Water Chemistry for Space Exploration

at NASA's Kennedy Space Center

National Aeronautics and
Space Administration

Luke Roberson, Ph.D

Senior Principal Investigator

Exploration Research/UB-G

NASA Kennedy Space Center, FL

Presented to the
NETSACS
February 24, 2022

www.nasa.gov

The Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies our path to the Moon as the name of NASA’s program to return astronauts to the lunar surface.

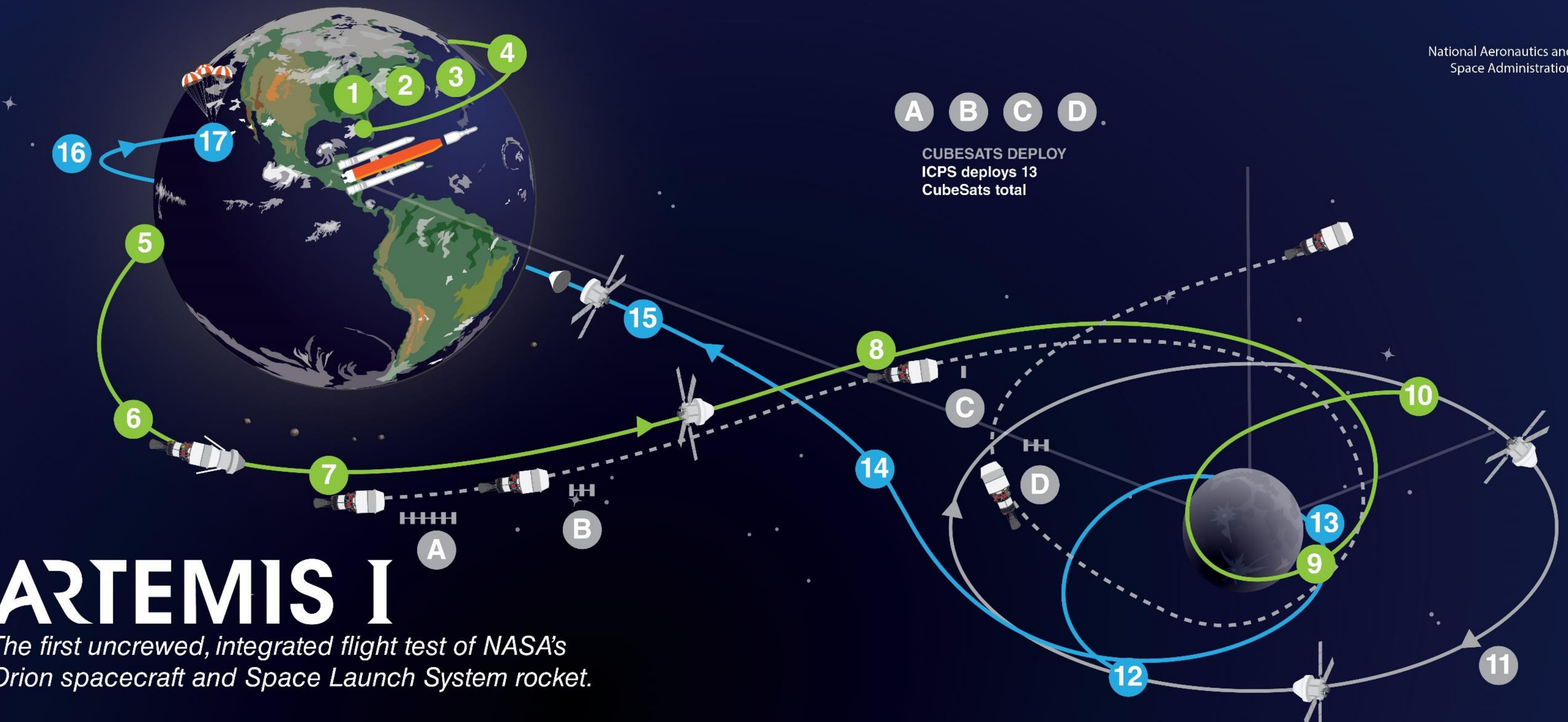
When they land, Artemis astronauts will step foot where no human has ever been before: the Moon’s South Pole.

With the horizon goal of sending humans to Mars, Artemis begins the next era of exploration.

National Aeronautics and Space Administration

ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket.

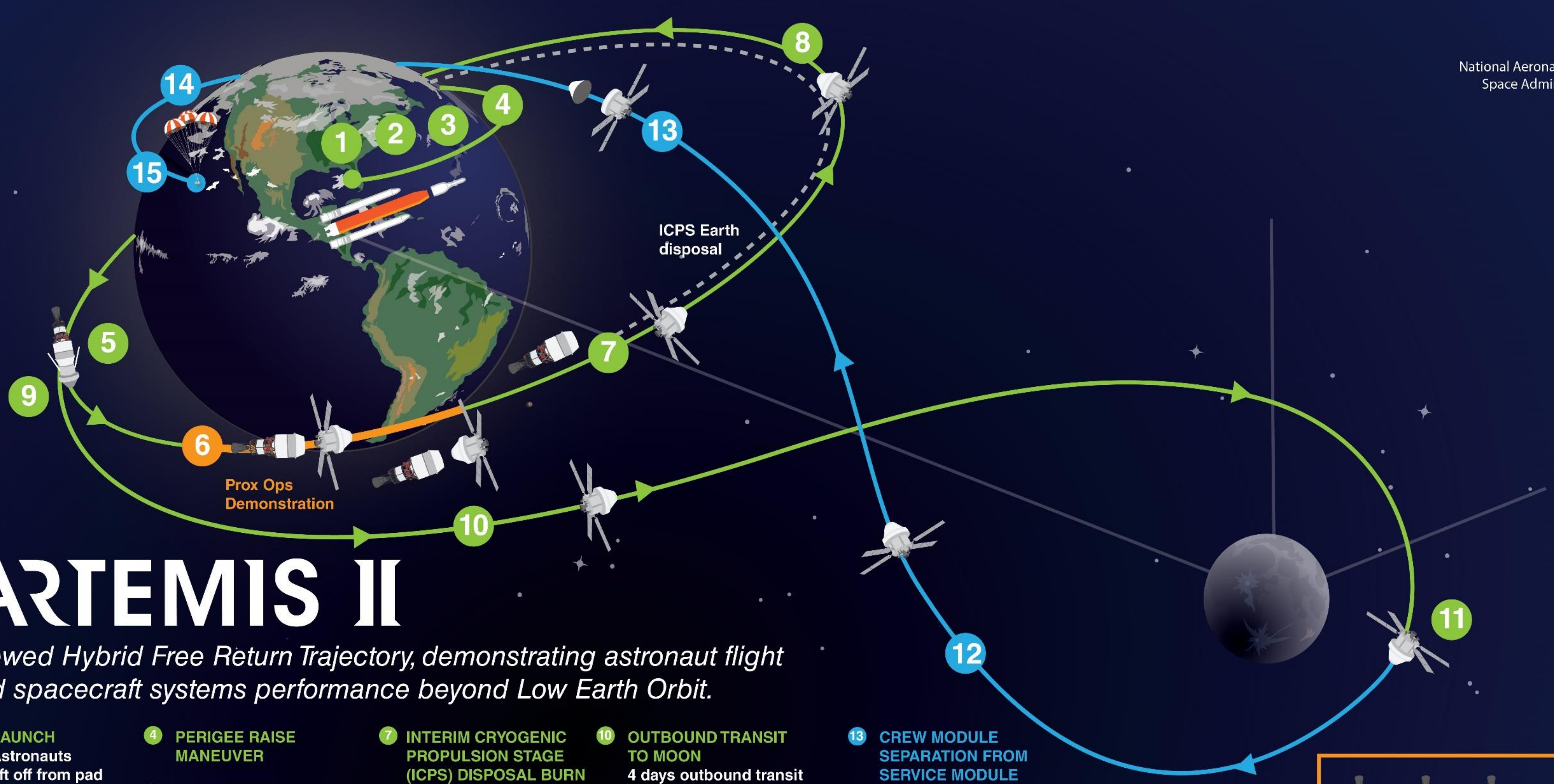


A B C D

CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

- ① **LAUNCH** SLS and Orion lift off from pad 39B at Kennedy Space Center.
- ② **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
- ③ **CORE STAGE MAIN ENGINE CUT OFF** With separation.
- ④ **PERIGEE RAISE MANEUVER**
- ⑤ **EARTH ORBIT** Systems check with solar panel adjustments.
- ⑥ **TRANS LUNAR INJECTION (TLI) BURN** Maneuver lasts for approximately 20 minutes.
- ⑦ **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL** The ICPS has committed Orion to TLI.
- ⑧ **OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS** As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
- ⑨ **OUTBOUND POWERED FLYBY (OPF)** 60 nmi from the Moon; targets DRO insertion.
- ⑩ **LUNAR ORBIT INSERTION** Enter Distant Retrograde Orbit for next 6-23 days.
- ⑪ **DISTANT RETROGRADE ORBIT** Perform half or one and a half revolutions in the 12 day orbit period 38,000 nmi from the surface of the Moon.
- ⑫ **DRO DEPARTURE** Leave DRO and start return to Earth.
- ⑬ **RETURN POWER FLY-BY (RPF)** RPF burn prep and return coast to Earth initiated.
- ⑭ **RETURN TRANSIT** Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 5-11 days.
- ⑮ **CREW MODULE SEPARATION FROM SERVICE MODULE**
- ⑯ **ENTRY INTERFACE (EI)** Enter Earth's atmosphere.
- ⑰ **SPLASHDOWN** Pacific Ocean landing within view of the U.S. Navy recovery ship.

National Aeronautics and
Space Administration



ARTEMIS II

Crewed Hybrid Free Return Trajectory, demonstrating astronaut flight and spacecraft systems performance beyond Low Earth Orbit.

① **LAUNCH**
Astronauts lift off from pad 39B at Kennedy Space Center.

② **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**

③ **CORE STAGE MAIN ENGINE CUT OFF**
With separation.

④ **PERIGEE RAISE MANEUVER**

⑤ **APOGEE RAISE BURN TO HIGH EARTH ORBIT**
Begin 42 hour checkout of spacecraft.

⑥ **PROX OPS DEMONSTRATION**
Orion proximity operations demonstration and manual handling qualities assessment for up to 2 hours.

⑦ **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) DISPOSAL BURN**

⑧ **HIGH EARTH ORBIT CHECKOUT**
Life support, exercise, and habitation equipment evaluations.

⑨ **TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**

⑩ **OUTBOUND TRANSIT TO MOON**
4 days outbound transit along free return trajectory.

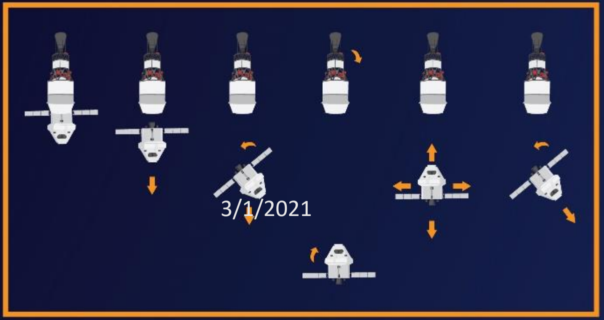
⑪ **LUNAR FLYBY**
4,000 nmi (mean) lunar farside altitude.

⑫ **TRANS-EARTH RETURN**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time approximately 4 days.

⑬ **CREW MODULE SEPARATION FROM SERVICE MODULE**

⑭ **ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.

⑮ **SPLASHDOWN**
Astronaut and capsule recovery by U.S. Navy ship.

