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National Aeronautics and Space Administration

Overview of Proposed ISRU Technology Development

Presented at the
Joint Space Resources Roundtable/Planetary & Terrestrial Mining and Sciences Symposium
June 7 - 9, 2016

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Introduction

- **NASA's Advanced Exploration Systems (AES) in the Human Exploration and Operations Mission Directorate (HEOMD) is assessing options for ISRU technology and system maturation focused on**
  - Volatiles resource acquisition
  - Volatiles and atmospheric processing into propellants and other consumable products
- **This presentation outlines preliminary definition of the objectives and approach of such an ISRU Technology Development plan**

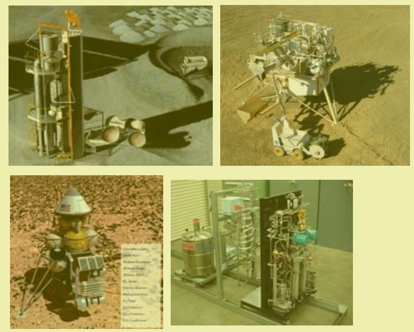
AES ISRU Technology Development Focus: Acquisition, Processing, Consumables Production

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural and discarded) to create products and services for robotic and human exploration

Resource Assessment (Prospecting)

Assessment of physical, mineral/ chemical, and volatile/ water resources, terrain, geology, and environment (orbital and local)

Resource Processing/ Consumable Production

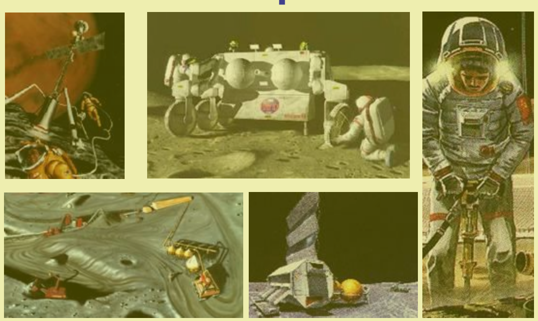


Processing resources into products with immediate use or as feedstock for construction and/or manufacturing
- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing

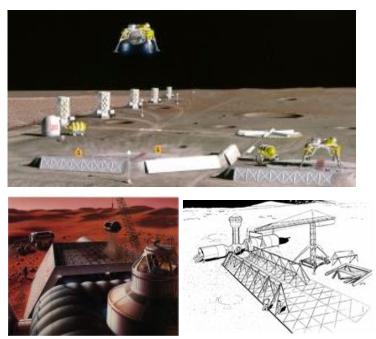
Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

Resource Acquisition



Extraction, excavation, transfer, and preparation before processing

In Situ Construction



Civil engineering, infrastructure emplacement, and structure construction using materials produced from in situ resources
- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy

Generation and storage of electrical, thermal, and chemical energy with in situ derived materials
- Solar arrays, thermal wadis, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, thermal management, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

Proposed Location and Resource Focus

- Focus on Mars O_2/CH_4 end-to-end system demonstration as primary long-term objective with the following rationale:
  - Regolith acquisition and processing should / could be similar for Mars and for lunar icy soils, so we will be advancing that subsystem for both locations simultaneously
    - Responds to current EMC requirements/plans for Mars
    - Keeps options open for ISRU proving ground demos on the Moon/asteroids and for using lunar volatiles as a resource
  - Atmosphere processing technology development can be structured around common components/subsystems needed for both CH_4 production from atmosphere/soil-water and O_2-only production from atmosphere
    - Leverage on-going work and maintain flexibility to evolving architecture
    - CO_2 acquisition and compression, water separation/condensation, water electrolysis, and gas / gas separation and recirculation subsystems all needed in multiple production system options
    - Advancing and scaling up Mars atmosphere-only subsystem and building off of/using lessons learned from MOXIE
  - Both regolith processing and CH_4 production can attract outside industries

