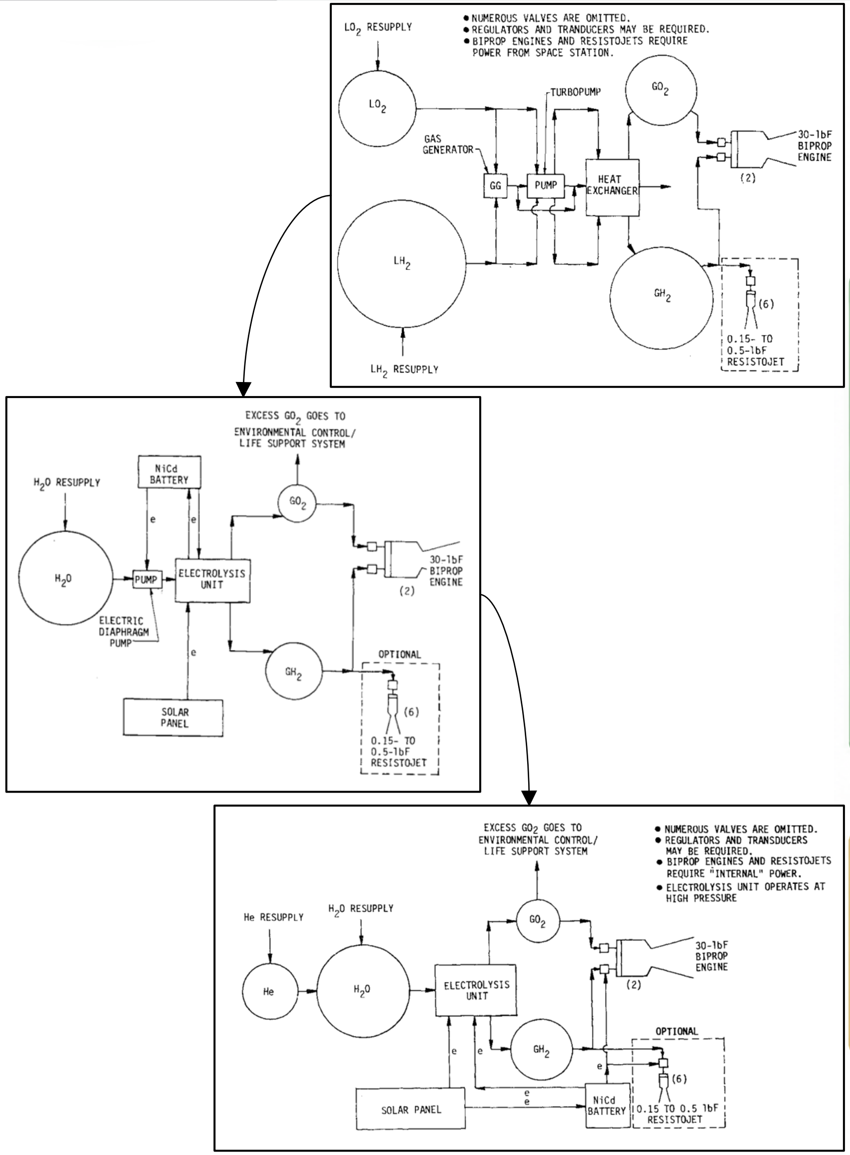
ECLSS and Prop Integration Concept

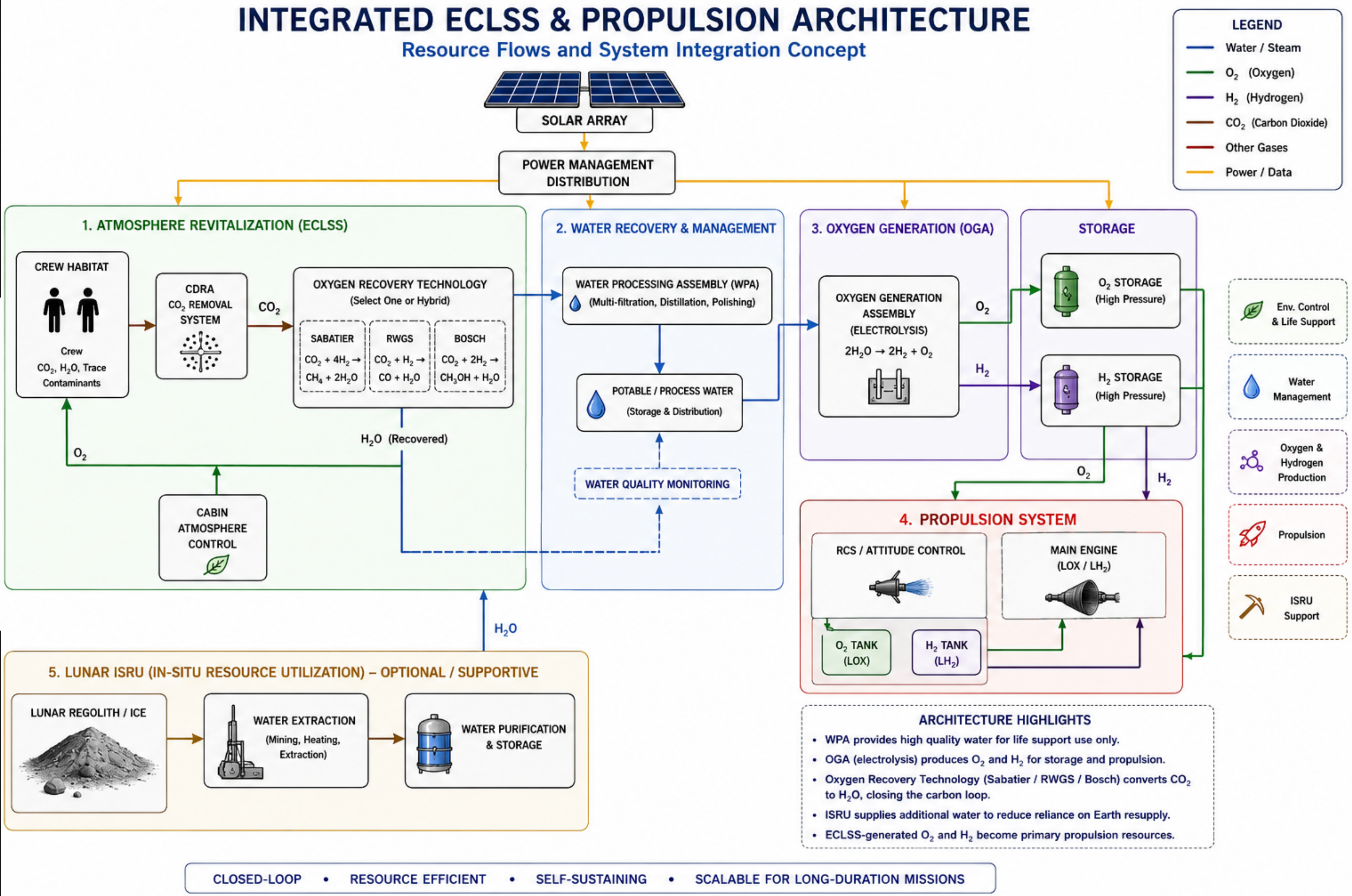
- Long-duration LEO and deep-space missions are logistics-limited
- ECLSS already manages O_2, H_2, CO_2, and H_2O
- Propulsion systems also require high-value chemical reactants
- Integration may reduce dedicated propellant resupply and increase resource utilization

Year	Study / Demonstration	Relevance
1985	Rosenberg et al.	Integrated O_2/H_2 propulsion and life support concept
1986	Propulsion–ECLSS Interaction Study	Use ECLSS effluents for propulsion
1987	NASA TM 100216	Oversized electrolyzer could support station propulsion
1988	Integrated Propulsion and Fluid Systems Study	Partial and full resource sharing options