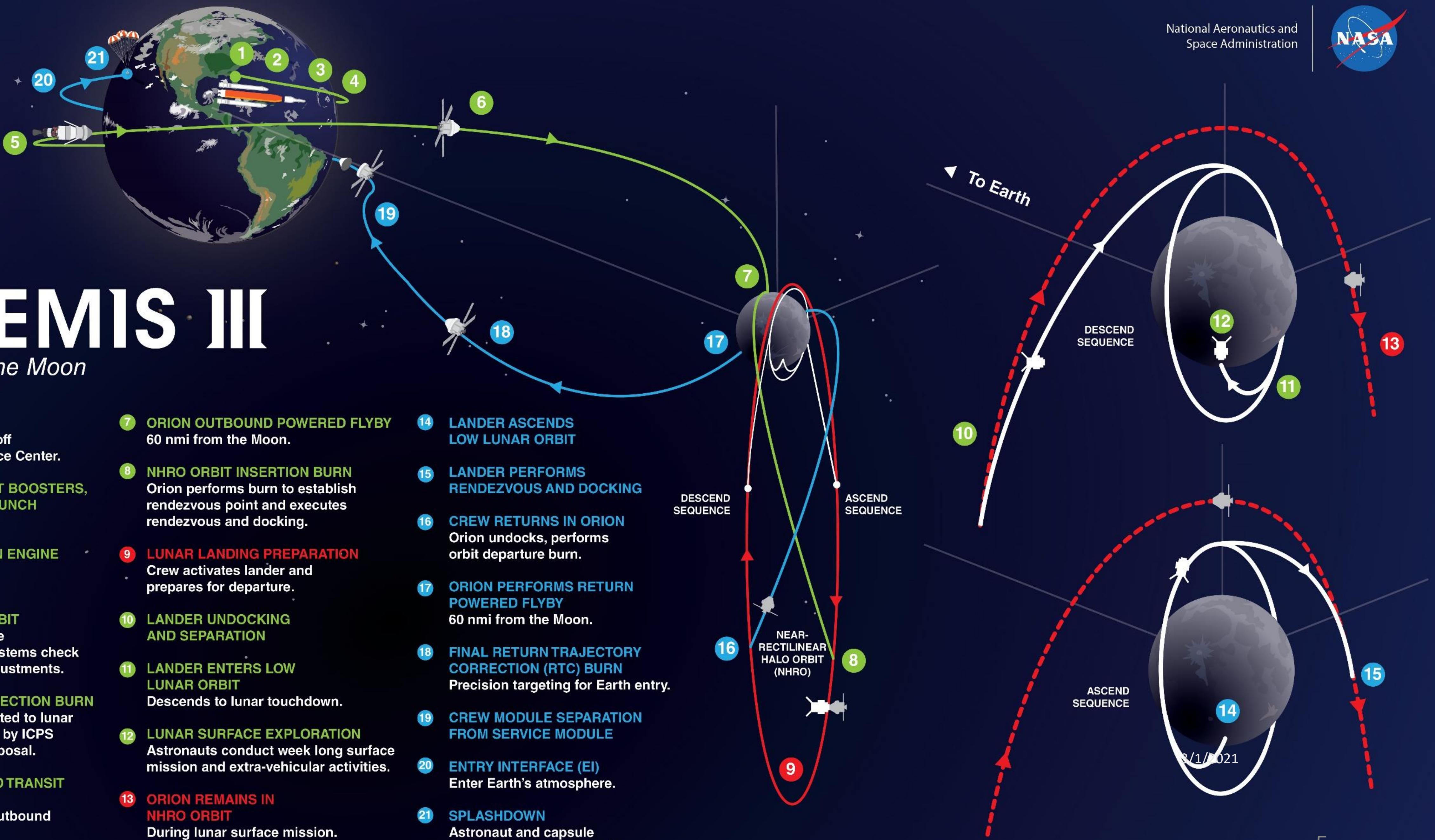


PROXIMITY OPERATIONS DEMONSTRATION SEQUENCE

National Aeronautics and
Space Administration

ARTEMIS III

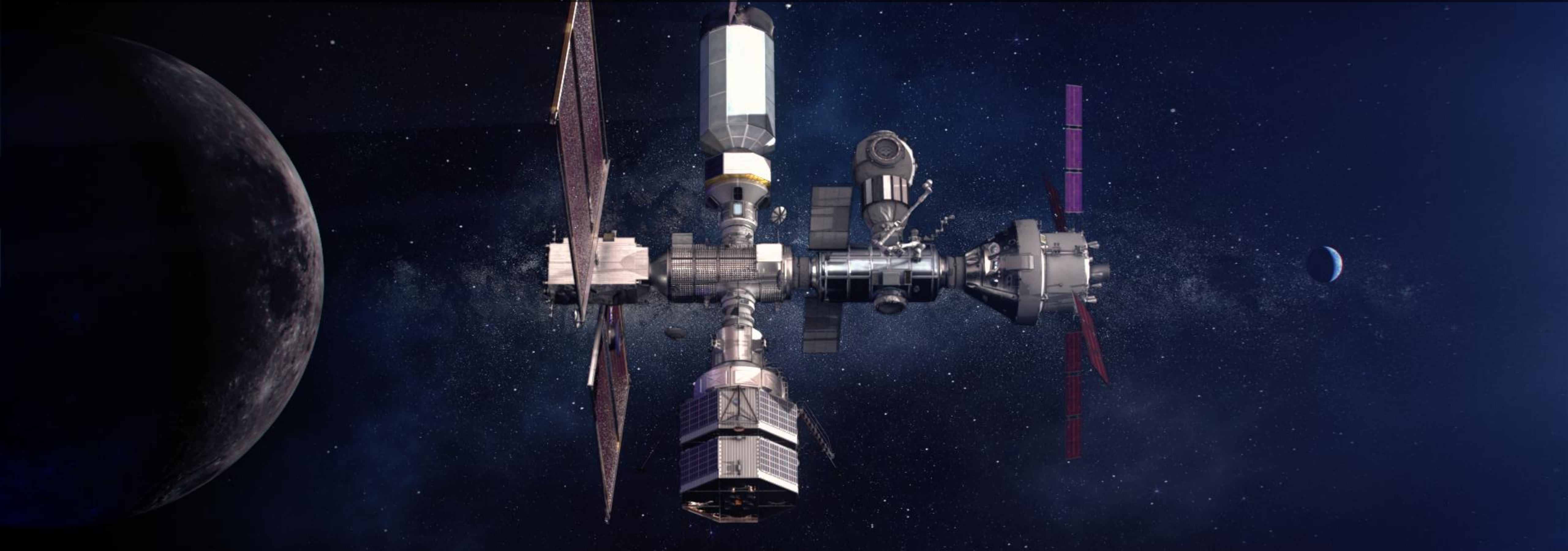
Landing on the Moon



1. **LAUNCH**
   SLS and Orion lift off from Kennedy Space Center.
2. **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
3. **CORE STAGE MAIN ENGINE CUT OFF**
   With separation.
4. **ENTER EARTH ORBIT**
   Perform the perigee raise maneuver. Systems check and solar panel adjustments.
5. **TRANS LUNAR INJECTION BURN**
   Astronauts committed to lunar trajectory, followed by ICPS separation and disposal.
6. **ORION OUTBOUND TRANSIT TO MOON**
   Requires several outbound trajectory burns.
7. **ORION OUTBOUND POWERED FLYBY**
   60 nmi from the Moon.
8. **NHRO ORBIT INSERTION BURN**
   Orion performs burn to establish rendezvous point and executes rendezvous and docking.
9. **LUNAR LANDING PREPARATION**
   Crew activates lander and prepares for departure.
10. **LANDER UNDOCKING AND SEPARATION**
11. **LANDER ENTERS LOW LUNAR ORBIT**
    Descends to lunar touchdown.
12. **LUNAR SURFACE EXPLORATION**
    Astronauts conduct week long surface mission and extra-vehicular activities.
13. **ORION REMAINS IN NHRO ORBIT**
    During lunar surface mission.
14. **LANDER ASCENDS LOW LUNAR ORBIT**
15. **LANDER PERFORMS RENDEZVOUS AND DOCKING**
16. **CREW RETURNS IN ORION**
    Orion undocks, performs orbit departure burn.
17. **ORION PERFORMS RETURN POWERED FLYBY**
    60 nmi from the Moon.
18. **FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN**
    Precision targeting for Earth entry.
19. **CREW MODULE SEPARATION FROM SERVICE MODULE**
20. **ENTRY INTERFACE (EI)**
    Enter Earth's atmosphere.
21. **SPLASHDOWN**
    Astronaut and capsule recovery by U.S. Navy ship.

Gateway International Partners

Building on ISS partnerships to expand deep space capabilities



NASA

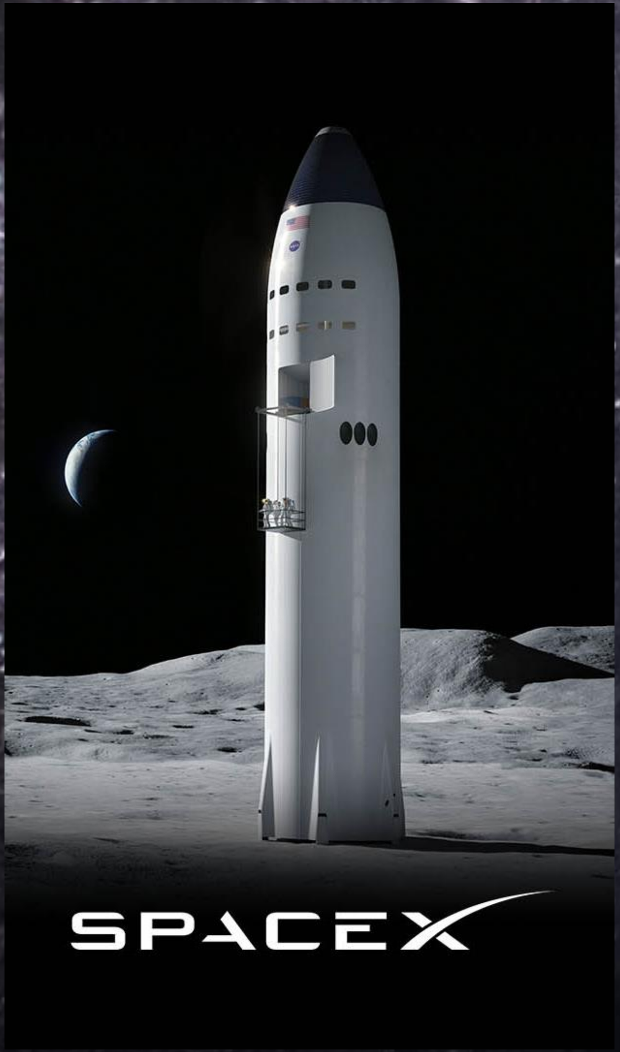
CSA ASC

esa
European Space Agency

JAXA

ROSCOSMOS

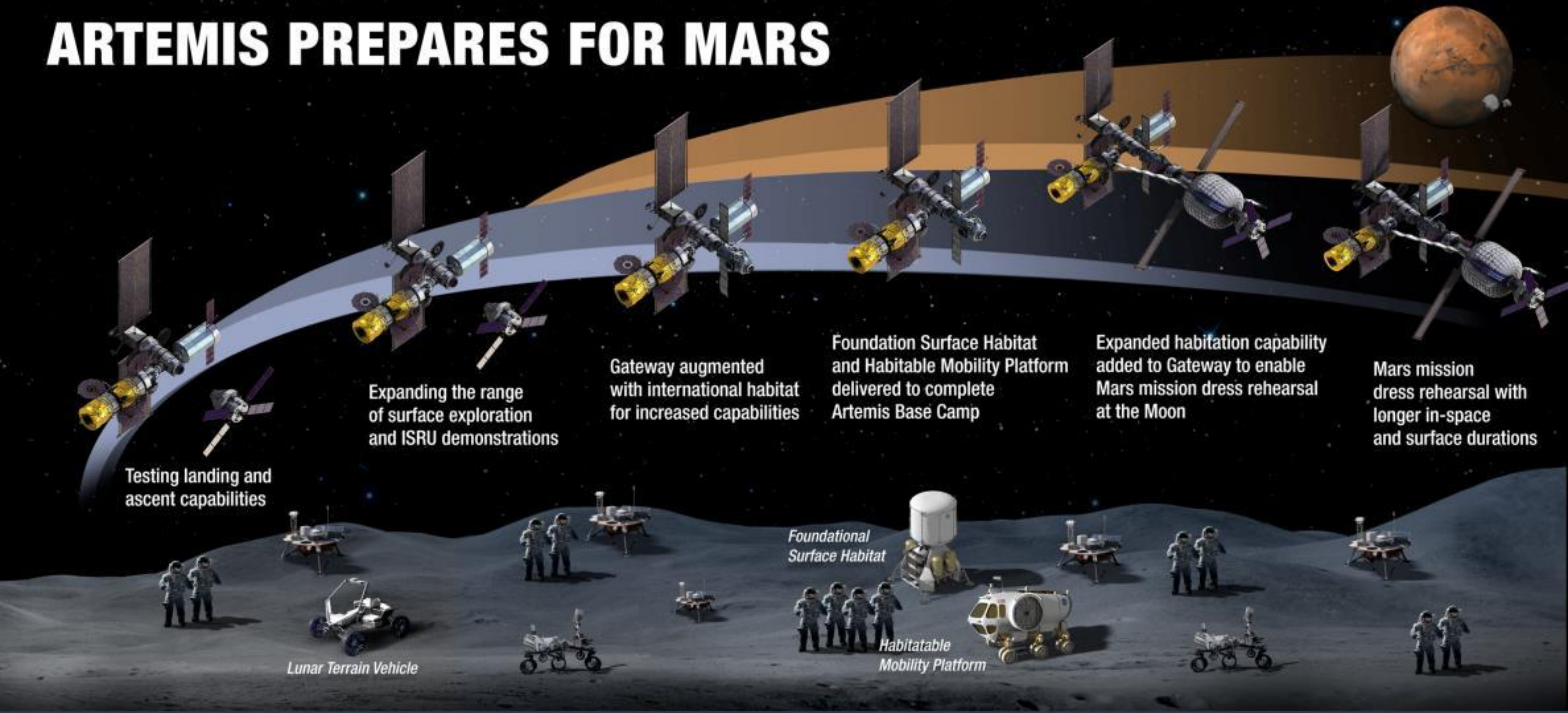
THE HUMAN LANDING SYSTEM



Mission Needs Drive Design

LOW EARTH RETURN	LUNAR RETURN	MARS RETURN
3 HOURS	3 DAYS	9 MONTHS
3,000°F	5,200°F	6,200°F
17,500 MPH	24,700 MPH	26,800 MPH
250 MILES	240,000 MILES	39,000,000 MILES

ARTEMIS PREPARES FOR MARS



Testing landing and ascent capabilities

Expanding the range of surface exploration and ISRU demonstrations

Gateway augmented with international habitat for increased capabilities

Foundation Surface Habitat and Habitable Mobility Platform delivered to complete Artemis Base Camp

Expanded habitation capability added to Gateway to enable Mars mission dress rehearsal at the Moon