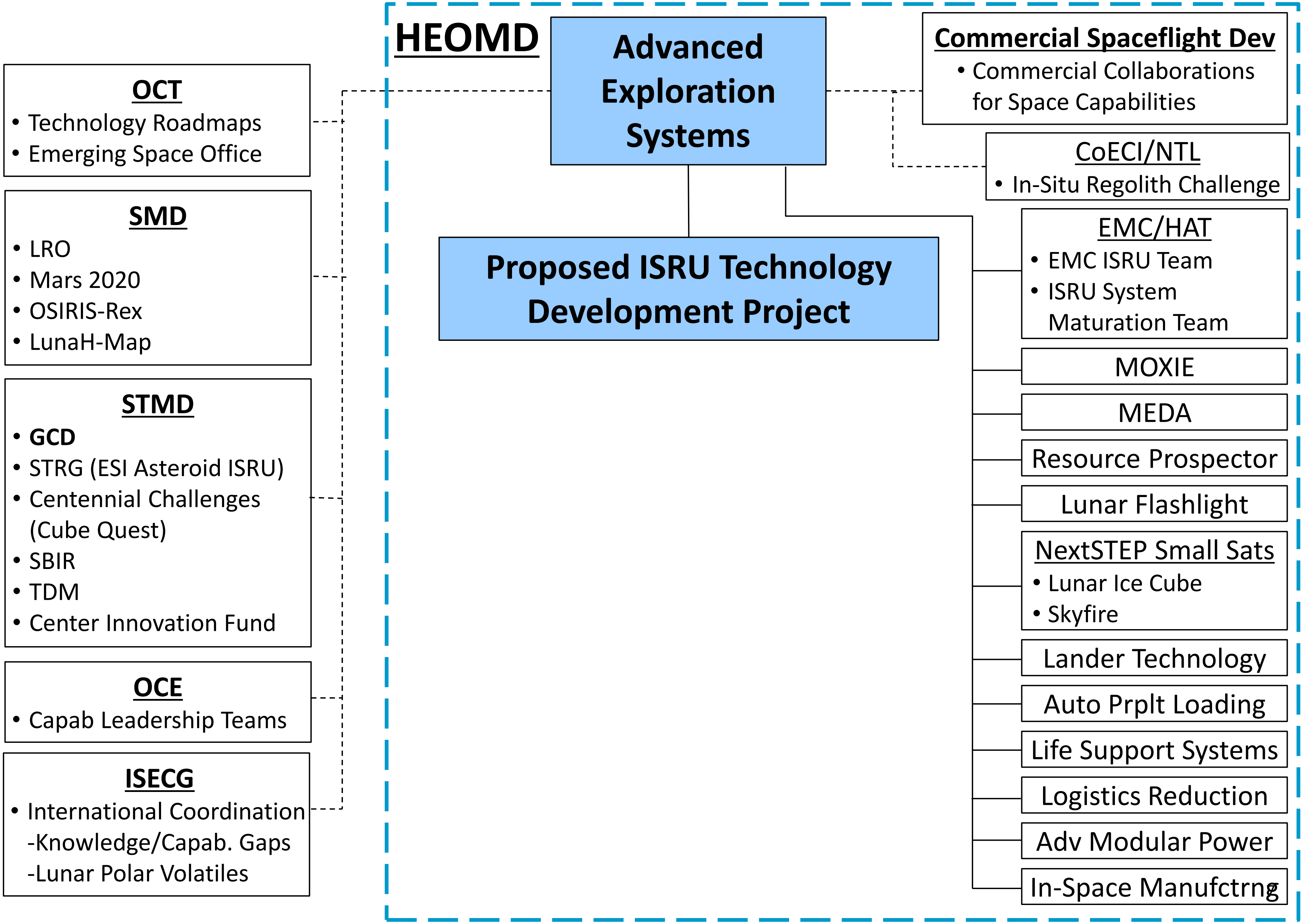
ISRU Technology Development Needed Now

- **ISRU is a *disruptive* capability**
  - Enables more affordable exploration than today's paradigm
  - Allows more sustainable architectures to be developed
- **Understand the ripple effect in the other Exploration Elements**
  - MAV: propellant selection, higher rendezvous altitude (higher DV capable with ISRU propellants)
  - EDL: significantly reduces required landed mass
  - Life Support: reduce amount of ECLSS closure, reduce trash mass carried through propulsive maneuvers
  - Power: ISRU drives electrical requirements, reactant and regeneration for fuel cells for landers, rovers, and habitat backup

ISRU Technology Development Needed Now (cont)

- **Every Exploration Element *except* ISRU has some flight heritage (power, propulsion, habitats, landers, life support, etc.)**
  - ISRU will require flight demonstration missions before it will be included in the critical path
    - Mission needs to be concluded at least 10 years before first human landed mission to ensure lessons learned can be incorporated into final design
  - ISRU Formulation team has generated a (still incomplete) list of over 75 technical questions on more than 40 components and subsystems that need to be answered before the ‘right’ ISRU system will be ready for this flight demo

Current NASA ISRU Landscape



ISRU State-of-the-Art: Resource Acquisition, Processing, Consumables Production

- Significant work has been performed to demonstrate feasibility of ISRU concepts and develop components and technologies (TRL 1-3)
  - Moon/Mars
    - Mars atmosphere collection, separation, and processing into O_2 or O_2/CH_4
    - Lunar regolith excavation, beneficiation, and processing to extract O_2
    - Civil engineering/soil stabilization
  - Asteroid
    - Acquisition concept work is just starting through STMD-ESI, BAAs, and SBIR/STTRs
- Some development & testing has been performed at the system level (TRL 4-6)
  - Moon (Lab, Analog sites)
    - RESOLVE, PILOT, ROxygen
  - Mars (Lab, Environment)
    - Portable Mars Production Plant (early ‘90s), MIP (flight experiment for cancelled Mars ’01)
- However, **significant work is needed to mature these technologies**
  - Development & testing much closer to full-scale for human mission needs
  - Much longer operational durations
  - Much more testing outside the laboratory to validate performance under relevant environmental conditions
  - Integrate many components and subsystems into system prototypes
  - Realize synergy between ISRU and other system technologies, such as life support/fuel cell, power, surface mobility