2014	Anaerobic waste-to-methane study	Waste conversion to propellant
2021	HYDROS water-electrolysis thruster demo	Water-to-thrust demonstrated in space
2024	ESA HISRU concept	Wastewater + CO_2 to methane and oxygen
2026	Present work	System-level ECLSS–propulsion trade study

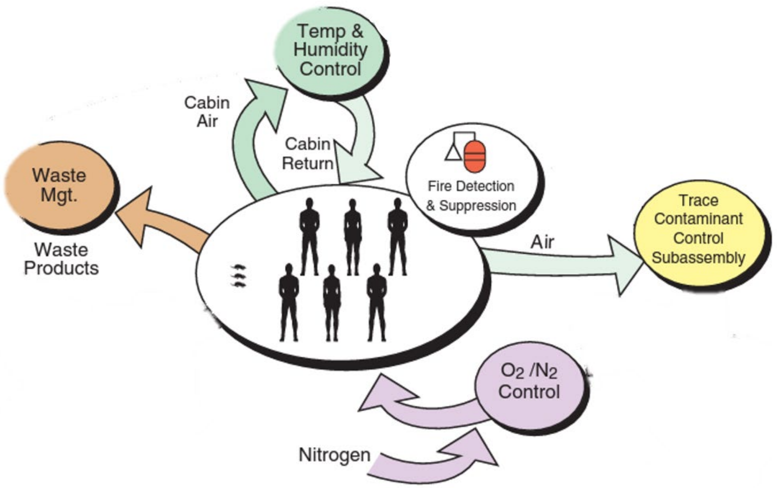


ECLSS and Prop Integration Concept





ECLSS Overview and Subsystems



Temperature and Humidity Control (THC) & Fire Detection and Suppression (FDS)
- Temperature, ventilation, humidity, fire detection/suppression

Atmosphere Revitalization (AR)
- Contaminant removal, atmospheric monitoring

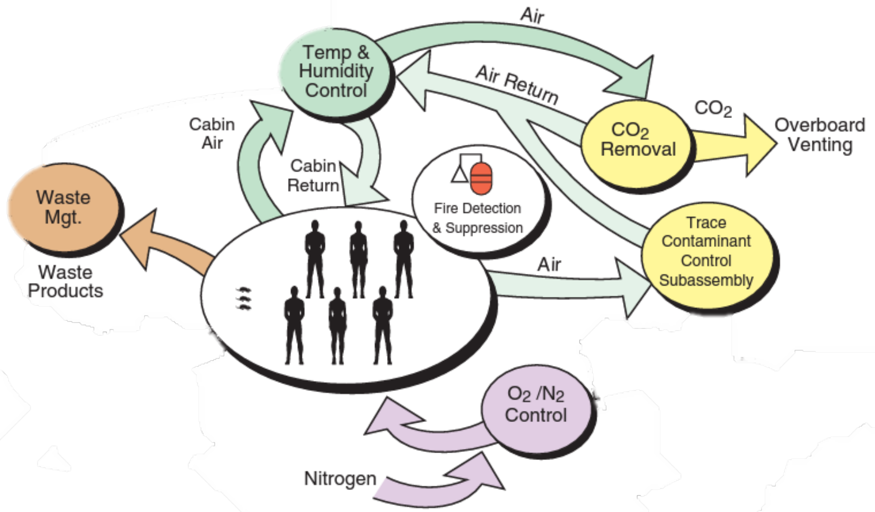
Atmosphere Control and Supply (ACS)
- Cabin pressure, gas distribution, emergency depressurization