Mars mission dress rehearsal with longer in-space and surface durations

SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

Humans on Mars

***Pushing the Boundaries
of Current Possibilities***

Go

***Rapid, safe, & efficient
space transportation***

Land

***Expanded access to
diverse surface
destinations***

Live

***Sustainable living
and working farther
from Earth***

Explore

***Transformative missions
and discoveries***

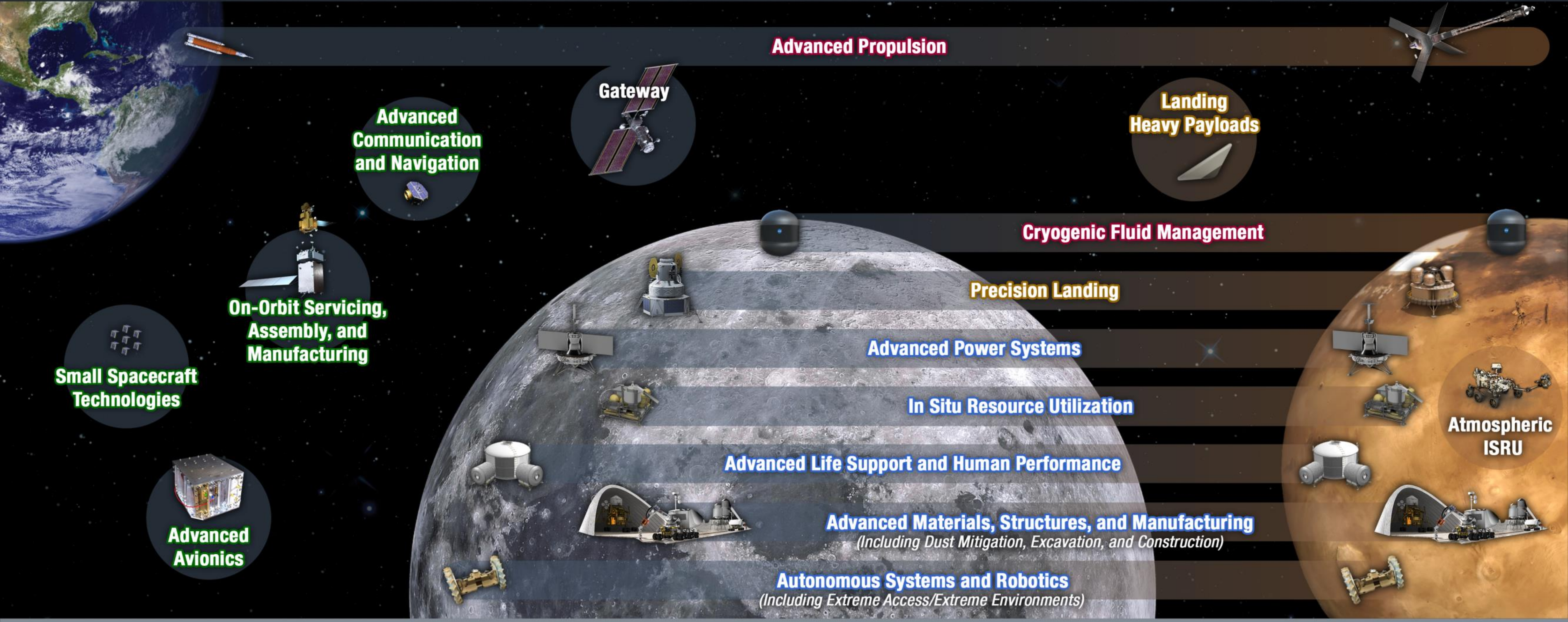
TECHNOLOGY DRIVES EXPLORATION

Rapid, Safe, and Efficient Space Transportation

Expanded Access to Diverse Surface Destinations

Sustainable Living and Working Farther from Earth

Transformative Missions and Discoveries



Advanced Propulsion

Gateway

Advanced Communication and Navigation

Landing Heavy Payloads

On-Orbit Servicing, Assembly, and Manufacturing

Small Spacecraft Technologies

Advanced Avionics

Cryogenic Fluid Management

Precision Landing

Advanced Power Systems

In Situ Resource Utilization

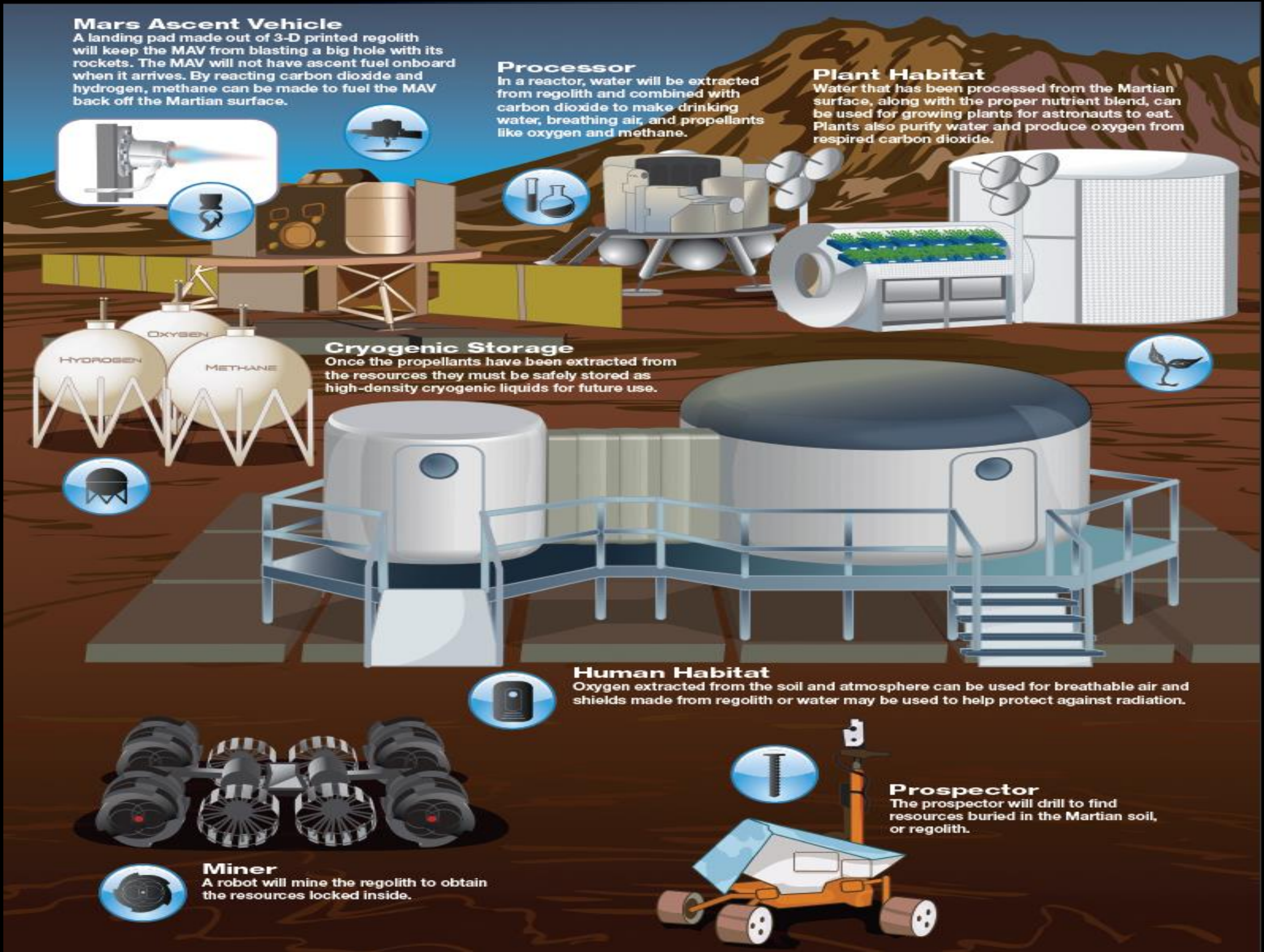
Atmospheric ISRU

Advanced Life Support and Human Performance

Advanced Materials, Structures, and Manufacturing
(Including Dust Mitigation, Excavation, and Construction)

Autonomous Systems and Robotics
(Including Extreme Access/Extreme Environments)

2020 **GO | LAND | LIVE | EXPLORE** **203X**



Mars Ascent Vehicle
A landing pad made out of 3-D printed regolith will keep the MAV from blasting a big hole with its rockets. The MAV will not have ascent fuel onboard when it arrives. By reacting carbon dioxide and hydrogen, methane can be made to fuel the MAV back off the Martian surface.

Processor
In a reactor, water will be extracted from regolith and combined with carbon dioxide to make drinking water, breathing air, and propellants like oxygen and methane.

Plant Habitat
Water that has been processed from the Martian surface, along with the proper nutrient blend, can be used for growing plants for astronauts to eat. Plants also purify water and produce oxygen from respired carbon dioxide.

Cryogenic Storage
Once the propellants have been extracted from the resources they must be safely stored as high-density cryogenic liquids for future use.

Human Habitat
Oxygen extracted from the soil and atmosphere can be used for breathable air and shields made from regolith or water may be used to help protect against radiation.

Prospector
The prospector will drill to find resources buried in the Martian soil, or regolith.

Miner
A robot will mine the regolith to obtain the resources locked inside.

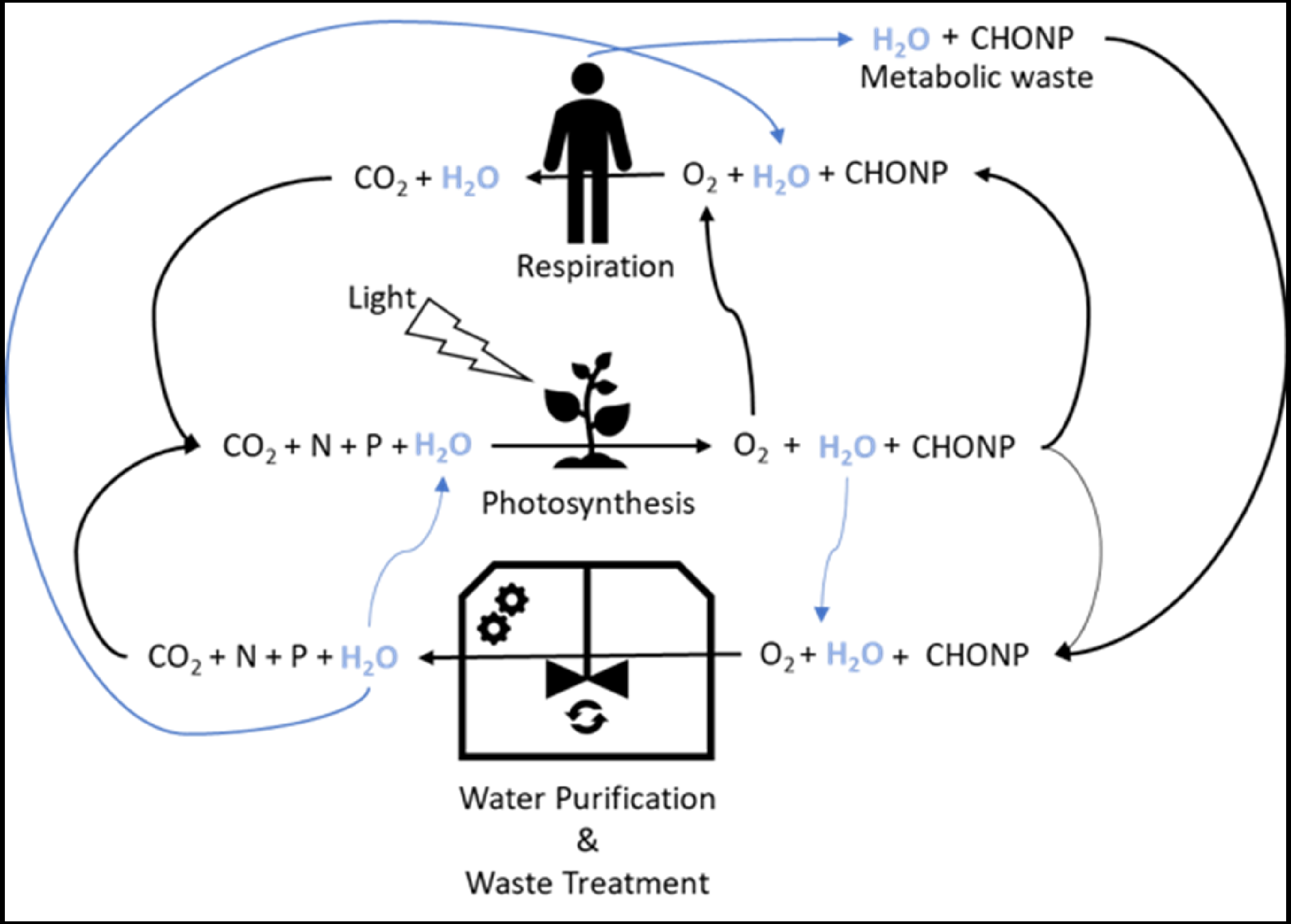
2020 NASA Technology Taxonomy (TX)

ECLSS Driven Challenges

	Goals	Challenges
TX 6.1.2 Water Recovery and Management	Increase re-useable water recovered from sources	Production of water with minimal expendables and maintenance Tolerance to dormancy Recovery of water from complex mixture of inorganic and organic sources
TX 6.1.3 Waste Management	Enable the utilization of solid and liquid metabolic wastes and trash	Effective separation and treatment of metabolic liquid and solid waste
TX 6.3.5 Food Production, Processing, and Preservation	Reduce food resupply requirement	Sustainable food growth, processing, and preparation

ECLSS Requirements

- For a 30-month mission, a single Crew Member (CM) will require:
  - 2250 kg water
  - 1359 kg food
- And generate:
  - 5678 kg total waste
    - 1612 kg metabolic waste
- Exceeds $16M/CM at a payload cost of $10,000/lb (~$4,535/kg)

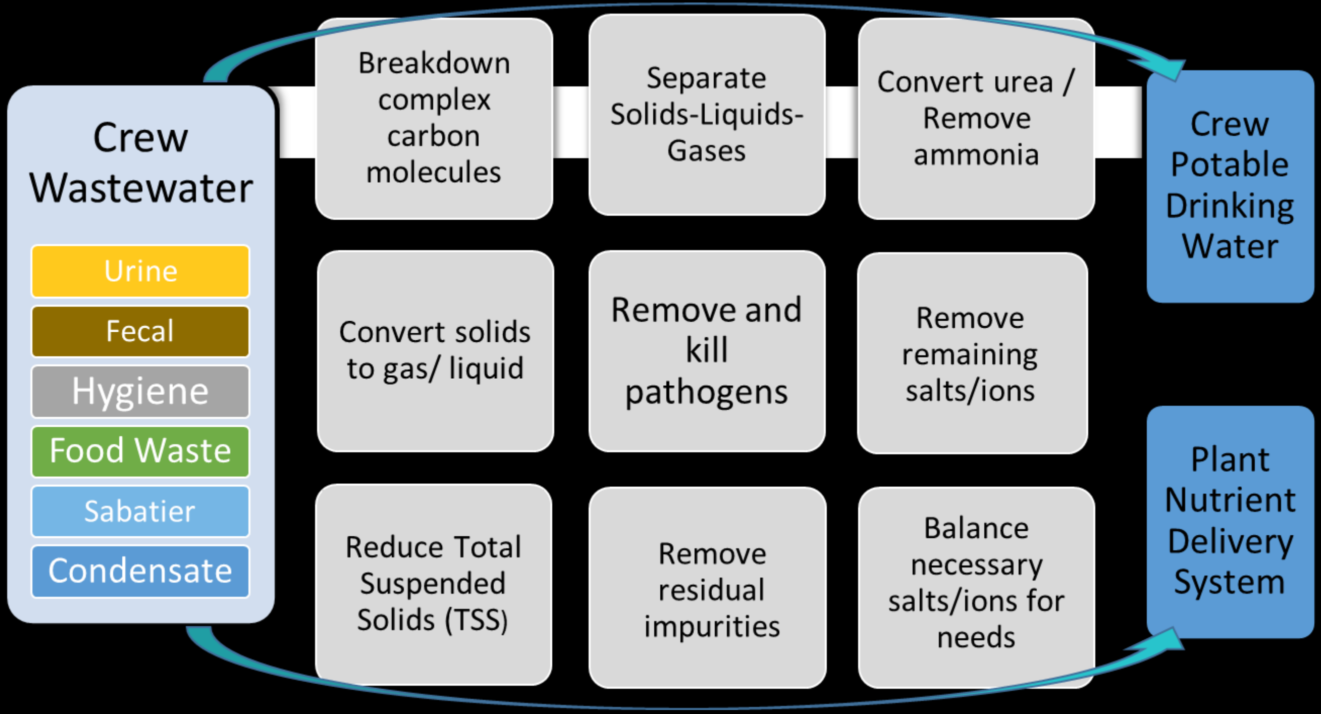


Adapted from Wheeler, R. M. (2003). CARBON BALANCE IN BIOREGENERATIVE LIFE SUPPORT SYSTEMS: Some Effects of System Closure, Waste Management, and Crop Harvest Index. *Adv. Space Res.*, *31*(1), 7.

Next-generation ECLSS

- Harvest and recycle not just water, but all elements (particularly C, H, O, N, P, K, S, Ca, Mg)
- Treat all organic matter as a resource – not waste
- Integrate water recycling, plant production, atmospheric revitalization, and waste management
- Need to be effective, reliable, robust, resilient, and safe
- Be bioregenerative – no consumables or resupply

Functional Flow Diagram



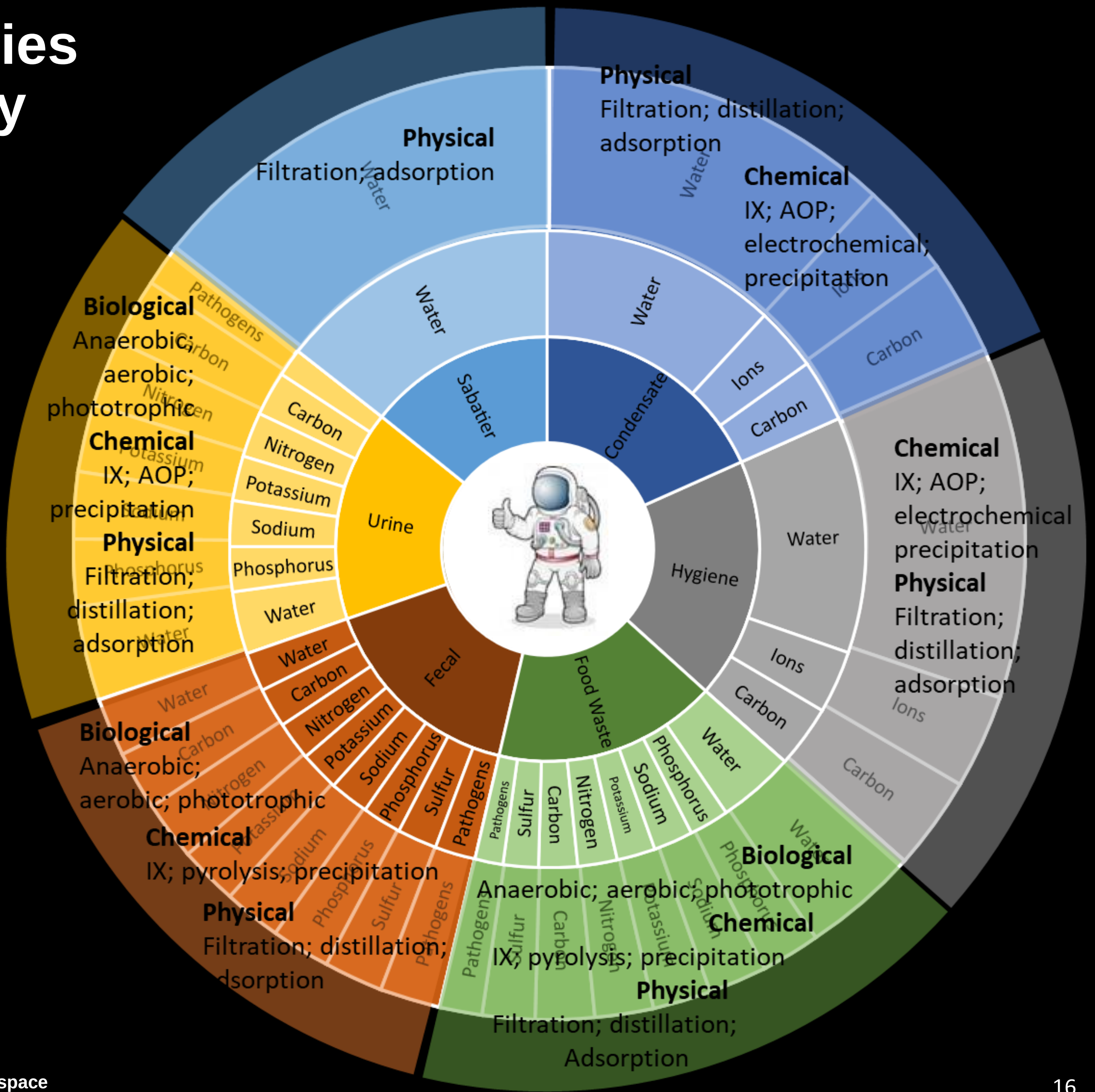
What are the enabling technologies?