ISRU Critical Challenges That Need to Be Addressed

- What is the 'right' set of components and subsystems to enable production of mission consumables from either regolith or atmospheric resources at a variety of destinations?
- What is the performance and life that can be expected from the ISRU system in the actual environment?
- *How does the ISRU system integrate and interact with other systems (e.g., power, lander, life support, etc.)*?
  - ConOps
  - Power sharing
  - Total surface thermal management
  - Maintenance and refurbishment

Overall Goal: System-level TRL 6 to support future Pathfinder missions

Objectives and Approach

- **Initial focus**
  Critical Technology Gap Closure
  – icy/hard soil excavation, soil-water extraction, microchannel reactors, gas and water cleanup and separations, solid oxide stacks and life
  Component Development in relevant environment (TRL 5)
  – Better control of test conditions to identify which operating parameters critically affect performance
  – Provide parametric data to validate and improve analytical models

- **Interim Goal:** *ISRU Subsystems Tests in relevant environment (Subsystem TRL 6)*
  – Use subsystem testbeds (CO_2 acquisition and compression, O_2 production, CH_4 production, water electrolysis, icy and hydrated soil acquisition, water extraction) to evaluate multiple technology options before downselect
  – Continue to use testbeds for new component technologies and long-duration testing

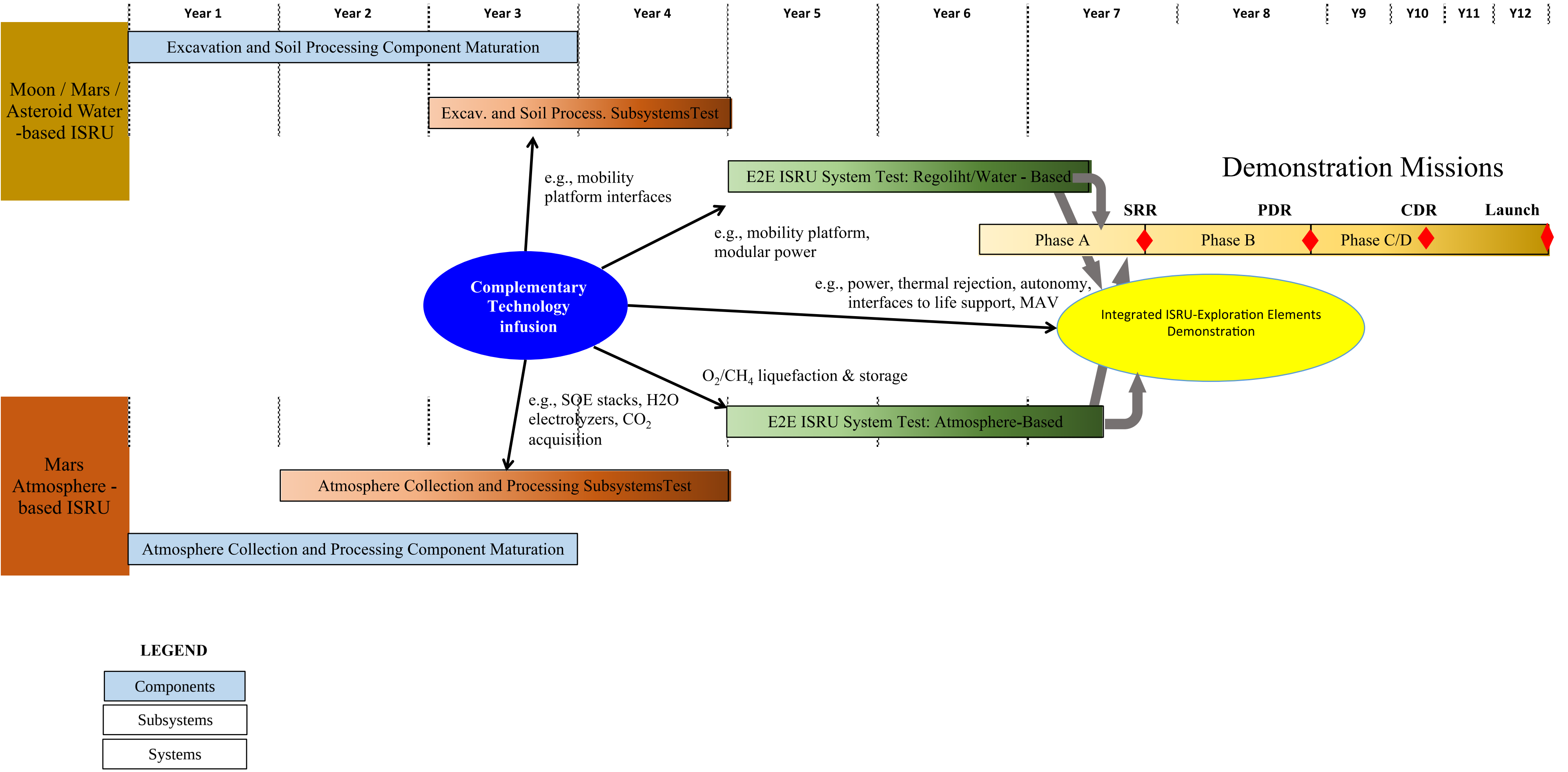
- **End-Goals**
  End-to-end ISRU System Tests in relevant environment (System TRL 6)
  – Oxygen & fuel production from atmosphere and soil resources including liquefaction and storage
  Integrated ISRU-Exploration Elements Demonstration in relevant environment
  – E2E ISRU System integrated with power system (including excavator recharging station), thermal rejection system, autonomous control, and interfaces to life support, MAV/Lander

Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, and volume of ISRU Systems

Complementary Technologies

- Complementary technologies needed for Integrated ISRU Demo include:
    - Water electrolyzers and subsystem components
    - CO_2 acquisition/sequestration components
    - Advanced solid oxide stacks for CO_2 reduction
    - O_2 and CH_4 liquefaction and storage subsystems
    - Mobility platform
    - High specific-power batteries for excavation and delivery

Possible Technology Development Schedule



Bottoms-up approach - example

CO2 Freezer	Design Questions
Requirements: CO2 collection rate, outlet pressure (minimum), purity of the CO2	What is the optimal thickness of frozen CO2 to design cold head surface area to balance time to acquire and power efficiency? (i.e., power to freeze additional CO2 increases as thickness increases
Requirements Drivers: Outlet Pressure: comes from SOE (lower pressure), RWGS and Sabatier (higher pressure better) CO_2 collection rate: 1) O_2 production rate required, 2) CO_2 conversion efficiency (O_2 production method and CO_2 recycling)	
	Size of vessel compared to cold head: Space between cold fins and wall - bigger vessel means lower max pressure upon thaw (i.e., becomes all vapor sooner) so thinner walls, but affects incoming flow around cold head and then heat transfer into cold head during thaw if walls too far away?
	How do you get good flow around the cold head as you scale up and the cold head becomes bigger and more complicated, and what is the scale limit?
	How do you control the flow (both pressure and mass flow) as you drain the pressurized CO_2 acquisition vessel, the temperature starts dropping along the liquid/vapor saturation curve)?
	Cryocooler scale up: efficiency needed? Type of cycle needed?

Summary

- An ISRU Technology Development plan has been proposed to the HEOMD AES program
  - Focus on acquisition and consumables production and storage
  - Component –> subsystem -> system progression
- Raise System-level TRL in preparation for potential demonstration mission
- Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, volume, and concept of operations

Back-up Slides

4.1 Atmosphere Carbon Dioxide (CO_2) Collection Subsystem

Dust Filtration / Mitigation

- Media filter
- Mechanism(s) to renew and/or clean filter media
- Electrostatic filter device
- Mechanism(s) to clean out electrostatic filter components
- Electronics for electrostatic filter
- Inlet duct and filter housing

Atmosphere Blower

- Low pressure/density gas blower with small (~2:1) compression ratio

CO2 Separation, Collection, and Pressurization

- High efficiency cryocooler (150 K cold-finger)
- CO2 collection chamber and cold head
- CO2 mass/pressure control for CO2 freezer
- Microchannel sorption pump(s) (multiple stages)
- Hot/cold thermal management system for sorption pumps
- Mechanical compressor (>100:1 pressure ratio)
- CO2 / atmospheric gas separation
- CO2 collection / buffer tank for sorption pumps and/or mechanical compressor

→

4.2 O2 Production Subsystem

4.3 Methane Production Subsystem

4.2 Oxygen (O_2) Production Subsystem (4.2.1 Reverse Water Gas Shift option)

4.1 CO_2 Acquisition Subsystem

Reverse Water Gas Shift reactor

H2O / gas separation (condenser)

Reactant / Product Recirculation

CO / CO2 separator

4.4 H2O Electrolysis Subsystem

- Conventional RWGS reactor
- Microchannel RWGS reactor
- RWGS catalyst
- Thermal and flow management components
- CO, CO2, and H2 sensors for flow control

- Water condenser
- Heat exchanger / thermal management components

- CO / CO2 separation
- Gas recirculation compressor

O_2

4.2 Oxygen (O2) Production Subsystem (4.2.2 SOE option)

4.1 CO2 Acquisition Subsystem

Solid Oxide Electrolyzer

- Solid oxide multi-cell stack(s)
  - Gas manifolds
  - Ceramic-to-metal plumbing connections
  - Electrical connections / interface plate
- Thermal management:
  - Heat exchangers
  - Heaters (800 °C min)
  - Insulation
  - Structure, furnace housing
- Flow management
- O_2 and CO sensors on outlets