Vacuum System (VS)
- Vacuum access

Early ISS ECLSS Systems → **Matured ISS ECLSS Systems**

LiOH Can
Water Bags
O_2 and N_2 Air Tanks

ECLSS Overview and Subsystems



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Major Constituent Analyzer
Carbon Dioxide Removal Assembly
Atmosphere Revitalization rack

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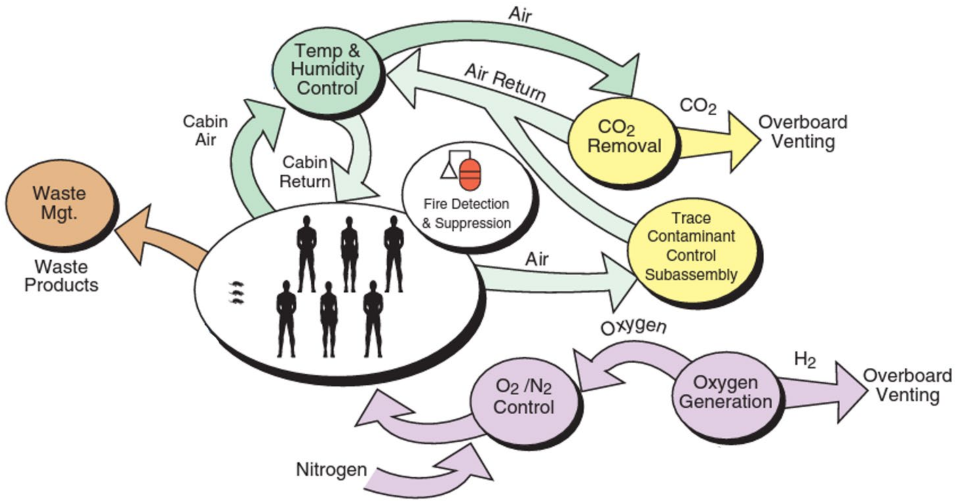

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Oxygen Generation Assembly (OGA)
- Oxygen generation

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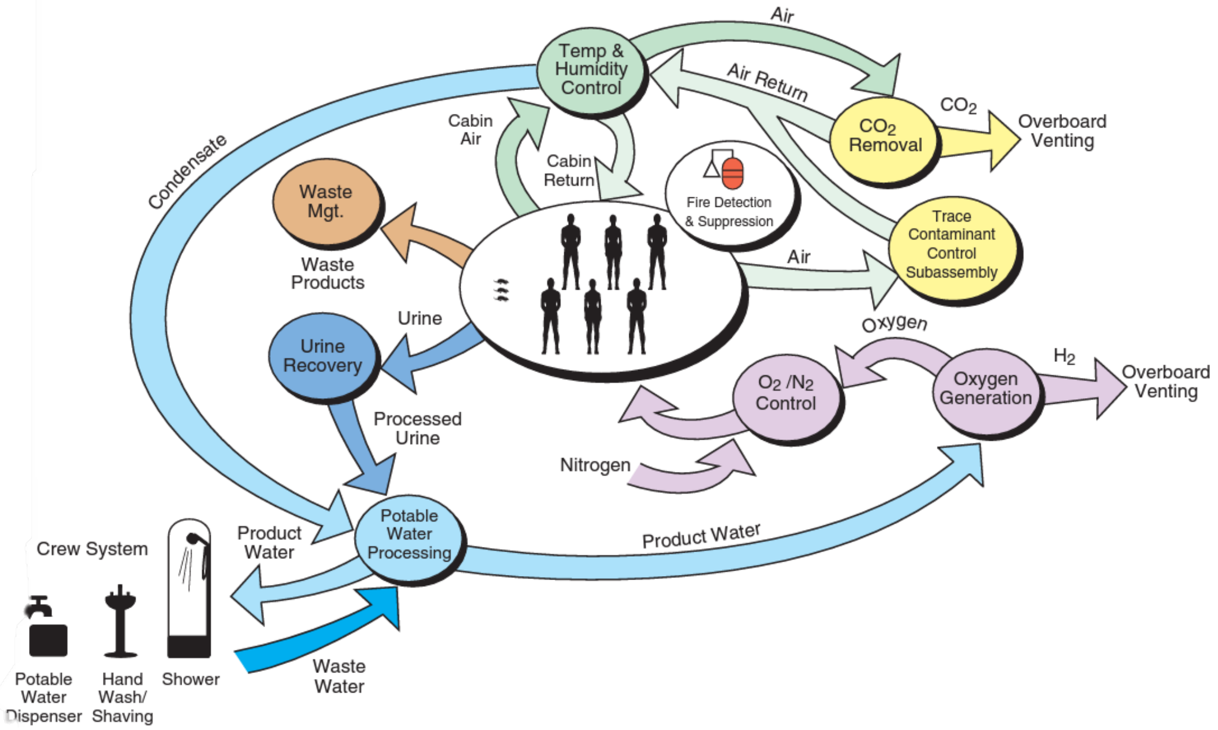
2007
Oxygen Generation System Rack
Oxygen Generation Assembly