Source: Pickett, M., L. Roberson, J. Calabria, T. Bullard, G. Turner, D. Yeh. 2020. Regenerative water purification for space applications: Needs, challenges, and technologies towards 'closing the loop'. *Life Science in Space Research, 24: 64-82.*

Primary Wastewater Streams: Constituents and potential technologies for treatment and resource recovery

		Constituents by type										Constituents by size		
Process Stream	**Description**	**C**	**N**	**P**	**K**	**S**	**Na**	**Ca**	**Mg**	**Other ions**	**Pathogens**	**Particulate**	**Colloidal**	**Dissolved**
Food Waste	**High content of complex particulate OM, fibers, COD**	4	3	3	2	3	2	2	2	2	2	4	4	3
Fecal	**High content of complex particulate OM, fibers, COD, pathogens**	4	3	3	2	3	2	2	2	2	4	4	4	3
Urine	Mod COD, organic N, urea, ammonium, phosphate, other salts	3	4	4	4	2	3	2	2	3	2	0	2	4
Hygiene	Low COD, constituents from skin and body secretions, environmental contaminants	2	2	1	1	1	2	1	1	2	2	2	2	3
Humidity	Mostly pure condensate, with contaminants from air and surfaces	1	1	0	1	0	1	0	0	1	1	0	0	2
Sabatier	Pure, potentially aggressive, can use for dilution, regeneration, backwash	0	0	0	0	0	0	0	0	1	1	0	0	0

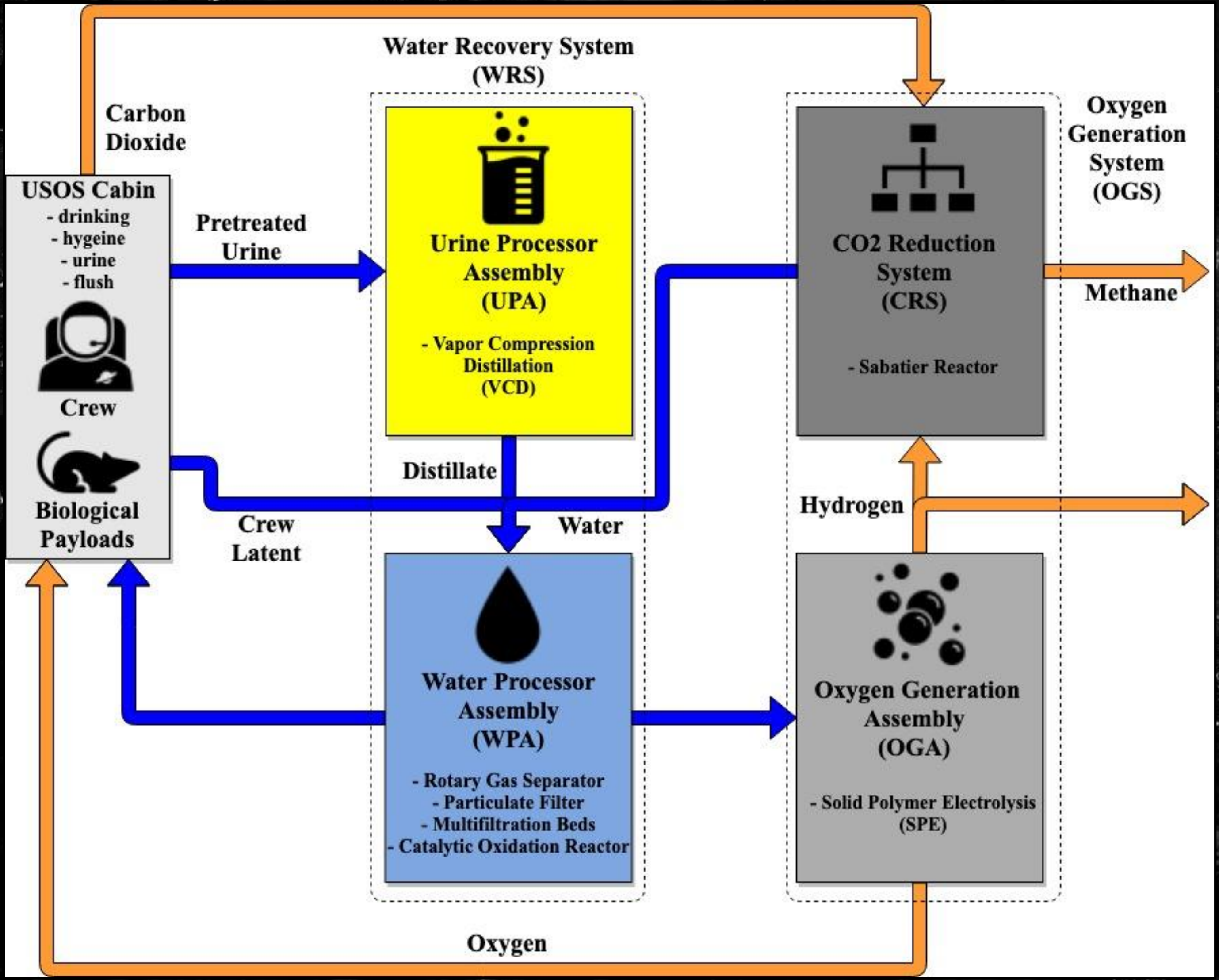
Notes: First two rows denote streams currently not addressed by technologies on ISS
Relative concentration: Very High (4) High (3), Medium (2), Low (1), Trace (0)
COD = chemical oxygen demand



Source: Pickett, M., L. Roberson, J. Calabria, T. Bullard, G. Turner, D. Yeh. 2020. Regenerative water purification for space applications: Needs, challenges, and technologies towards 'closing the loop'. *Life Science in Space Research, 24: 64-82.*

Current ECLSS

- Water Recovery System (WRS)
  - Urine Processor Assembly (UPA)
  - Water Processor Assembly (WPA)
  - Brine Processor Assembly (BPA)



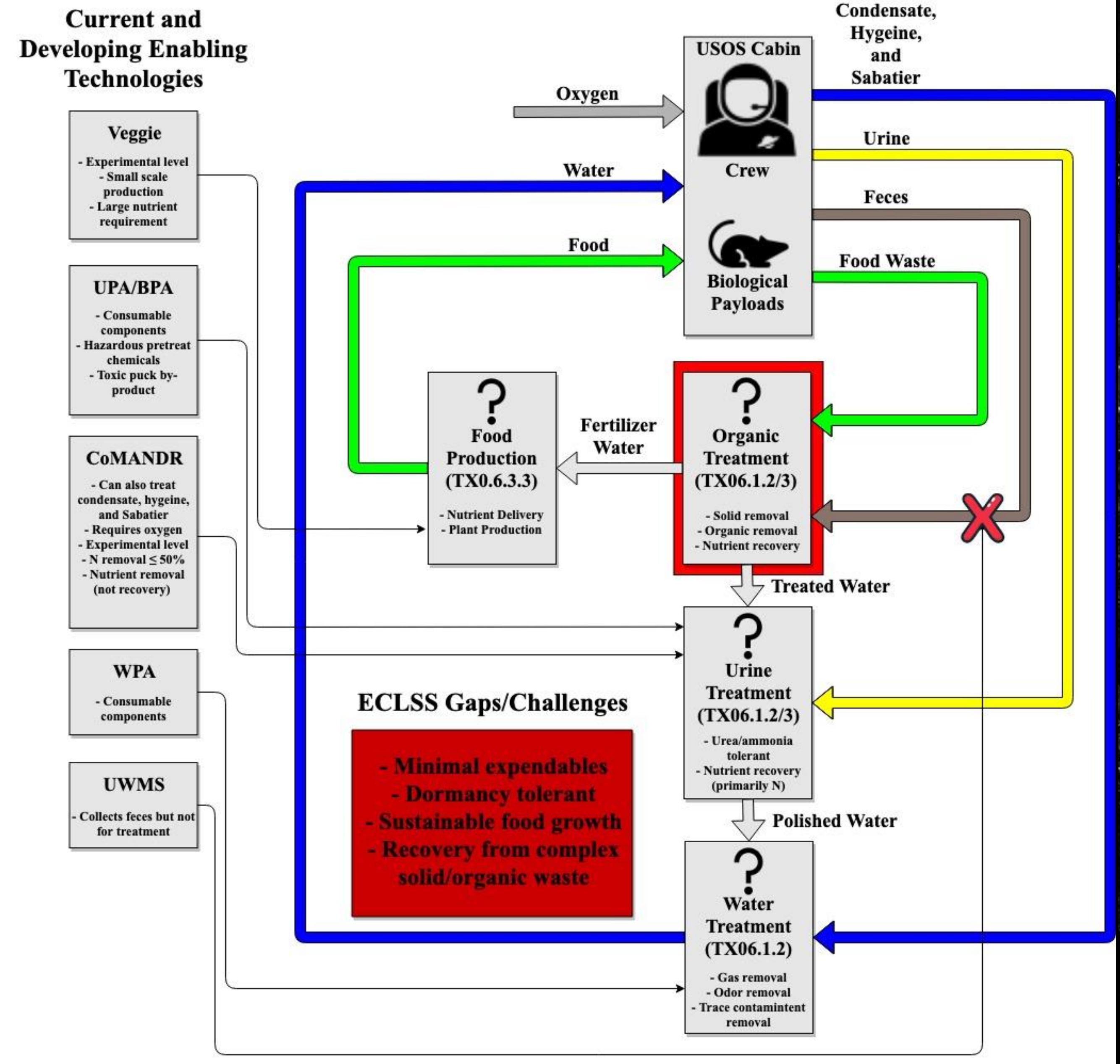
New ECLSS Technologies on ISS

Universal Waste Management System (UWMS)

- Fecal waste collected and sealed in hydrophobic bag
  - Not designed for fecal waste to be treated for recovery
- Consumable activated carbon filter to remove odor

Developing Future ECLSS

- Current and developing technologies available to enable addressing these gaps
  - EXCEPT concentrated waste (i.e., fecal/food)
- Benefits
  - Increased water recovery
  - Enables sustainable food production
  - Decreases requirement for waste storage



Current and Developing Enabling Technologies

Veggie
- Experimental level
- Small scale production
- Large nutrient requirement

UPA/BPA
- Consumable components
- Hazardous pretreat chemicals
- Toxic puck by-product

CoMANDR
- Can also treat condensate, hygeine, and Sabatier
- Requires oxygen
- Experimental level
- N removal ≤ 50%
- Nutrient removal (not recovery)

WPA
- Consumable components

UWMS
- Collects feces but not for treatment

USOS Cabin

Crew

Biological Payloads

Oxygen

Water

Food

Condensate, Hygeine, and Sabatier

Urine

Feces

Food Waste

Food Production (TX0.6.3.3)
- Nutrient Delivery
- Plant Production

Fertilizer Water

Organic Treatment (TX06.1.2/3)
- Solid removal
- Organic removal
- Nutrient recovery

Treated Water

Urine Treatment (TX06.1.2/3)
- Urea/ammonia tolerant
- Nutrient recovery (primarily N)

Polished Water

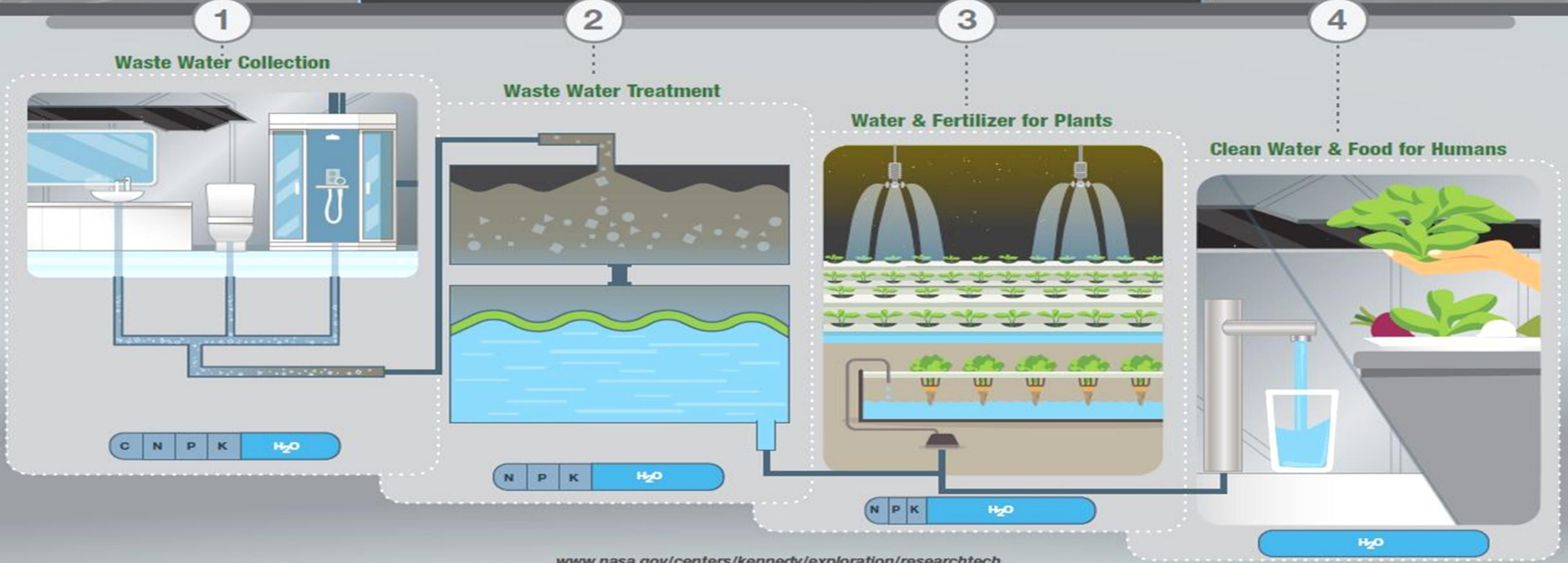
Water Treatment (TX06.1.2)
- Gas removal
- Odor removal
- Trace contamintent removal

ECLSS Gaps/Challenges
- Minimal expendables
- Dormancy tolerant
- Sustainable food growth
- Recovery from complex solid/organic waste

National Aeronautics and Space Administration

WATER: SUSTAINING LIFE ON THE MOON

Sustainably exploring the Moon will require a safe habitat for the crew. To stay on the Moon, new technology is needed to simulate Earth's environment that will reliably regenerate water, air, and food. Smart water recycling within the habitat will treat wastewater, provide necessary fertilizers and water for food crops, and create safe drinking water for our explorers. Proving these technologies will then take us to Mars and beyond.



