CARLO GAVAZZI SPACE SpA

Initially Identified Areas of Interest for Europe

Utilisation of In-Situ Resources

CGS

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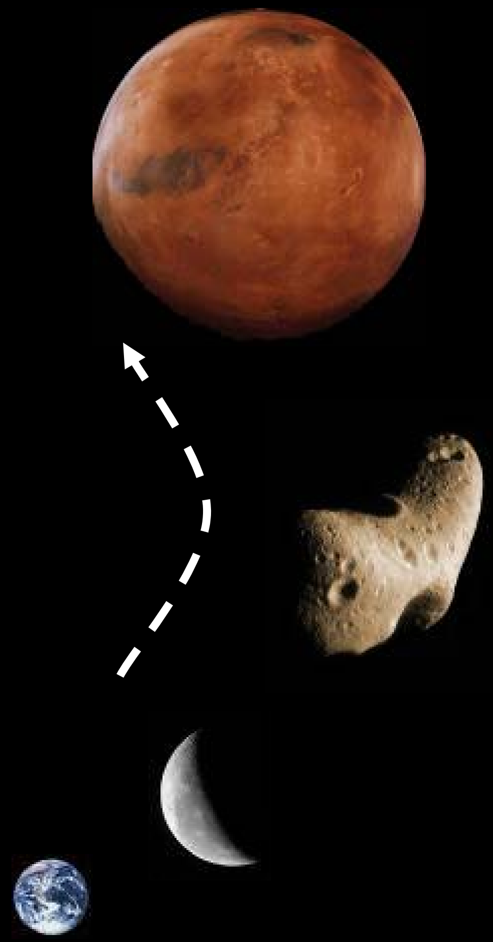
Utilisation of In-Situ Resources

Essential for a sustainable space exploration program



- Considered Celestial Bodies:
  - Moon
  - Mars

- ISRU Aspects:
  - Process
    - for transforming the in-situ material to the final utilizable form
    - e.g. physico-chemical processes
  - Elements
    - physical components of the system that perform the required functions
    - also "support" external elements can be needed (e.g. power provision)
  - Architecture
    - overall system allowing the production of the required resource
  - Timeline
    - sequence of developments and missions that deliver the required functionality in the correct timeframe

Main Trade-offs

Types of Lunar Resources

- **Diffused**
  - Minerals / metals
  - Oxygen
  - Helium-3
- **In permanently shadowed areas**
  - Hydrogen / water

Uses of Lunar Resources

- **Life Support**
  - On surface
  - In space
- **Transportation**
  - On surface
  - Surface → Orbit, ...
- **Energy Provision**
  - Fuel Cell Reactants
- **Construction and Manufacturing**
  - Radiation Shielding
  - Roads
  - Devices

Assumptions done in the context of the Architecture Analysis

- **Material Produced**
  - Oxygen
- **Exploited resource**
  - Regolith
- **Extraction Location**
  - South Pole
- **Utilization Location**
  - Lunar Surface Base
- **Process (after a trade-off analysis)**
  - Carbothermal Reduction
- **Uses**
  - Life Support Consumables

Requirements: how much for which use

Production of Oxygen for Life Support needs

Two cases were considered:
- **Case A**: Low Oxygen Needs
- **Case B**: High Oxygen Needs

Case A

▪ **Main features:**
- Lunar Surface Base needs (1 year): ~133kg (assuming 90% loop closure of the Life Support System Air Management)
- Pressurized Rover needs (1 year): ~336kg (open loop Life Support System)

▪ **Total O_2 needs for 1 year: ~470kg**

Case B

▪ **Main features:**
- Lunar Surface Base needs (1 year): ~1083kg (assuming an open loop for the Life Support System Air Management)
- Pressurized Rover needs (1 year): ~336kg (open loop Life Support System)

▪ **Total O_2 needs for 1 year: ~1419kg**

ISRU Process Trade-off

Carbothermal Process vs. Ilmenite Reduction Process

Carbothermal Process

Pros:

- High efficiency (about 20%)
- Terrestrial counterpart exists for a number of the process steps
- Very low dependence on site selection
- Easily scalable plant
- Solid-gas reaction performed

Contras:

- Methane must be brought from Earth
- Catalyst lifetime might be limited (2-3 years)

The **Carbothermal Reduction Process based on solid-gas reaction** has been chosen because:

- it does not imply any technological issue correlated with the handling of high temperature and corrosive materials
- it has less dependency on the Moon site selection

Ilmenite Reduction Process

Pros:

- Easy Process Chemistry
- Terrestrial counterpart exists for a number of the process steps
- Low density of Hydrogen – resupply mass is expected to be small
- Process temperatures are below the melting point of the Ilmenite feed
- Easily scalable plant

Contras:

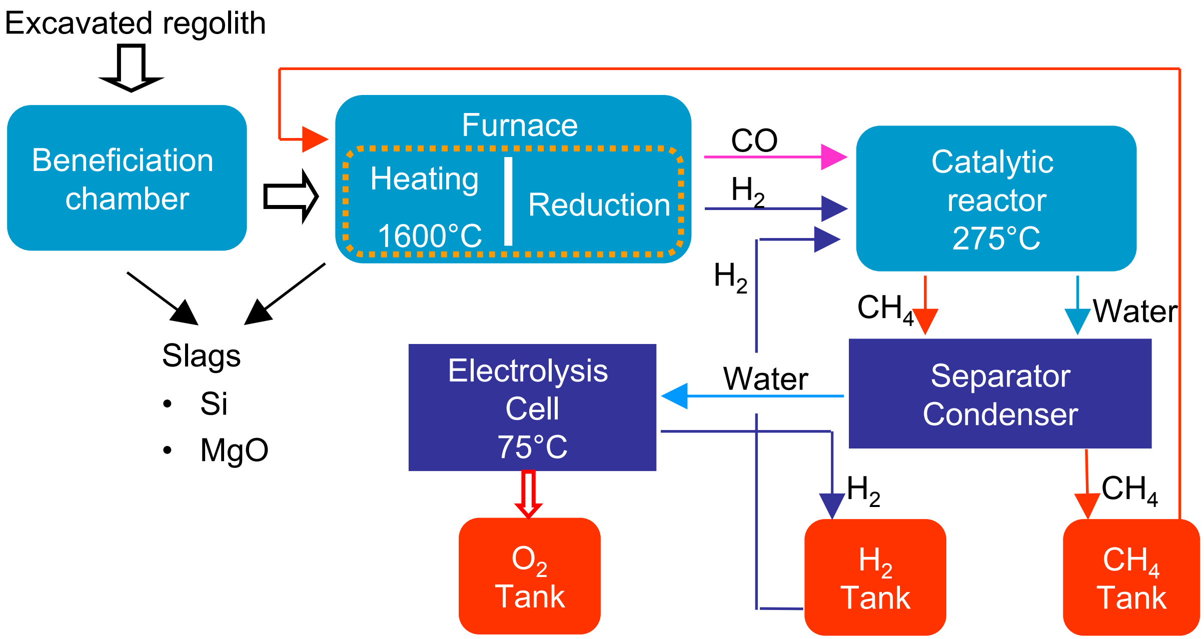
- H_2 feed must be brought from Earth
- High concentration of Ilmenite (or glass) in regolith is required; the process is strongly dependant on the site selection
- The kinetics for the hydrogen reduction reaction is slow
- The thermodynamics of hydrogen reduction impose rather low equilibrium per-pass conversion of H_2 to water
- Small efficiency (<5%)