ECLSS Overview and Subsystems



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Vacuum System (VS)
- Vacuum access

Oxygen Generation Assembly (OGA)
- Oxygen generation

Water Recovery and Management (WRM)
- Potable/hygiene water, wastewater recycling

Urine Processing Assembly (UPA)
- Recover water from urine

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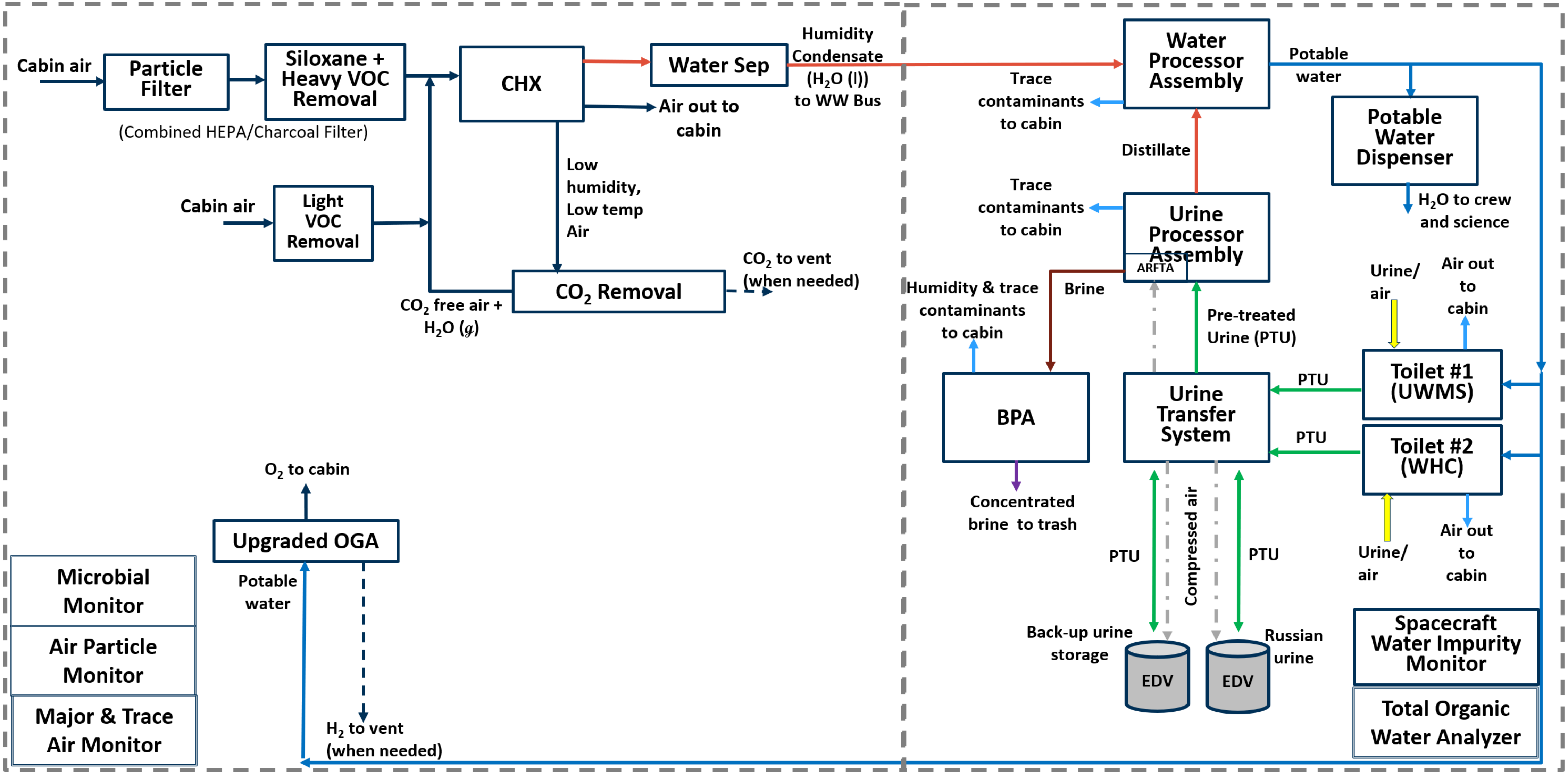
2007
Oxygen Generation System Rack
Oxygen Generation Assembly