1 Waste Water Collection

2 Waste Water Treatment

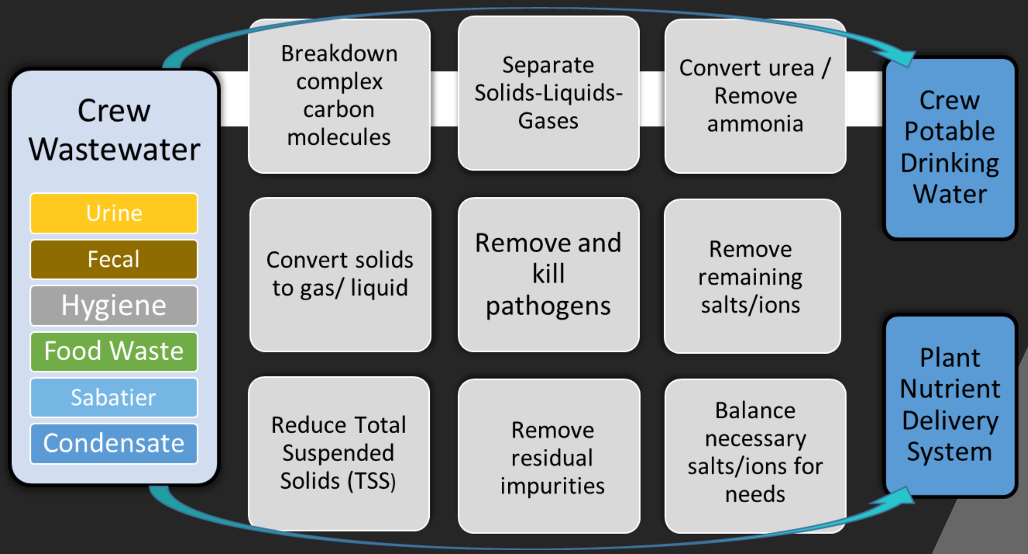
3 Water & Fertilizer for Plants

4 Clean Water & Food for Humans

www.nasa.gov/centers/kennedy/exploration/researchtech

www.nasa.gov

Functional Flow Block Diagram (FFBD) for EPB Treatment



Crew Wastewater
- Urine
- Fecal
- Hygiene
- Food Waste
- Sabatier
- Condensate

Breakdown complex carbon molecules

Separate Solids-Liquids-Gases

Convert urea / Remove ammonia

Convert solids to gas/ liquid

Remove and kill pathogens

Remove remaining salts/ions

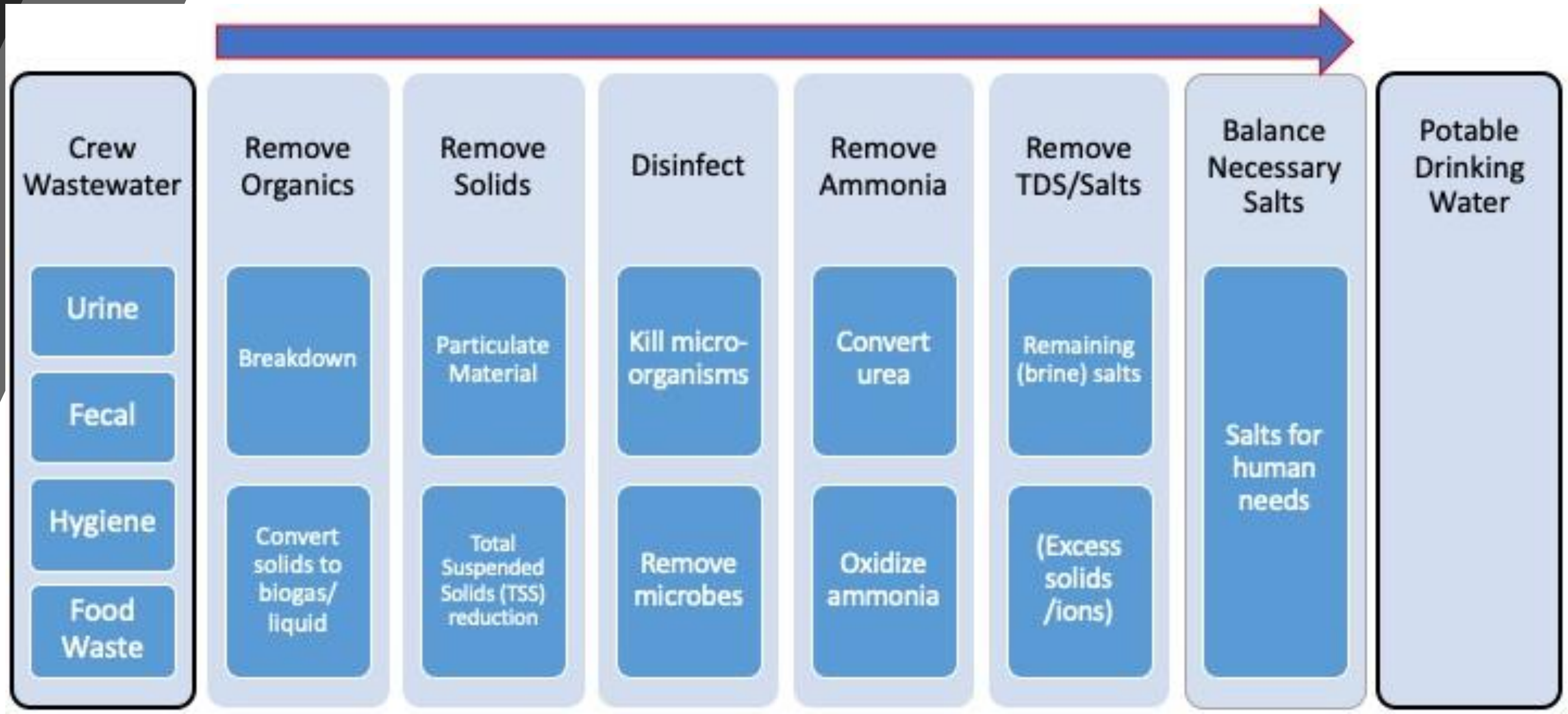
Reduce Total Suspended Solids (TSS)

Remove residual impurities

Balance necessary salts/ions for needs

Crew Potable Drinking Water

Plant Nutrient Delivery System



Crew Wastewater
- Urine
- Fecal
- Hygiene
- Food Waste

Remove Organics
- Breakdown
- Convert solids to biogas/ liquid

Remove Solids
- Particulate Material
- Total Suspended Solids (TSS) reduction

Disinfect
- Kill micro-organisms
- Remove microbes

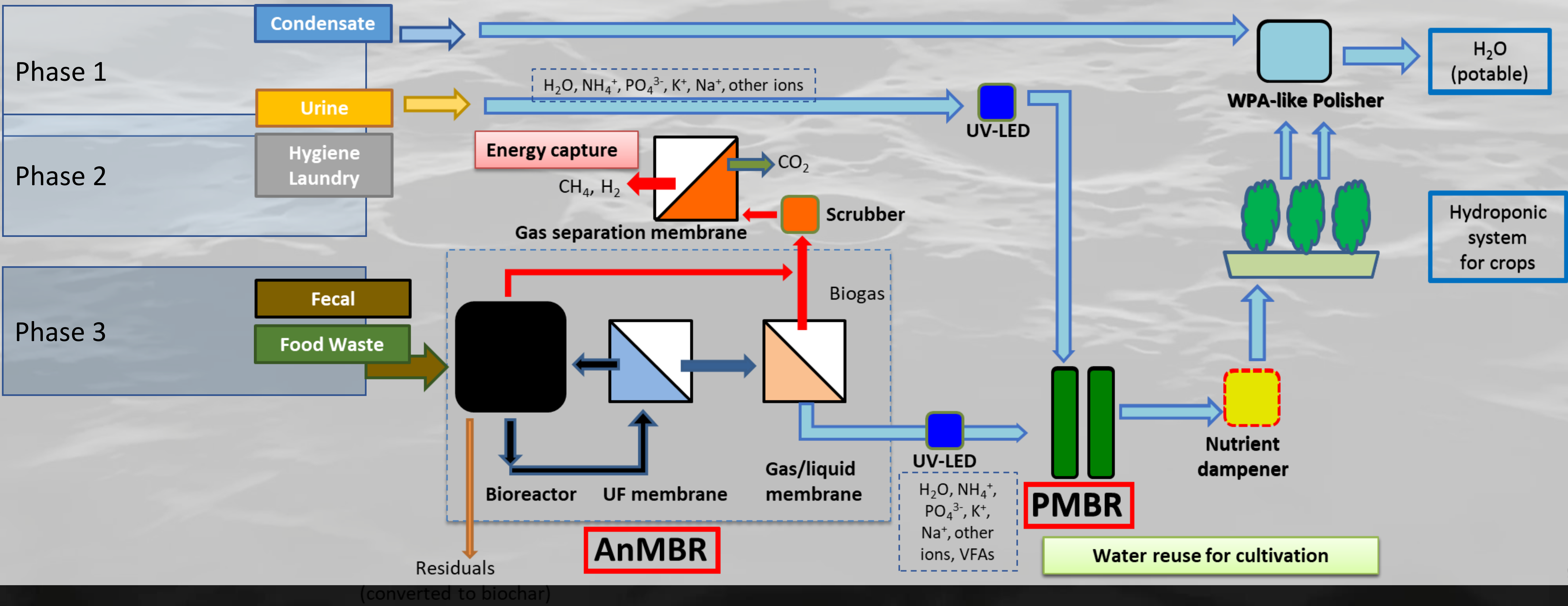
Remove Ammonia
- Convert urea
- Oxidize ammonia

Remove TDS/Salts
- Remaining (brine) salts
- (Excess solids /ions)

Balance Necessary Salts
- Salts for human needs

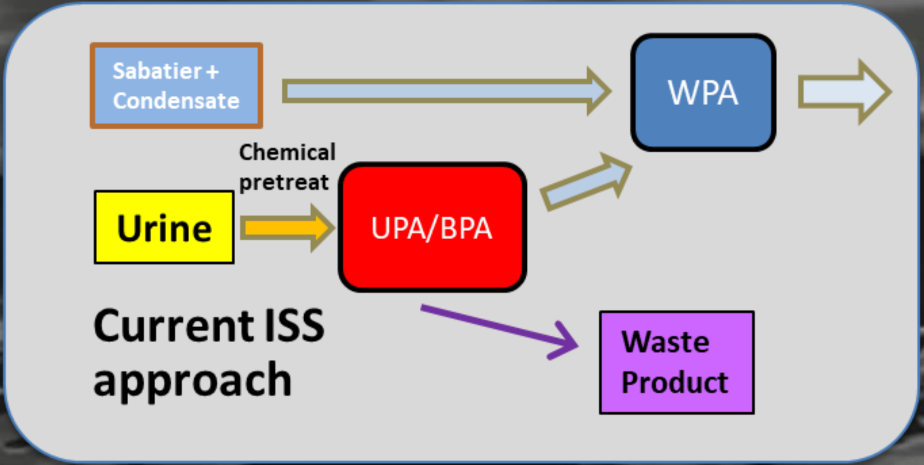
Potable Drinking Water

System Architecture Design



Patent Filed 6/29/21

System Architecture Approach for EPB



Sabatier + Condensate

WPA

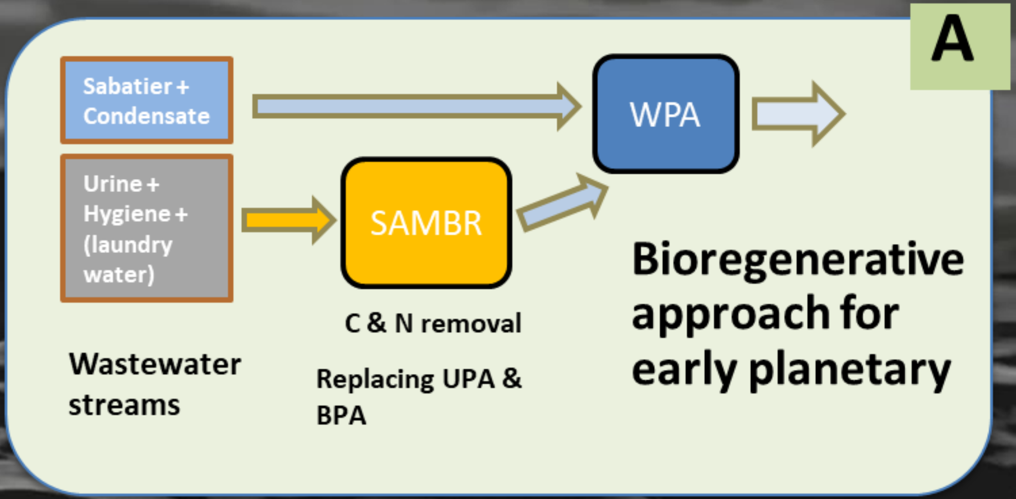
Chemical pretreat

Urine

UPA/BPA

Current ISS approach

Waste Product



A

Sabatier + Condensate

WPA

Urine + Hygiene + (laundry water)

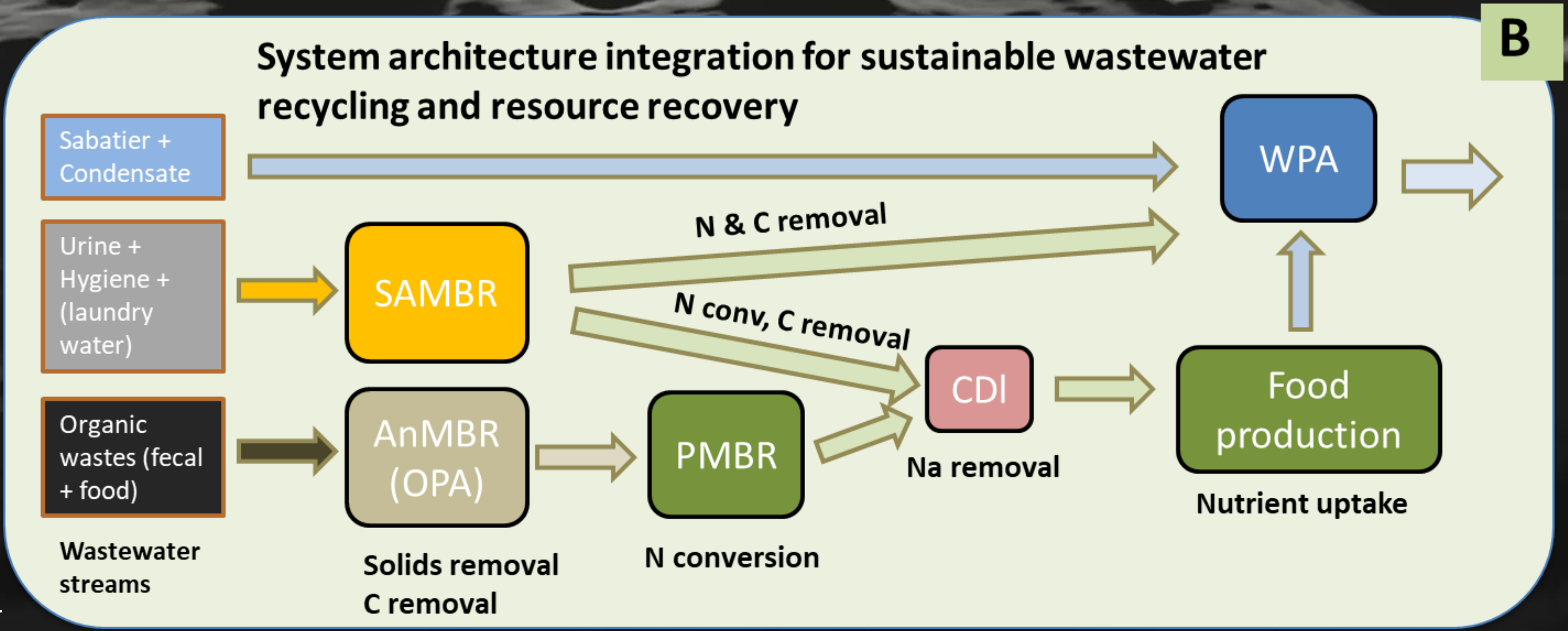
SAMBR

C & N removal

Wastewater streams

Replacing UPA & BPA

Bioregenerative approach for early planetary



B

System architecture integration for sustainable wastewater recycling and resource recovery

Sabatier + Condensate

WPA

Urine + Hygiene + (laundry water)

SAMBR

N & C removal

N conv, C removal

CDI

Na removal

Food production

Nutrient uptake

Organic wastes (fecal + food)

AnMBR (OPA)