Reactant / Product Recirculation

- CO / CO_2 separation
- Gas recirculation compressor (high- or low-temperature)
- Gas-gas heat exchanger

4.5 Product Storage Subsystem

O_2

4.3 Methane (CH_4) Fuel Production Subsystem

4.1 CO2 Acquisition Subsystem

Sabatier Reactor

H2O / gas separator (condenser)

H2 / CH4 separator

4.4 H2O Electrolysis Subsystem

4.5 Product Storage Subsystem

Sabatier Reactor

- Conventional Sabatier reactor
- Microchannel Sabatier reactor
- Sabatier catalyst
- Thermal and flow management components
- Gas species sensors for flow control
  - H_2, CO_2 on inlet
  - CH_4, CO_2, and H_2 on outlet

H2O / gas separator (condenser)

- Water vapor/gas separation
- Water condenser
- Heat exchanger / thermal management components

H2 / CH4 separator

- H_2 / CH_4 electrochemical separator
- H_2 / CH_4 membrane separator
- H_2 / CH_4 adsorption separator
- Gas recirculation compressor
- Regenerative CH_4 dryer

O_2

4.4 Water Electrolysis Subsystem

4.2 O2 Production Subsystem (RWGS)

4.3 Methane Processing Subsystem

4.8 Soil Processing for H2O Subsystem

PEM Water Electrolyzer

- Multi-cell electrolysis stack: Anode feed, cathode-feed, static-vapor-feed

Balance of Plant

- O2 / water separation and water storage tanks
- H2 / water separation and water storage tanks
- Water recirculating pump/compressor
- Heat exchanger, thermal management, heat rejection

Regenerative Dryers

- Regenerative O2 and H2 dryers
- Regenerative H2O deionizer

4.2 O2 Production Subsystem (RWGS)

4.3 Methane Processing Subsystem

4.5 Product Storage Subsystem

O_2

H_2

4.5 Product Storage and Distribution Subsystem

4.2 O2 Production Subsystem

4.3 Methane Processing Subsystem

O2 / CH4 Liquefaction & Maintenance

- Cryocoolers
- Cryocooler heat exchanger (cold head, broad area, etc.)
- Boiloff control devices
- Pressure control devices

O2 / CH4 Storage

- Storage tank
- Vacuum jacketing
- Tank insulation
- Fluid level gauging

O2 / CH4 Transfer

- Liquid acquisition devices
- Cryogenic pumps
- Liquid quality control devices
- Fluid and electrical connects/disconnects with dust mitigation
- Zero-vent fill management
- Mass flow measurement

O_2

4.7 Excavation and 4.8 Soil Processing Subsystems

Mobility Platform | Soil Excavation for Water | Soil Hoppers / Transfer | Soil Dryer | H2O Collection, Clean-up, and Storage

Soil Excavation for Water

- Excavation tool to acquire soil (icy soil, hydrated soil)
- Holding/transfer bin
- Mechanism to get soil out of holding/transfer bin
- Interfaces (electrical, mechanical, data) to and interactions with mobility platform
- Situational awareness sensors/cameras for excavation and soil transfer activities

Soil Hoppers / Transfer

- Hopper to hold excavated soil before processing
- Size sorter (if needed)
- Means to capture evolved volatiles during hold period
- Mechanisms to get soil out of hopper and into reactor/dryer
- Hopper to hold spent soil after processing
- Mechanism to get spent soil out of hopper and into dumper

Soil Dryer

- Mechanism to get/receive soil from hopper
- Reactor to extract water from soil
- Components to capture and send evolved water downstream (e.g. purge gases, valves, compressors, pumps)
- Regenerative dust/particle filter on gas outlet stream
- Components to recycle working fluids (if required)
- Mechanism to send spent soil out of reactor into hopper