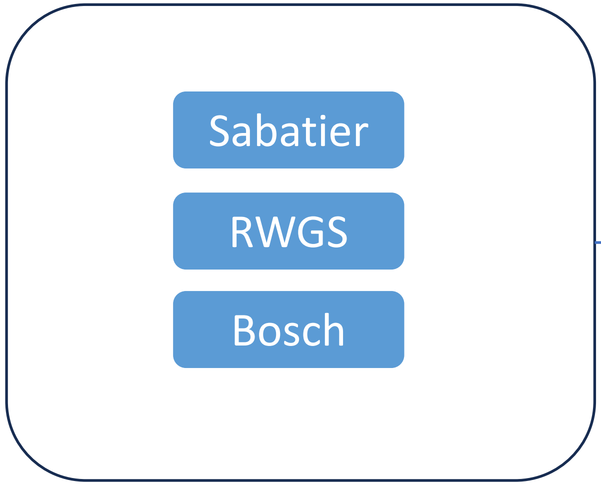
2008
Urine Processing Assembly
Water Processing Assembly
Water Recovery System Racks

Current State-of-the-art ECLSS onboard ISS



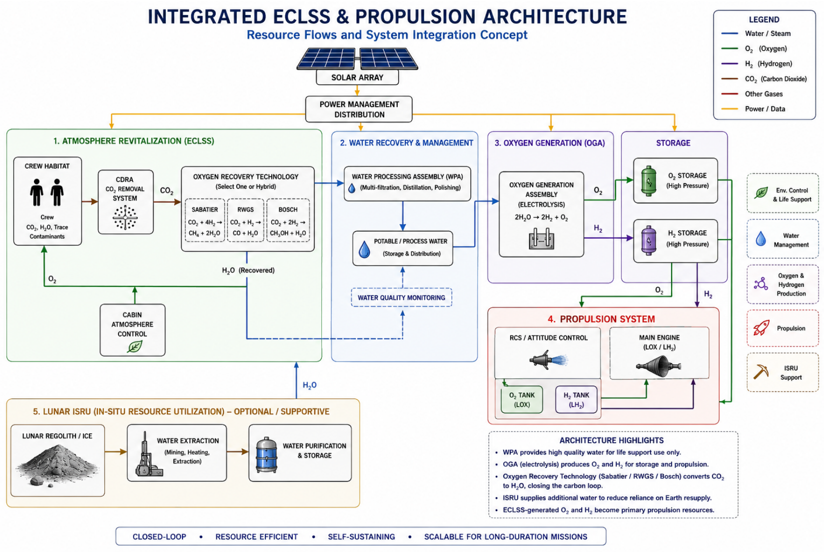
System Gap and Technological Advancements

- Technologies, Sabatier, RWGS or Bosch, have the great potential to fill the system gap to further close the loop and provide more resource to propulsion system
- limited system-of-systems comparison of CO_2 reduction options for propulsion benefit



Technology System of System Evaluation

SoS Impact



Integrated Architecture

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Sabatier

$$CO_2 + H_2 \rightarrow CO + H_2O$$

RWGS

$$CO_2 + 2H_2 \rightarrow 2H_2O + C(s)$$

Bosch

System Gap and Technological Advancements

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Sabatier

- Flight-proven on the ISS (operated >20,000 hours prior to degradation)
- High hydrogen-to-carbon dioxide requirement (4:1 stoichiometric ratio)
- Discards half the hydrogen as methane (CH_4), which is vented overboard
- Limits theoretical oxygen recovery from CO_2 to ~50% without additional processing (like Plasma Pyrolysis)

$$CO_2 + H_2 \rightarrow CO + H_2O$$

RWGS

- More hydrogen-efficient (1:1 stoichiometric ratio).
- 50% hydrogen recycle efficiency, massively reducing net hydrogen demand compared to Sabatier.
- Operates at 500°C with favorable thermal integration potential.
- Produces toxic Carbon Monoxide (CO), which must be vented or further processed.

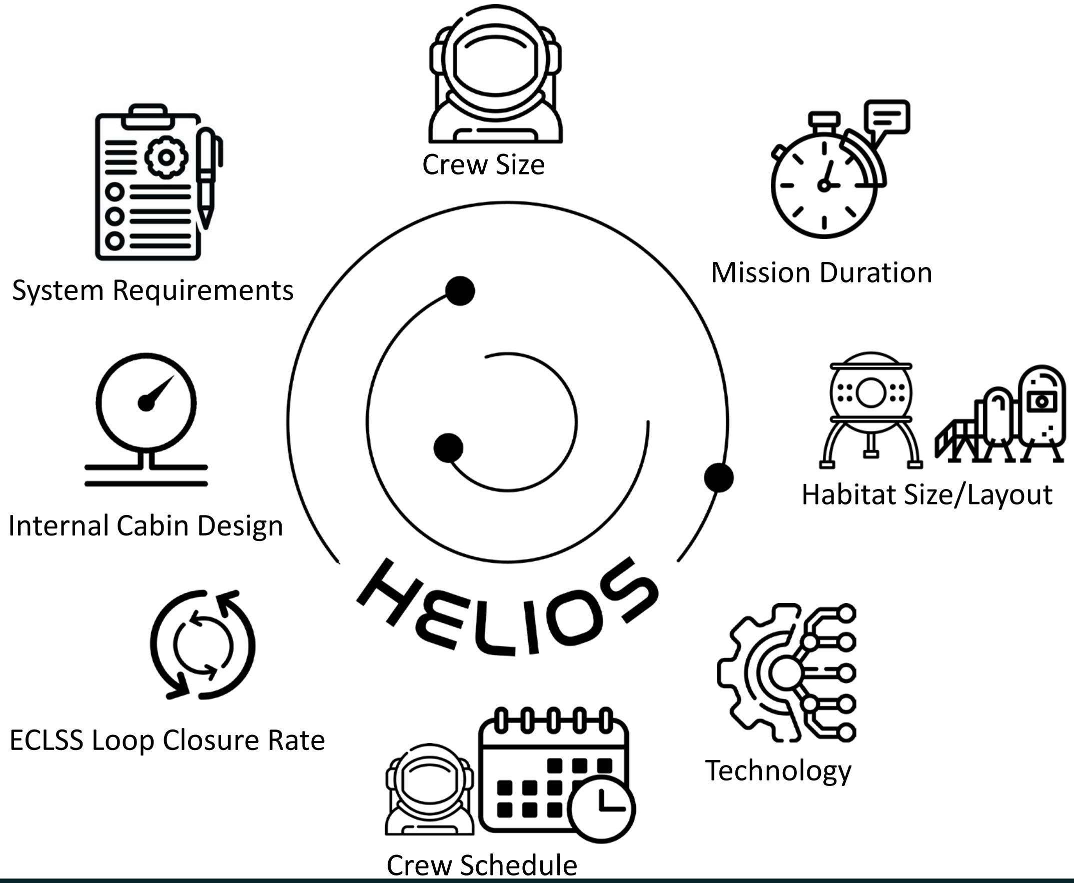
$$CO_2 + 2H_2 \rightarrow 2H_2O + C(s)$$