PMBR

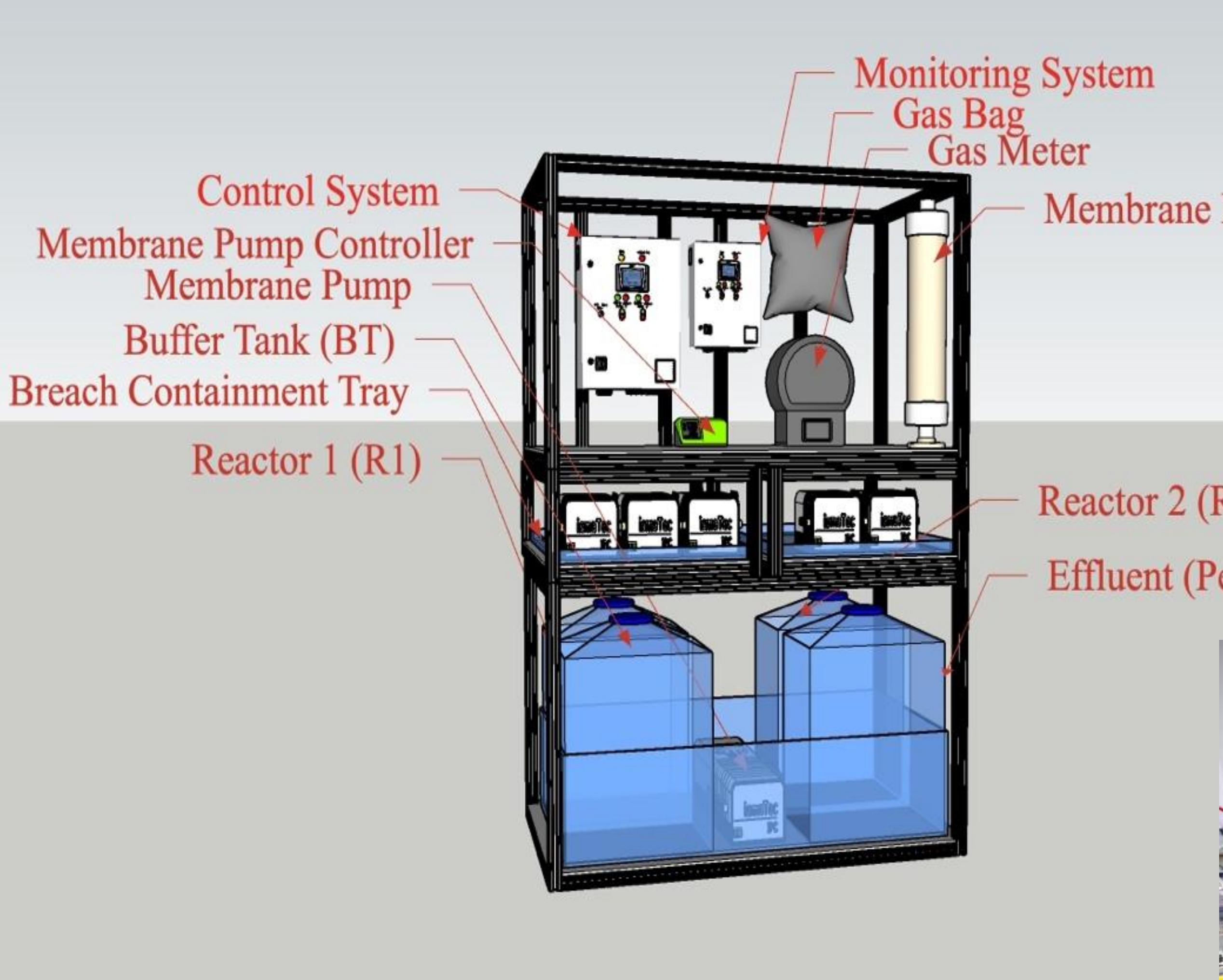
Wastewater streams

Solids removal
C removal

N conversion

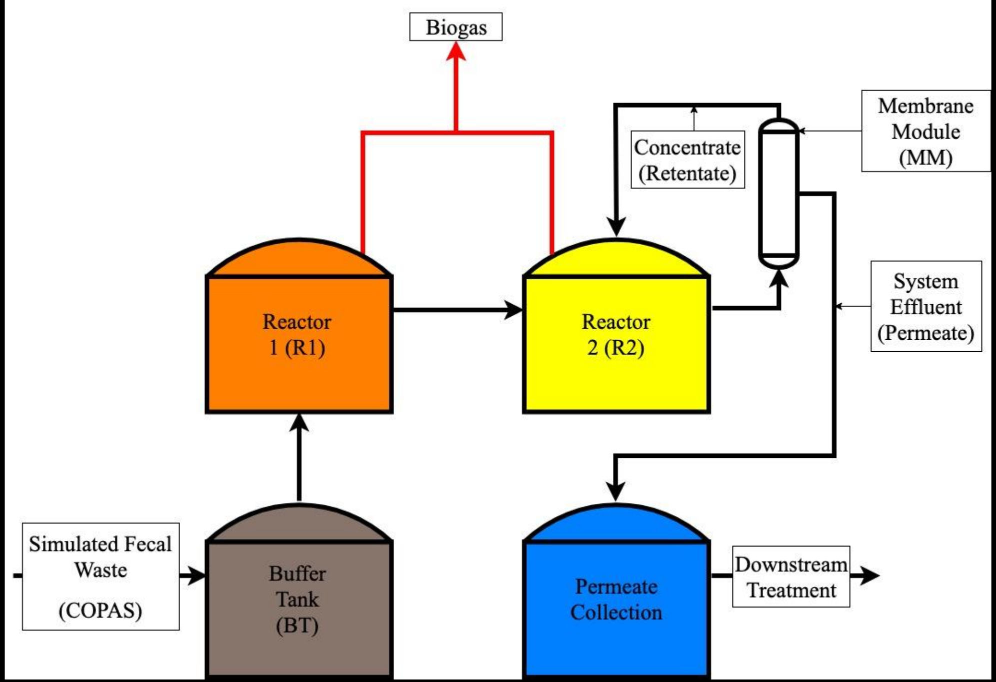
Patent Filed 6/29/21

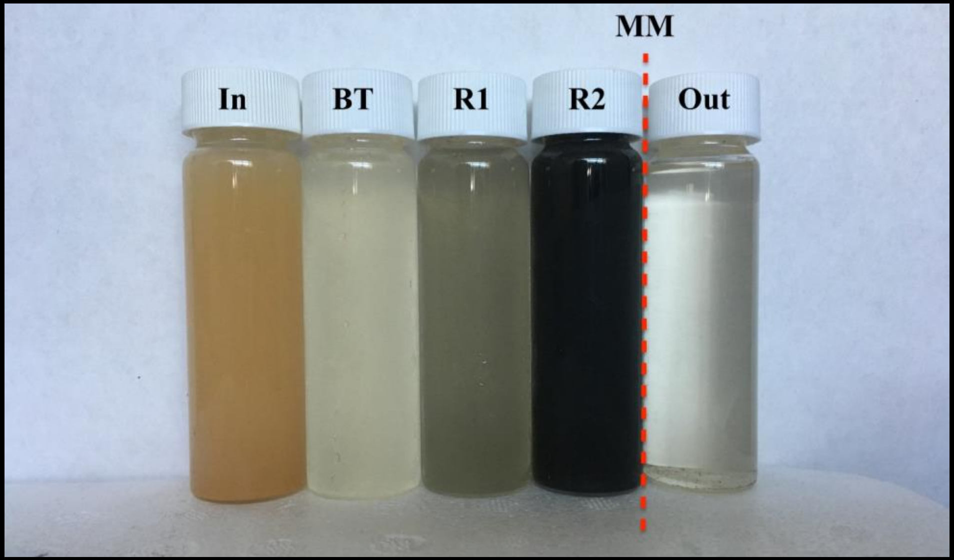
AnMBR Design and Fabrication



https://images.nasa.gov/details-KSC-20200819-PH-CSH01_00136

AnMBR Experimental Plan

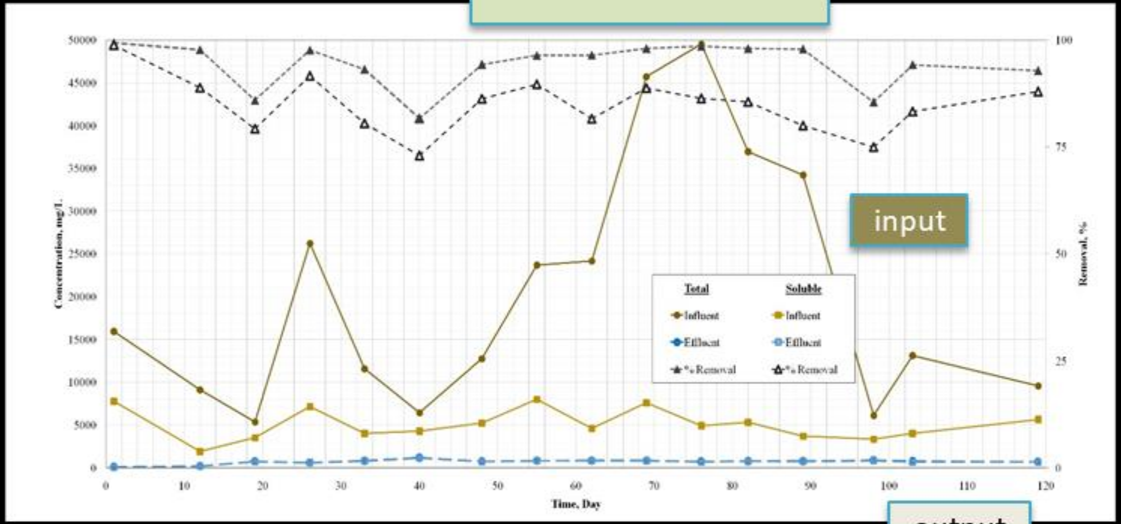




Waste Stream	Stage A	Stage B	Stage C	EPB Fecal and Flush
Solids (g/L)	1% (10)	3% (30)	5% (50)	5% (50)
Carbon (mg/L)	4761	14282	23803	21266
Nitrogen (mg-N/L)	566	1698	2830	2373
Phosphorous (mg/L)	140	420	700	791
COD (mg/L)	11902	35705	59508	N/A
COD Relative to Typical Municipal Wastewater	23x	71x	119x	
Organic Loading (OLR) (g-COD/L-d)	0.53	1.28	2.64	