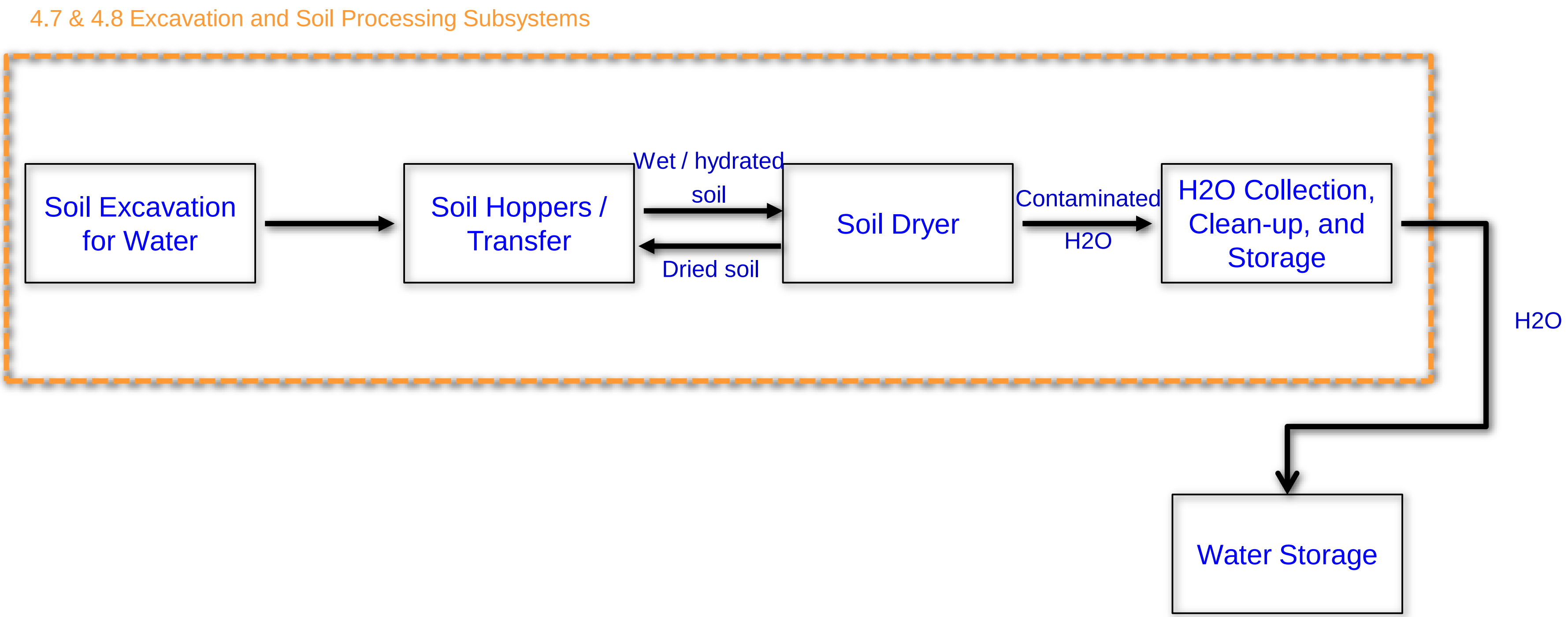
H2O Collection, Clean-up, and Storage

- H_2O / gas membrane separator(s)
- Solid particle removal
- H_2O condensers and storage tanks
- H_2O gas-phase regenerative contaminant clean-up beds
- H_2O liquid-phase regenerative contaminant clean-up beds
- Balance-of-plant components (pumps, compressors, sensors, etc.)