The **Ilmenite Reduction** has been considered as the back-up process

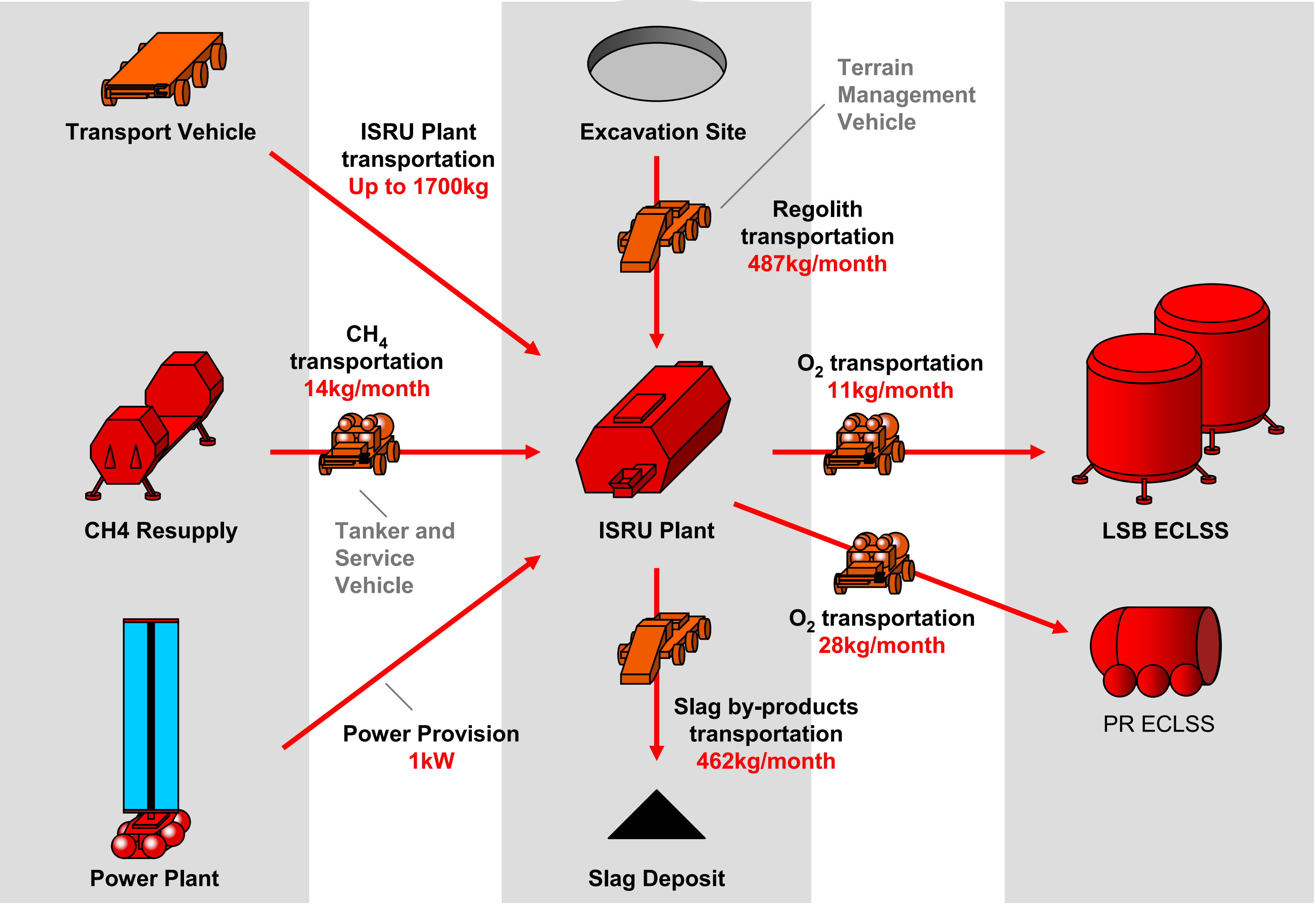
Moon ISRU : O_2 Production Process

Carbothermal Reduction

- A three step process which requires a feedstock of methane from Earth to reduce metallic silicates and titanates
- **Step 1:**
  - Mg_2SiO_4 (Olivine) + $2CH_4 \rightarrow 2MgO + Si + 4H_2 + 2CO$ (~1600°C)
  - $MgSiO_3$ (Pyroxene) + $2CH_4 \rightarrow MgO + Si + 4H_2 + 2CO$ (~1600°C)
- **Step 2:** $4CO + 12H_2 \rightarrow 4CH_4 + 4H_2O$ (275°C)
- **Step 3:** $4H_2O \rightarrow 4H_2 + 2O_2$