Bosch

- Most oxygen-efficient method; allows 100% theoretical recovery
- Produces two moles of water per mole of CO_2 and solid carbon
- Challenges: Lower TRL, highest power demand, requires handling of solid carbon fouling on catalysts (650°C operating temp)

System Evaluation Framework - HELIOS

- To address the gaps of ECLSS system modeling capability, inspired by Helios Aerospace from For All mankind, HELIOS simulation model was utilized
- HELIOS is a modular, physics-based simulation framework developed to evaluate the performance, mass, power, and operational characteristics of ECLSS for long-duration lunar surface missions
- The HELIOS model represents ECLSS as a fully integrated system-of-systems, capturing subsystem interactions across air and water loops



*Detail can be seen in ICES-2026-117

Research Objectives and Configuration

- This study evaluates
  - Propellant accumulation from ECLSS-derived O_2 and H_2
  - Delta-V capability over a 365-day mission
  - Mixture ratio effects relative to optimal LOX/LH_2 operation
  - Water balance and byproduct management
  - Technology-level trade-offs among Sabatier, RWGS, and Bosch
- Tracks O_2, H_2, water, byproducts, propellant accumulation, and delta-V
- The study is not only about "how much propellant is produced," but also whether that propellant is usable and sustainable

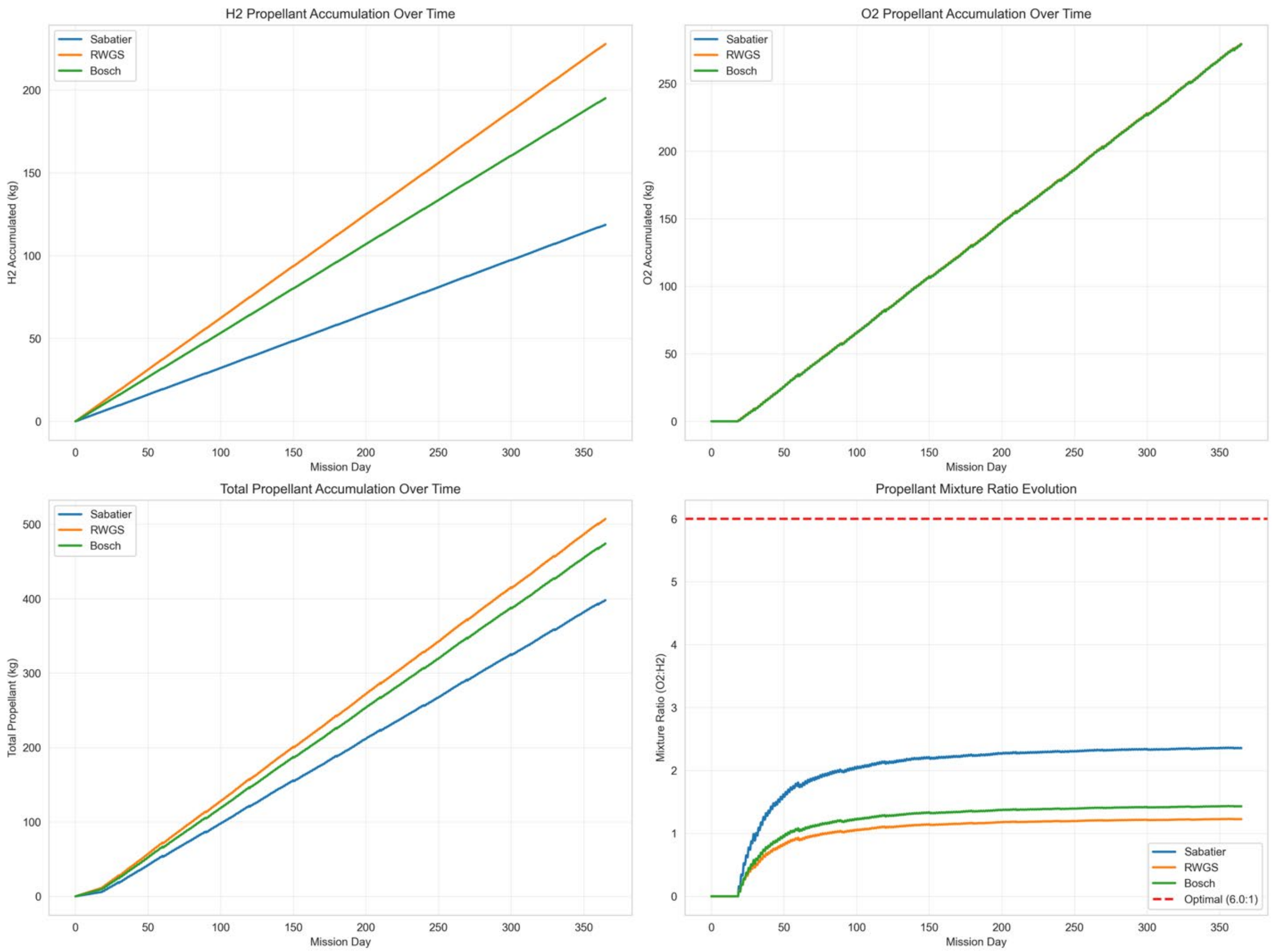
Configuration

Parameter	Value
Mission Duration	365 days
Crew Size	4
Spacecraft Dry Mass	50,000 kg
Initial O_2 Store	350 kg
Initial N_2 Store	45 kg

Result: Final Propellant Accumulation

- **Oxygen Accumulation**: Nearly identical across all technologies (~279 kg)
- **Hydrogen Accumulation**: RWGS achieved the highest hydrogen accumulation at 227.76 kg, followed by Bosch at 195.03 kg, while Sabatier produced the lowest amount at 118.61 kg
- **Accumulation Trend**: Near-linear growth over time once excess production becomes available beyond ECLSS operational reserves
- **Oxygen is the Bottleneck**:
  - Oxygen accumulation is primarily constrained by crew metabolic demand and accumulation thresholds, not by the specific CO_2 reduction pathway
- **Stoichiometry Drives H_2**:
  - The large variance in total mass is entirely driven by hydrogen recycling efficiency
  - RWGS consumes only one mole of H_2 per mole of CO_2, allowing a much larger fraction of electrolytic hydrogen to accumulate compared to Sabatier, which consumes four