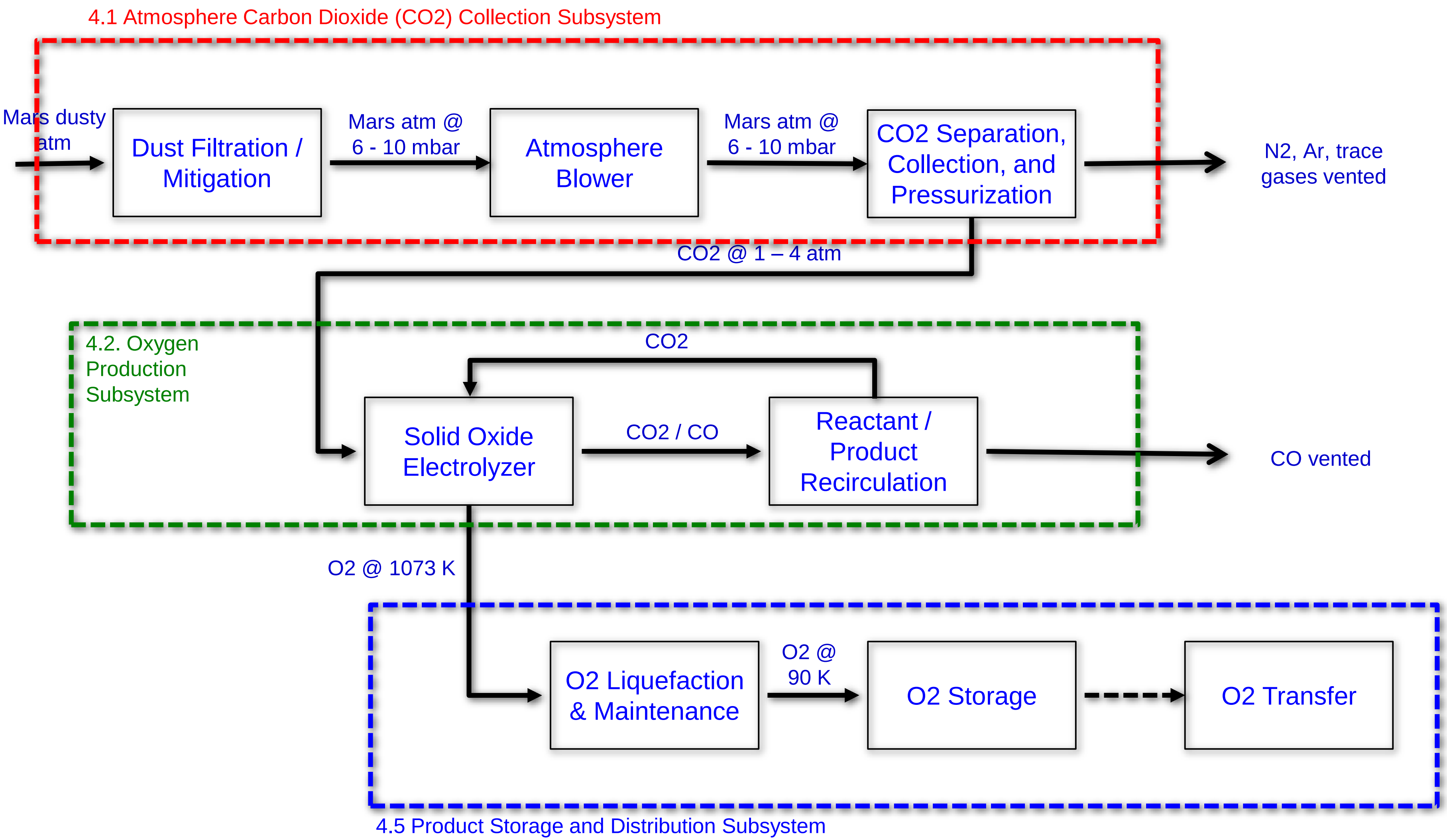
H_2O

ISRU Integrated Systems

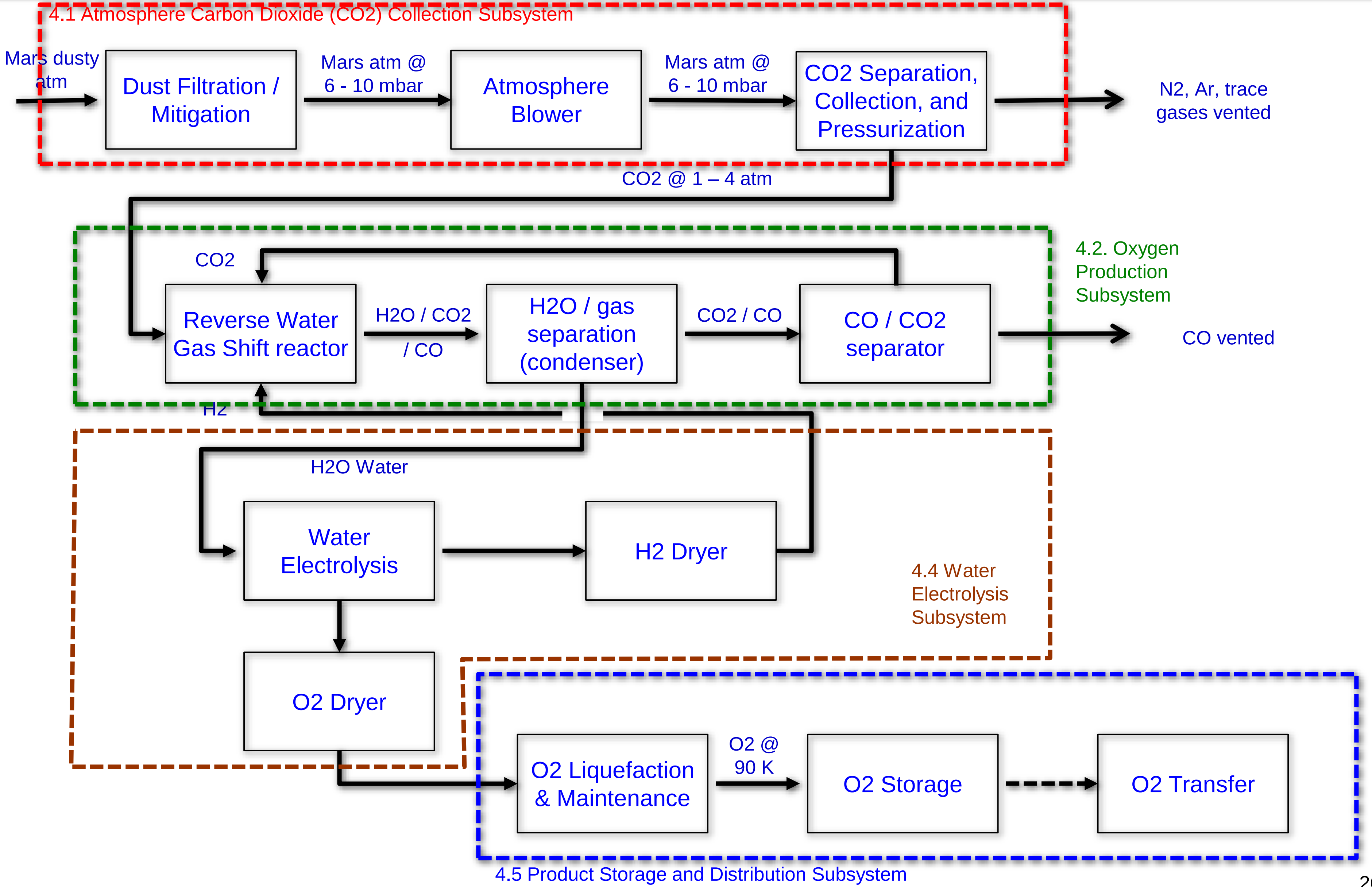
Soil Processing (for Water) Integrated System