AnMBR 1 Status Update from USF

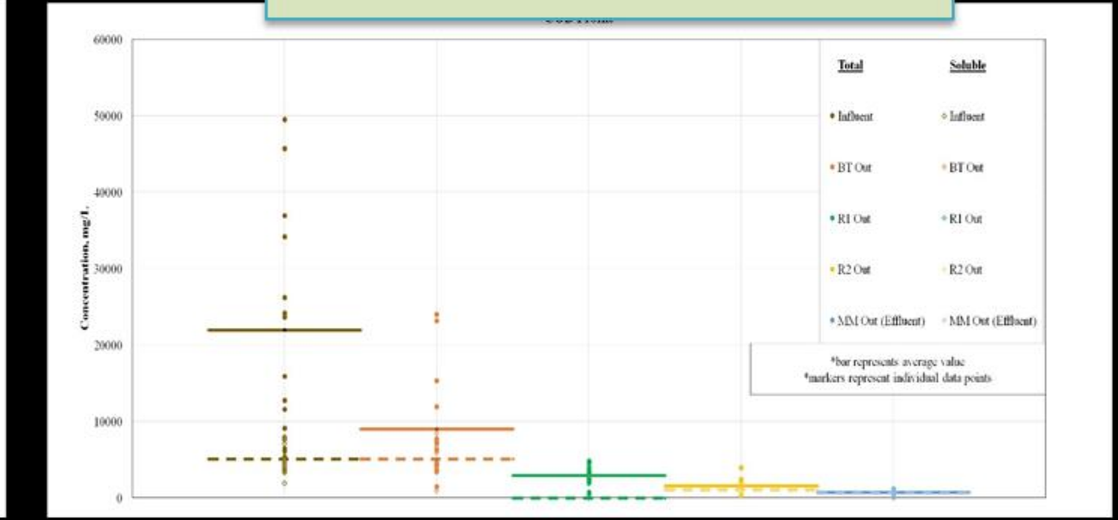
COD



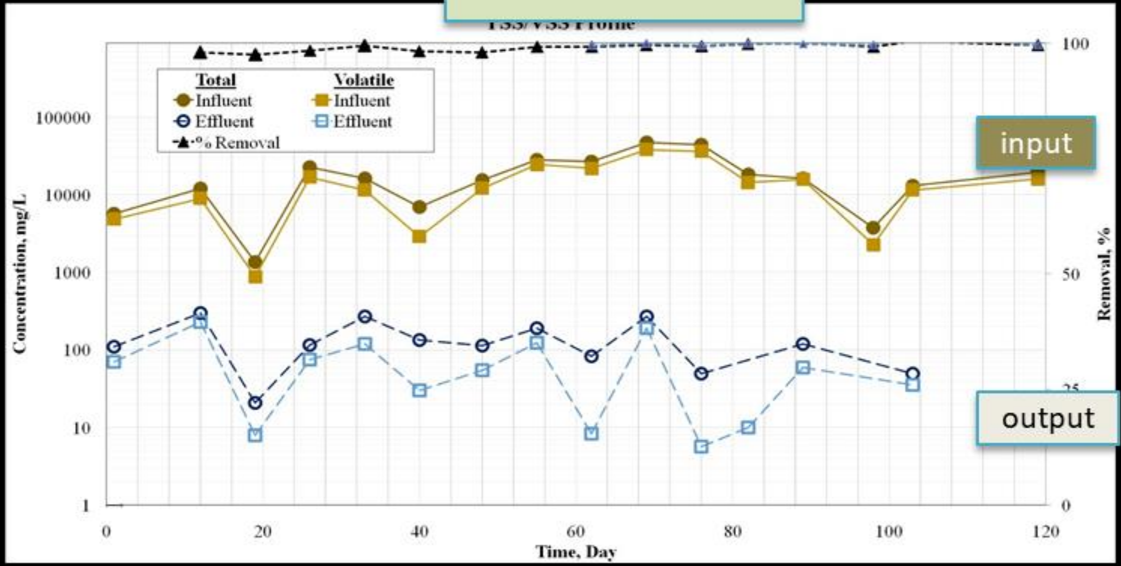
input

output

COD – reduction at each treatment step



Solids



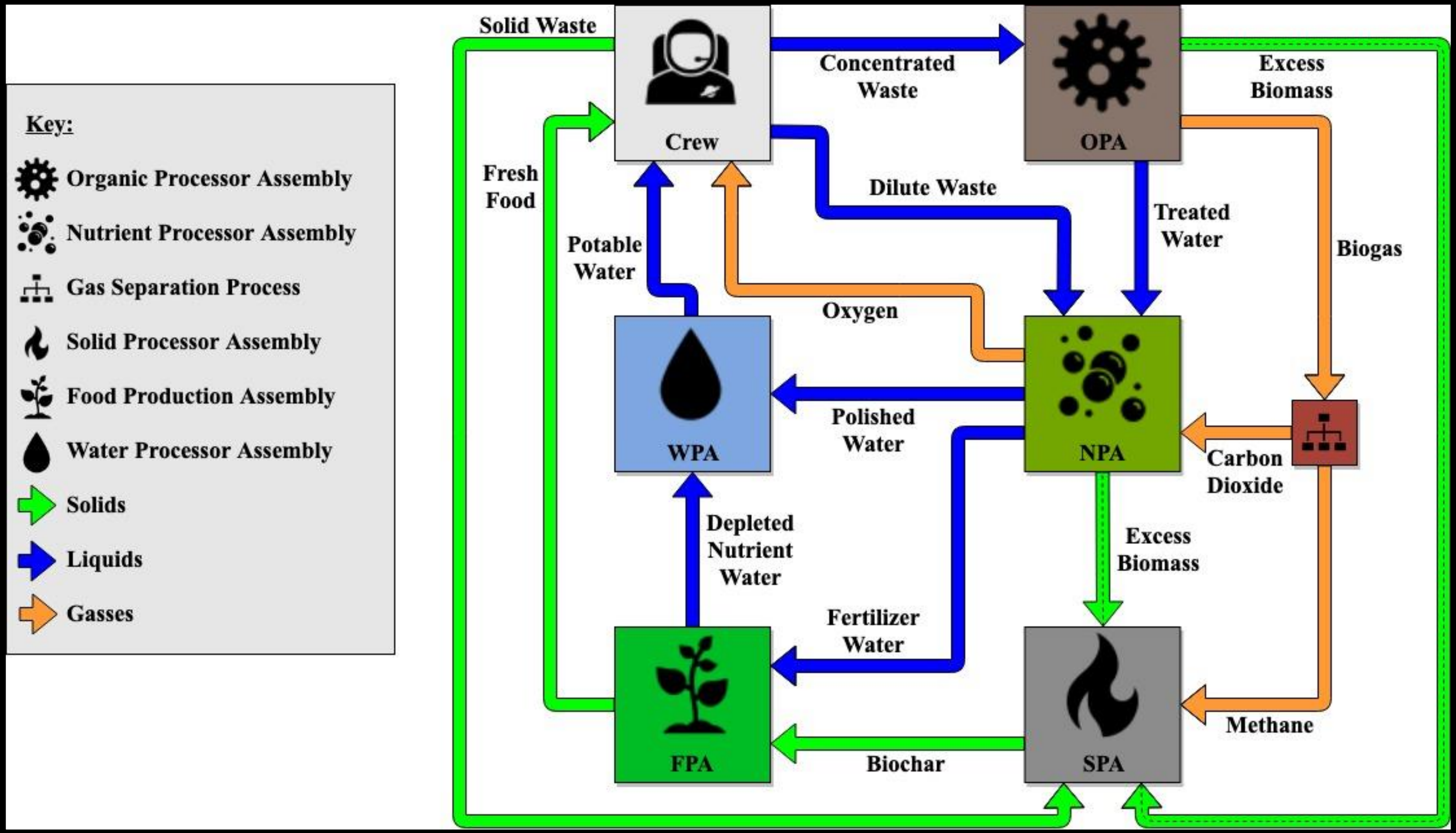
input

output

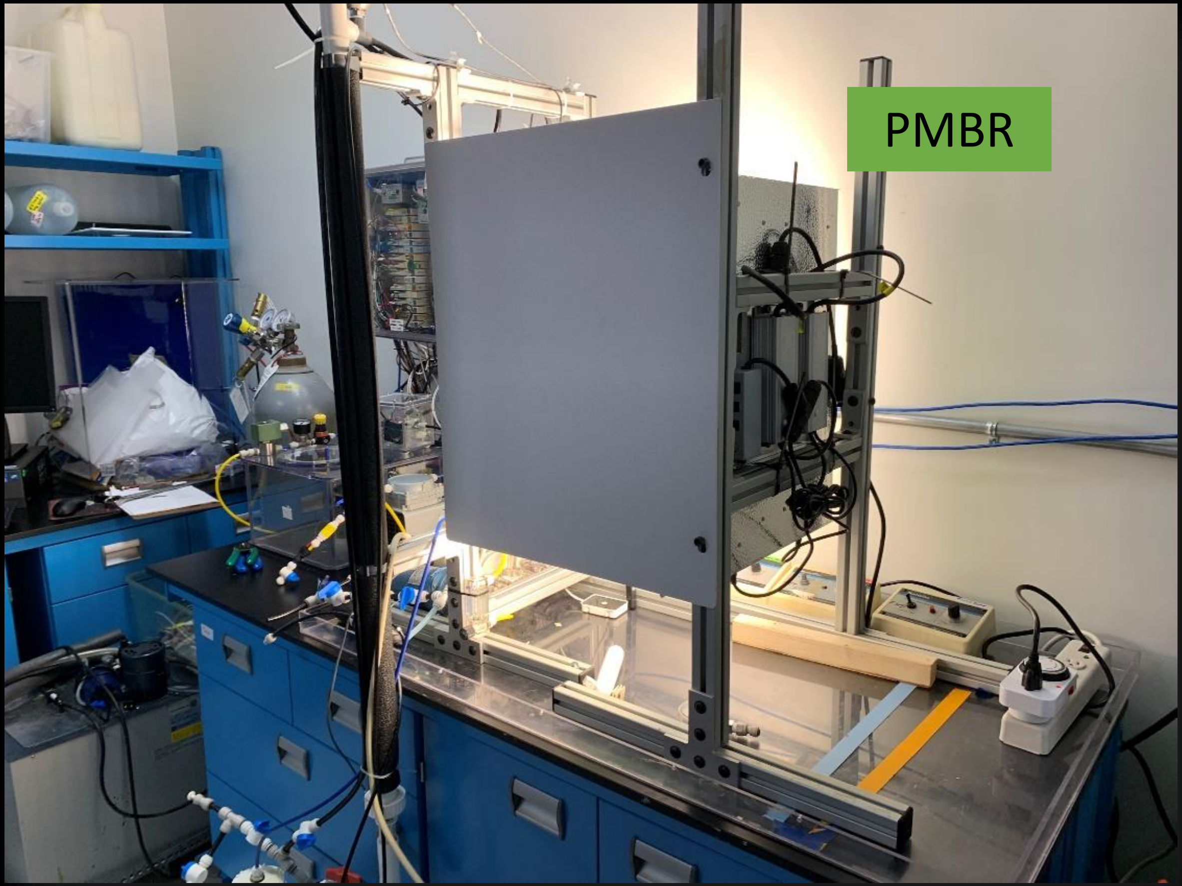
Solids – reduction at each treatment step

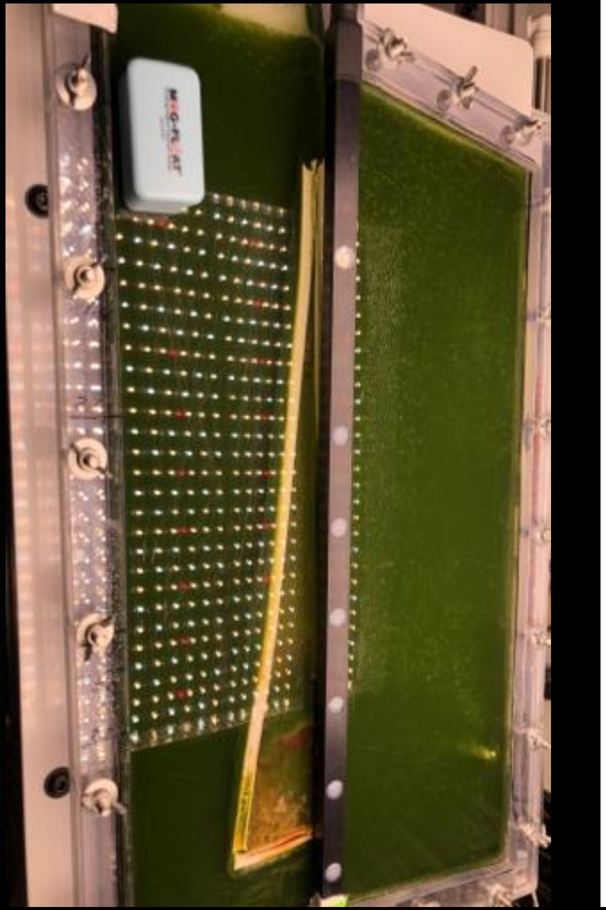
AnMBR Improvements and Future Work

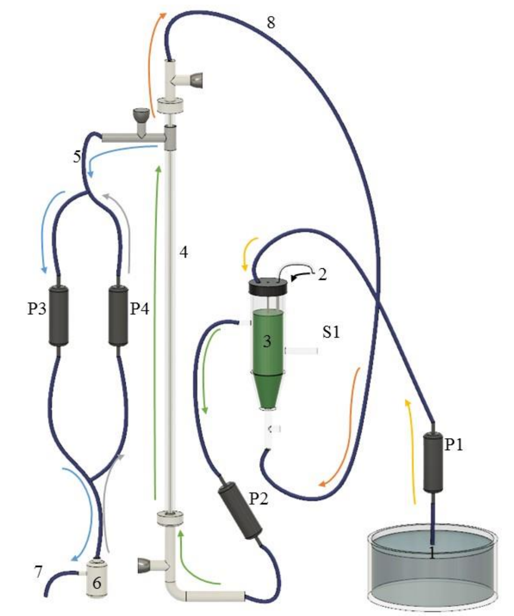
- Operating at full strength waste (5% solids)
- Expand to treat food waste
- Operate with real waste
- Enhanced pretreatment in BT
- Microbial static loop in permeate collection
- Integrate with complimentary systems for comprehensive sustainable architecture



PMBR Design and Fabrication



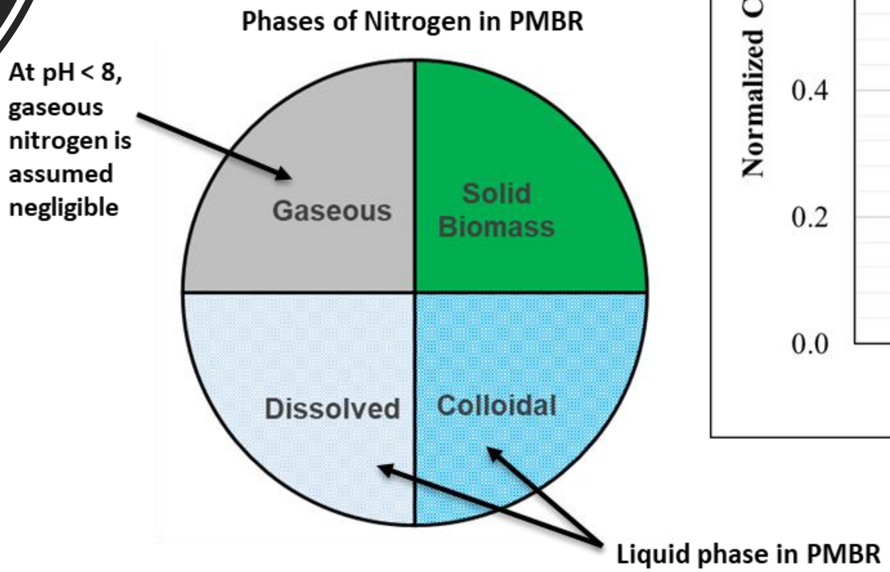


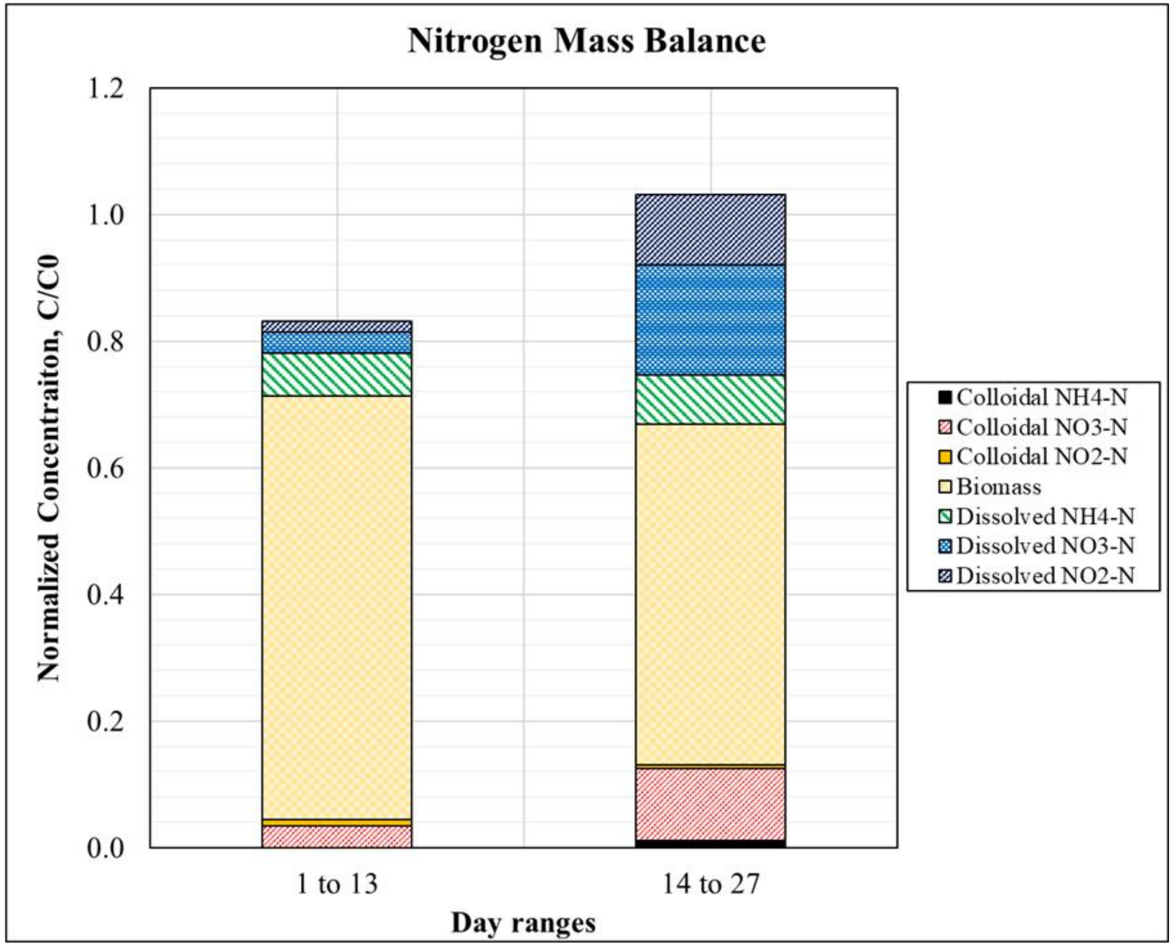


1	Feed Tank	5	Permeate/ Backwash	P1	Feed Pump	S1	Reactor Sample Port	→	Permeate (System Effluent)
2	Air in	6	Permeate Collection	P2	Membrane Feed Pump	→	Feed (Wastewater)	→	Backwash
3	Algae Bioreactor	7	Permeate Overflow	P3	Permeate Pump	→	Air Intake	→	Concentrate
4	Membrane Cartridge	8	Concentrate Return	P4	Backwash Pump	→	Algae Culture		