Technology	H_2 (kg)	O_2 (kg)	Total (kg)	Mixture Ratio	Delta-V (m/s)
Sabatier	118.61	279.37	397.98	2.36:1	35.39
RWGS	227.76	279.44	507.20	1.23:1	45.05
Bosch	195.03	279.04	474.07	1.43:1	42.12
Optimal	–	–	–	6.0:1	–



Result: Delta-V Capability

- **ISS Baseline Target:** ~130.0 m/s per year for station-keeping (100%)
- **ECLSS-Derived Delta-V Achieved:**
  - RWGS: 45.05 m/s (34.7% of target)
  - Bosch: 42.12 m/s (32.4% of target)
  - Sabatier: 35.39 m/s (27.2% of target)
- **Supplemental, Not Standalone:**
  - All three technologies fall substantially short of the ISS baseline, with a gap of 65–73%
  - Under this configuration, ECLSS-derived propellant cannot fully replace dedicated station-keeping fuel
- **Diminishing Returns:**
  - Because delta-V scales logarithmically with propellant mass (Tsiolkovsky rocket equation), even moderate increases in mass yield diminishing returns
  - Closing this gap requires architectural changes, not just longer accumulation times

Results: Mixture Ratio Analysis

- **Assuming Target Optimal Mixture Ratio (MR):** 6.0:1 (O_2:H_2 by mass) for LOX/LH_2 engines
- **Actual MR Achieved (Highly H_2-Rich):**
  - Sabatier: 2.36:1
  - Bosch: 1.43:1
  - RWGS: 1.23:1
- **Propellant Utilization & Excess H_2:**
  - Sabatier: 90.3% efficiency (only 38.74 kg excess H_2)
  - Bosch: 67.3% efficiency (155.10 kg excess H_2)
  - RWGS: 62.9% efficiency (187.83 kg excess H_2)
- **The True Dominant Limiter:** Mixture ratio, rather than total propellant mass, is the primary constraint on propulsion effectiveness
- **The Parasitic Mass Penalty:** In hydrogen-rich mixtures like RWGS, excess hydrogen does not contribute to energy release. It lowers combustion temperature and becomes unusable dead weight. Although RWGS generates the most mass, its severe mixture imbalance makes nearly 200 kg of that mass effectively useless, giving Sabatier the actual mass-economy advantage

$$m_{H_2,usable} = \frac{m_{O_2}}{MR_{optimal}}$$

$$\eta_{util} = \frac{m_{prop,usable}}{m_{prop,total}} \; X \; 100\%$$

$$m_{prop,usable} = m_{H_2,usable} \cdot \left(MR_{optimal} + 1\right)$$

Technology	Actual MR	Optimal MR	Excess H_2 (kg)	Utilization Efficiency
Sabatier	2.36:1	6.0:1	38.74	90.3%
RWGS	1.23:1	6.0:1	187.83	62.9%
Bosch	1.43:1	6.0:1	155.10	67.3%