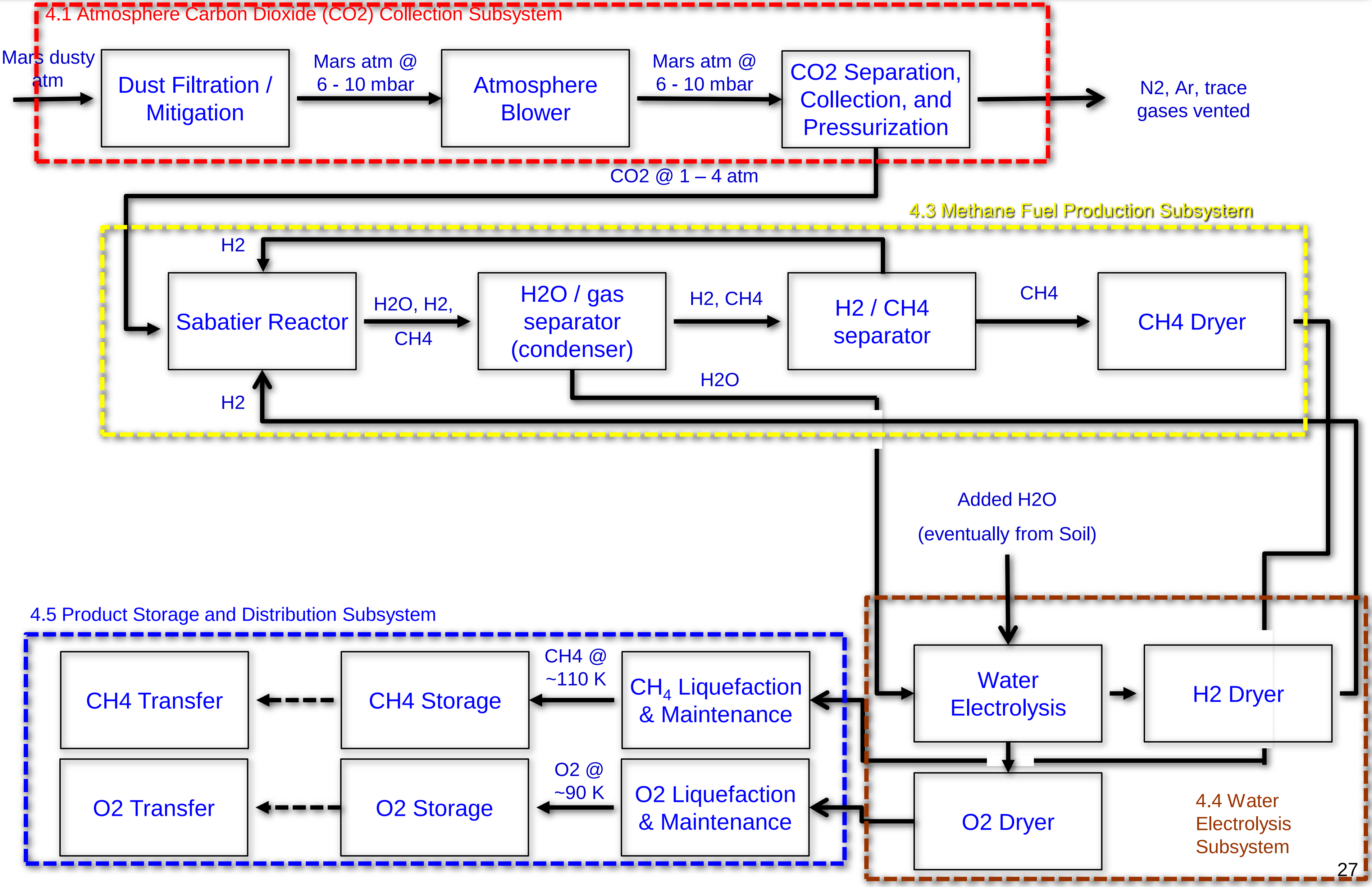
Oxygen Production from Atmosphere Integrated System (SOE Option)



Oxygen Production from Atmosphere Integrated System (RWGS Option)



Fuel and Oxygen Production Integrated System



ISRU Fuel and Oxygen Production End-to-End Integrated System