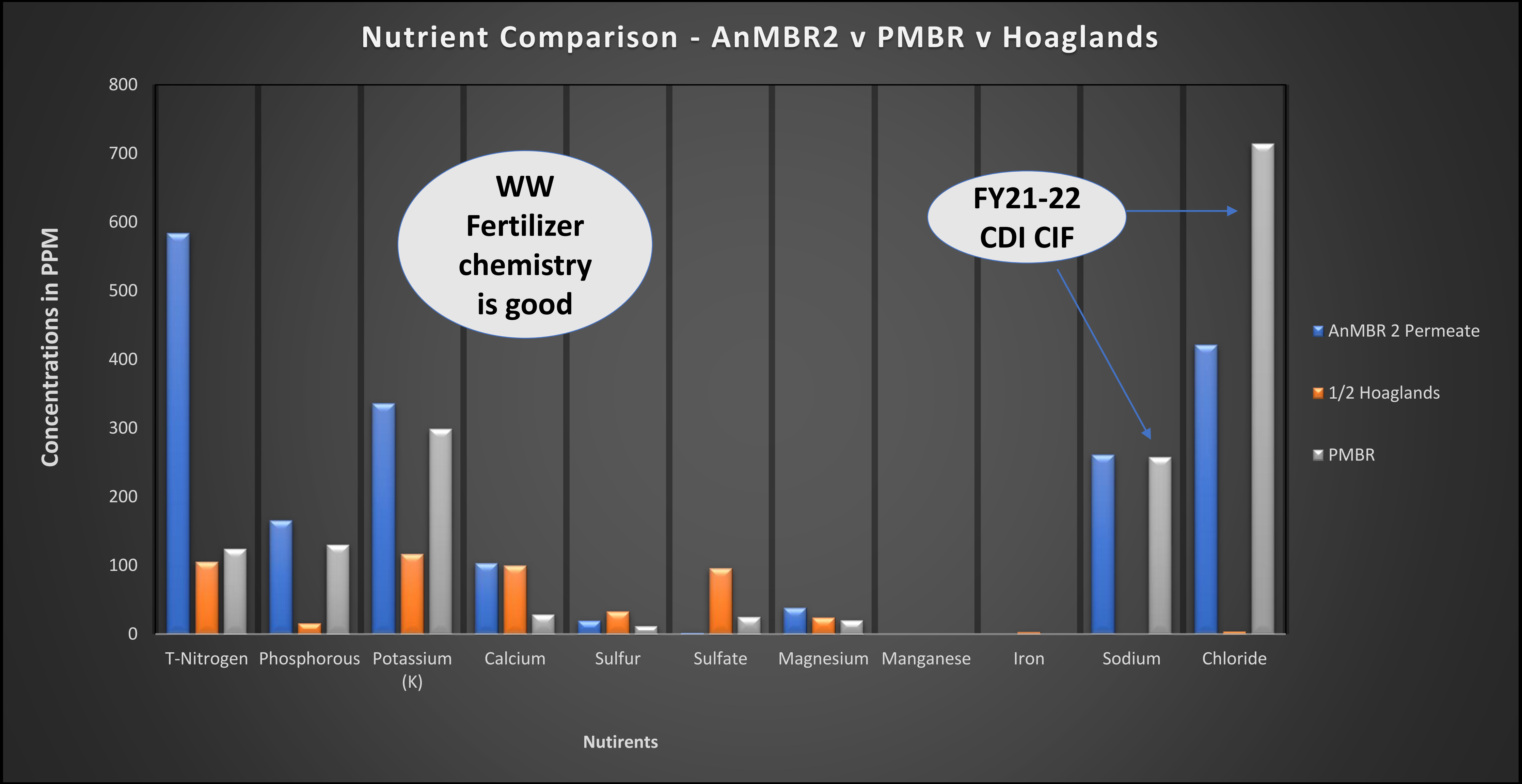
PMBR Nitrogen Balance

Daniella, Riley, and Jason in front of OPA 2 and PMBR





Wastewater as Fertilizer



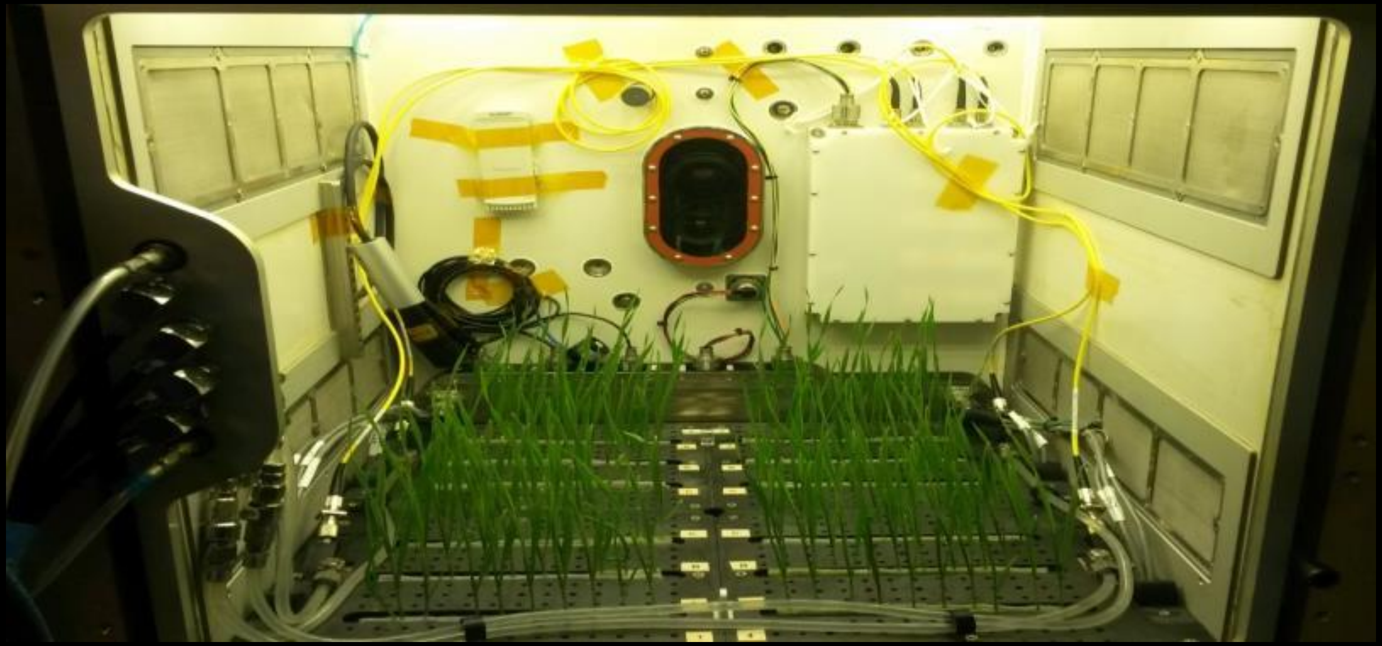
WW Fertilizer chemistry is good

FY21-22 CDI CIF

Food Production Challenges

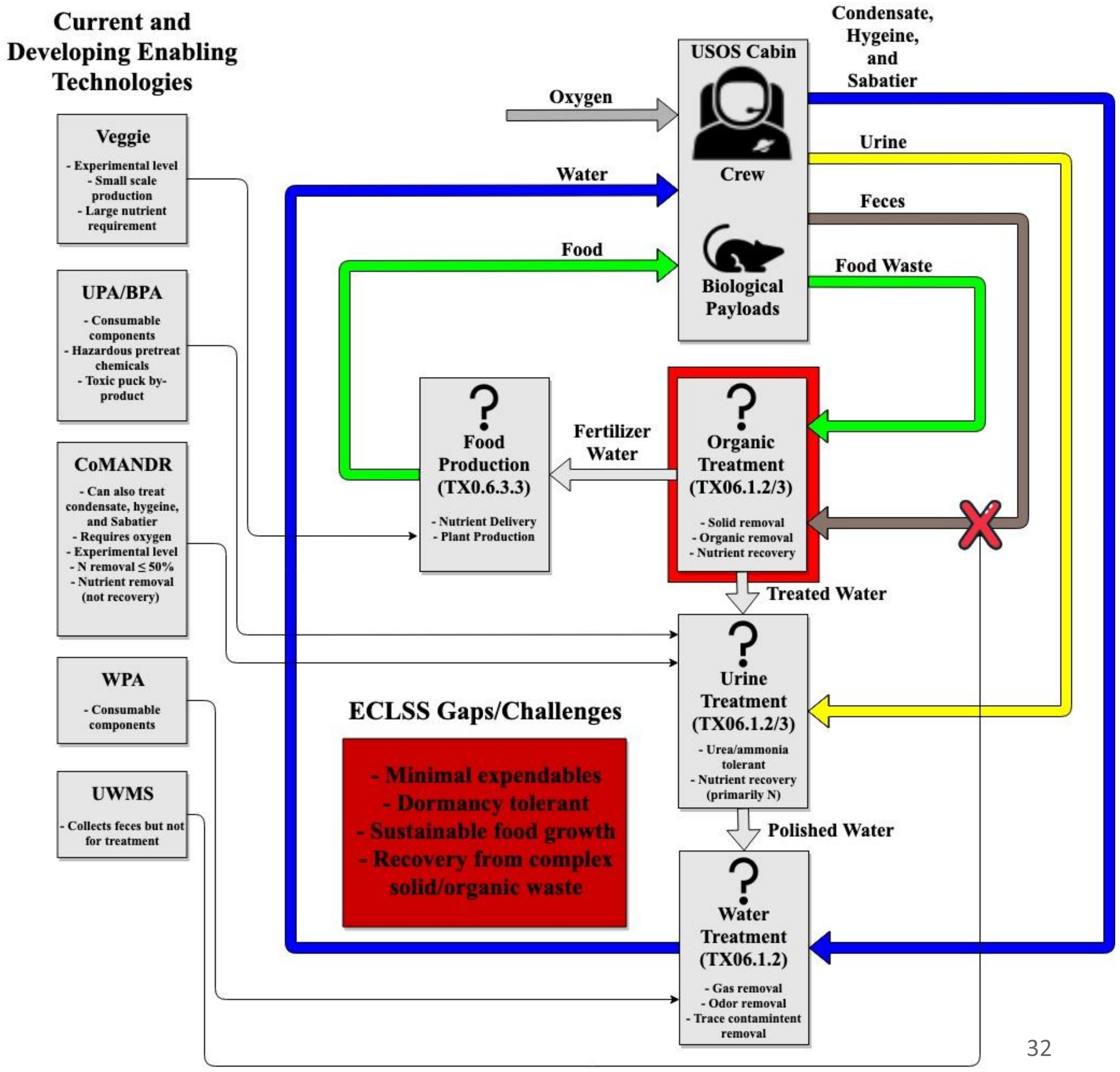
Sustainable technologies: Veggie/APH at TRL5, OHALO TRL 2

Cultivation resources (fertilizer, water, seeds) depend on resupply



Developing Future ECLSS

- Current and developing technologies available to enable addressing these gaps
  - EXCEPT concentrated waste (i.e., fecal/food)
- Benefits
  - Increased water recovery
  - Enables sustainable food production
  - Decreases requirement for waste storage



Current and Developing Enabling Technologies

Veggie
- Experimental level
- Small scale production
- Large nutrient requirement

UPA/BPA
- Consumable components
- Hazardous pretreat chemicals
- Toxic puck by-product

CoMANDR
- Can also treat condensate, hygeine, and Sabatier
- Requires oxygen
- Experimental level
- N removal ≤ 50%
- Nutrient removal (not recovery)

WPA
- Consumable components

UWMS
- Collects feces but not for treatment

USOS Cabin

Crew

Biological Payloads

Oxygen

Water

Food

Condensate, Hygeine, and Sabatier

Urine

Feces

Food Waste

?
Food Production (TX0.6.3.3)
- Nutrient Delivery
- Plant Production

Fertilizer Water

?
Organic Treatment (TX06.1.2/3)
- Solid removal
- Organic removal
- Nutrient recovery

Treated Water

?
Urine Treatment (TX06.1.2/3)
- Urea/ammonia tolerant
- Nutrient recovery (primarily N)

Polished Water

?
Water Treatment (TX06.1.2)
- Gas removal
- Odor removal
- Trace contamintent removal

ECLSS Gaps/Challenges

- Minimal expendables
- Dormancy tolerant
- Sustainable food growth
- Recovery from complex solid/organic waste

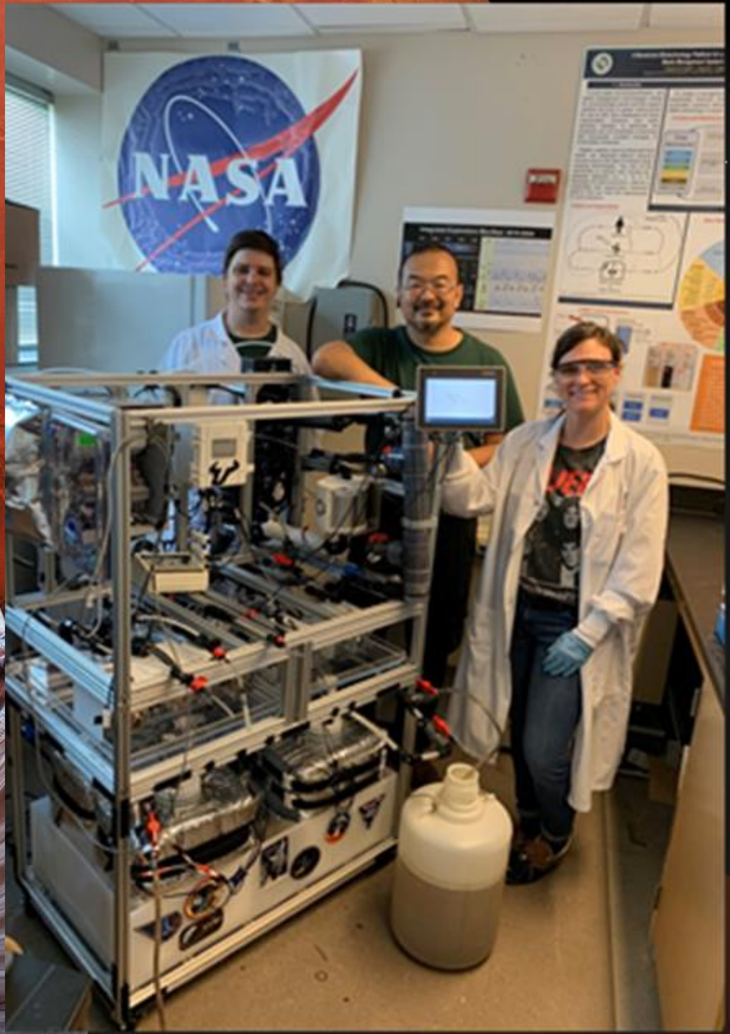
OPPORTUNITIES FOR YOU!!!

www.intern.nasa.gov

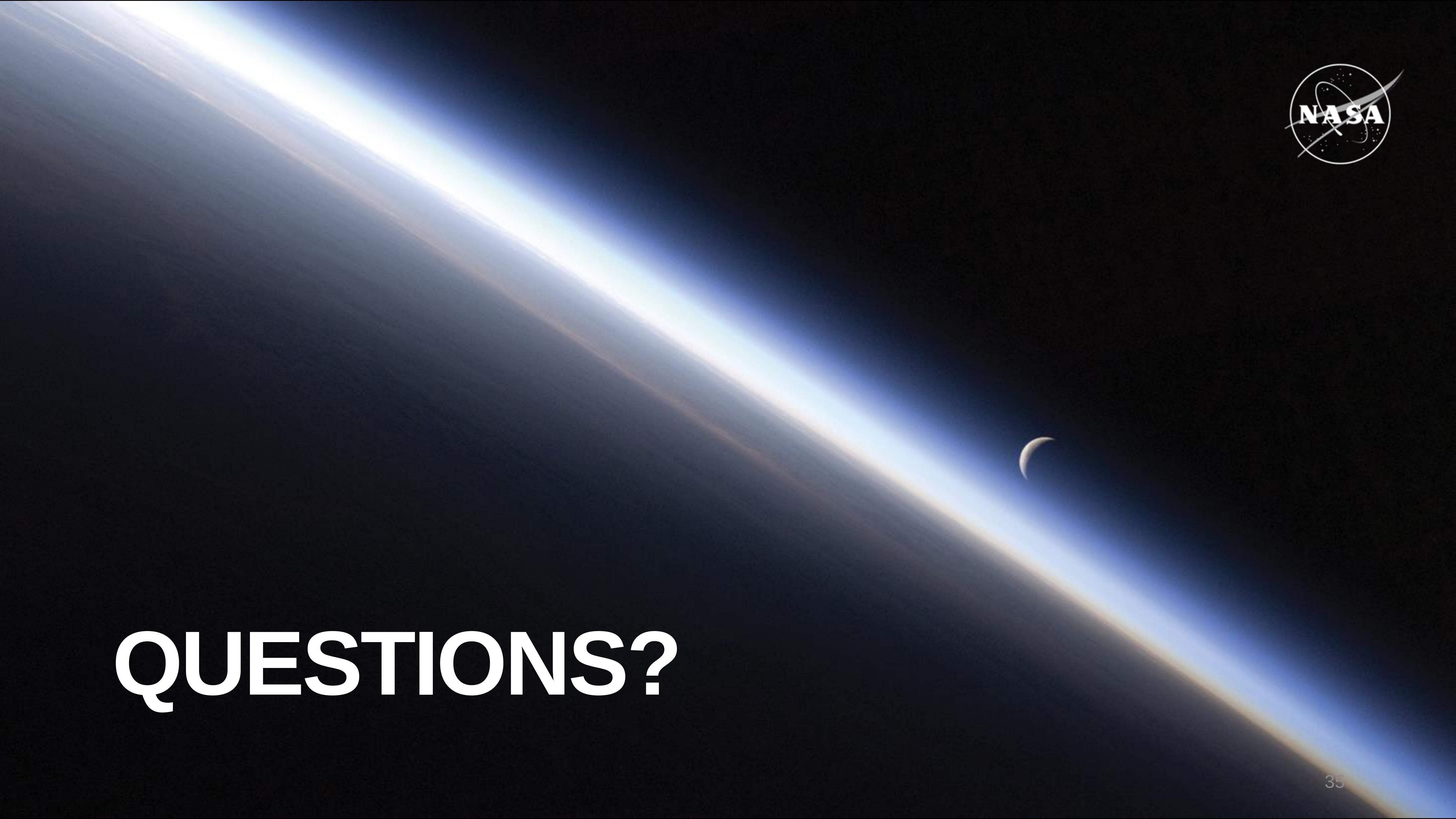
www.usajobs.gov

www.nspires.nasa.gov

www.KSCpartnerships.ksc.nasa.gov



Acknowledgements



QUESTIONS?