Results: Water Balance and Byproduct Accumulation

Water Balance

- **Starting Inventory:** 2,000 L of potable water
- **Final Water Levels & Deficits (365 Days):**
  - Sabatier: 555.46 L remaining (*Lost 1,444.54 L*)
  - Bosch: 489.77 L remaining (*Lost 1,510.23 L*)
  - RWGS: 261.41 L remaining (*Lost 1,738.59 L*)
- **The Oxygen/Water Contradiction:** Technologies that improve oxygen recovery and propellant generation (RWGS, Bosch) impose a severe penalty on the water loop by increasing upstream electrolysis demand
- **Sabatier's Hidden Advantage:** Sabatier partially offsets this water depletion because its reaction pathway intrinsically produces water. Architectures favoring RWGS for propulsion would require increased water resupply, which could cancel out the propulsion mass savings

Byproduct Accumulation

- **RWGS:** Produced 11.05 kg of Carbon Monoxide (CO)
  - **RWGS Penalties:** CO is toxic. It must be vented, which results in a direct loss of processed carbon and imposes safety and contamination control requirements
- **Bosch:** Produced 3.78 kg of Solid Carbon (C)
  - **Bosch Penalties:** Solid carbon requires mechanical containment and periodic removal to prevent reactor fouling, increasing operational complexity
- **Sabatier:** Produced 278.9 kg of Methane (CH_4)
  - **Sabatier's Dual-Use Opportunity:** Methane represents a highly valuable secondary resource. Rather than discarding it, this 278.9 kg of CH_4 could be stored and utilized in a secondary LOX/CH_4 propulsion system, giving Sabatier unique architectural flexibility

Discussion and Conclusion

Discussion

- **Scaling OGA Capacity:** Doubling the Oxygen Generation Assembly output could increase O_2 to 450–500 kg, improving mixture ratios by 60–90% with *Penalty: +1.5 kW power requirement*
- **Methane Utilization:** Using Sabatier's byproduct in a LOX/CH_4 engine (Isp ~350s). *Benefit: Improves overall delta-V by ~19% without requiring additional O_2.*
- **Extending Mission Duration:** Over 730 days, O_2 accumulates proportionally, naturally improving mixture ratios. *Penalty: Higher operational risk and boiloff sensitivity.*
- **System-Level Trade-offs:** To make ECLSS-derived propulsion fully viable, spacecraft designers must choose between spending more power (scaling OGA) or accepting increased system complexity (hybrid multi-propellant engines or cryogenic methane storage)

Conclusion

- Mixture ratio, not total mass, is the dominant limiter of performance
- RWGS produces the most fuel but suffers from massive H_2 underutilization and severe water loop penalties
- Sabatier provides the highest efficiency, best water conservation, and offers a usable byproduct (CH_4)

Future work

- Explicitly modeling hybrid propulsion strategies (LOX/LH_2 combined with LOX/CH_4)
- Relaxing zero-boiloff assumptions to study realistic cryogenic storage impacts

Integrated ECLSS-propulsion architectures could be viewed as a complementary capability to enhance mission flexibility, rather than a total replacement for dedicated propulsion. Currently, Sabatier offers the most balanced and mature path forward for mass-efficient deep space habitats

Questions & Discussion

	Paper Number	Title	Track	Date	Time	Location
Monday						
	425	Status of ISS Water Management and Recovery	404	13-Jul	1030-1200	SALON 9
	118	Parametric Modeling and Performance Evaluation of Lunar ISRU Oxygen and Water Extraction Within the HELIOS Framework	308	13-Jul	1400-1600	SALON 10
	424	The eXploration Potable Water Dispenser Aboard the ISS: Exploration Technology Demonstration Status Review	404	13-Jul	1630-1830	SALON 9
Tuesday						
	117	HELIOS: A System of Systems Based Methodology for Evaluating ECLSS Architectures with Integrated ISRU and Reliability Modeling	300	14-Jul	1400-1600	EL MORRO 2
Wednesday						
	139	Integrating ISRU Into Lunar Habitat Design: Effects on ECLSS Loop-Closure Requirements	308	15-Jul	0800-1000	SALON 10
	189	System-of-Systems Evaluation of Oxygen Recovery Technologies for Extended Space Missions	302	15-Jul	0800-1000	SALON 4
	136	Evaluating Artemis Candidate Landing Sites for Future Lunar Architecting: an Enhanced Framework for ECLSS and ISRU Considerations	506	15-Jul	1030-1230	SALON 2
	34	Automation of Artemis Candidate Landing Sites Selection for Future Lunar Architecting	506	15-Jul	1030-1230	SALON 2
	137	Establishing Self-Sustaining Lunar Habitats: Experimental Evaluation of ECLSS Loop Closure and Mission-Level Feasibility	305	15-Jul	1400-1600	EL MORRO 1
	138	Lifecycle Mass-Economic Evaluation and Breakeven Analysis of Self-Sustaining ECLSS Designs for Lunar Habitats	305	15-Jul	1400-1600	EL MORRO 1
	190	Mass Economy Evaluation for Integrated ECLSS and Propulsion Architecture	305	15-Jul	1400-1600	EL MORRO 1
Thursday						
	25	Evaluating Artemis Candidate Landing Sites for Future Lunar Architecting: an Enhanced Framework for Assessing for Power Considerations	109	16-Jul	1330-1500	SALON 1