Moon ISRU Operational Scenario, Case A



Transport Vehicle

ISRU Plant transportation
Up to 1700kg

Excavation Site

Terrain Management Vehicle

Regolith transportation
487kg/month

CH_4 transportation
14kg/month

O_2 transportation
11kg/month

CH4 Resupply

Tanker and Service Vehicle

ISRU Plant

LSB ECLSS

O_2 transportation
28kg/month

PR ECLSS

Slag by-products transportation
462kg/month

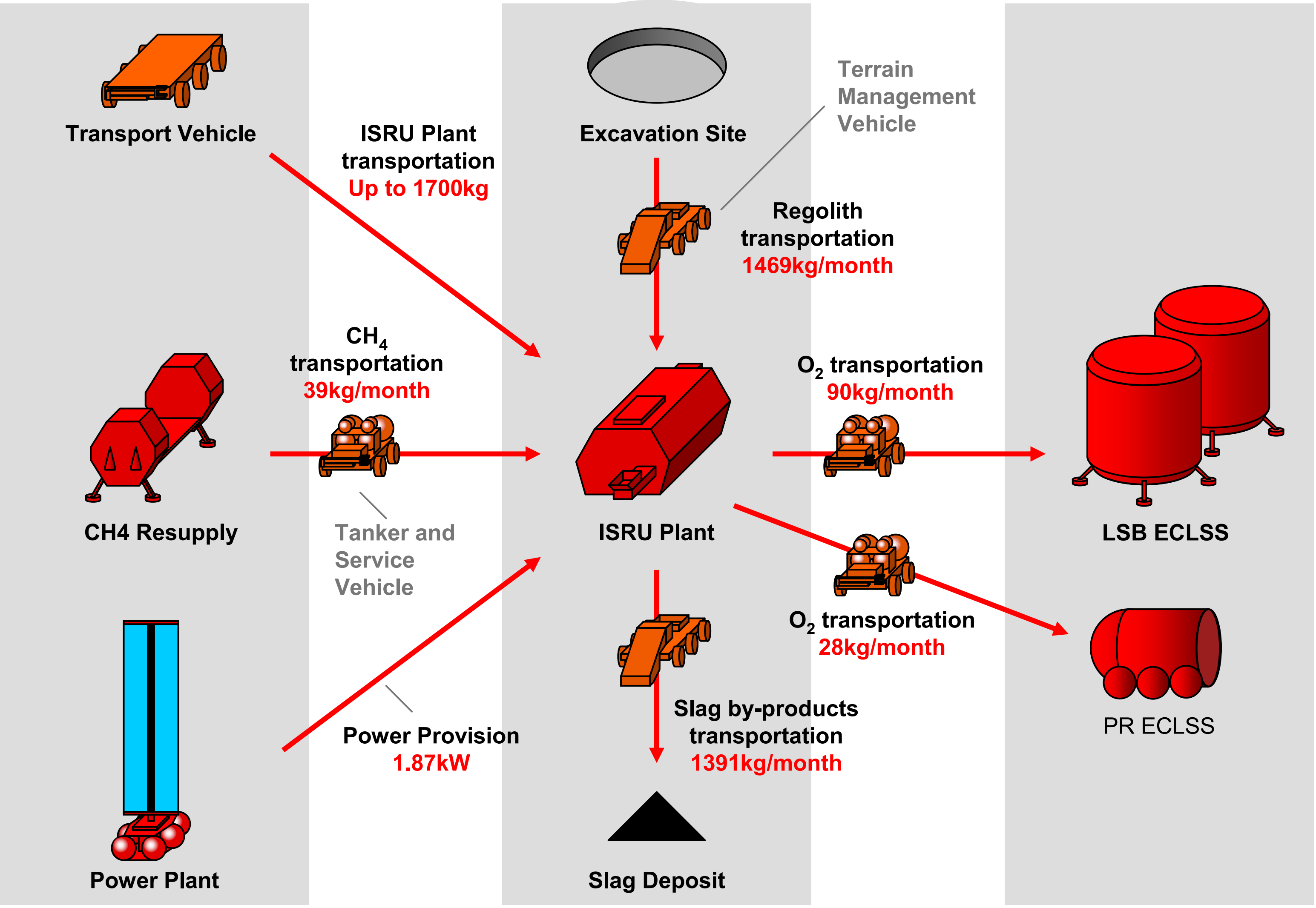
Power Provision
1kW

Power Plant

Slag Deposit

ISRU Support ***ISRU Core*** ***ISRU Users***

Moon ISRU Operational Scenario, Case B



Transport Vehicle

ISRU Plant transportation
Up to 1700kg

Excavation Site

Terrain Management Vehicle

Regolith transportation
1469kg/month

CH_4 transportation
39kg/month

O_2 transportation
90kg/month

CH4 Resupply

Tanker and Service Vehicle

ISRU Plant

LSB ECLSS

O_2 transportation
28kg/month

PR ECLSS

Slag by-products transportation
1391kg/month

Power Provision
1.87kW

Power Plant

Slag Deposit

ISRU Support

ISRU Core

ISRU Users

Moon ISRU Benefits: Case A

Production rate requirement: ~470 kg of O_2 / year (39 kg / month)

- Process: carbothermal reduction
  - inputs to the process: regolith and methane
  - outputs of the process: oxygen and waste

- Features of the resulting plant:
  - Mass: 322 kg
  - Inputs: ~14 kg / month of CH_4 (+ ~487 kg/month of regolith)
  - Power consumption: ~1 kW
- Required support elements:
  - Power plant, mass: 218 kg
  - Terrain management vehicle: 442 kg (conservative: sized for 4.5 t O_2 / year)

- Assumed maintenance mass: 10% of total elements (ISRU plant + support elements) mass / year (conservative)
- When the ISRU maintenance task (in EVA) is added, the LSB ECLSS O_2 needs variation is negligible due to the PLSS regenerative assumption
- Mass Savings:
  - “initial investment”: 322 kg + 218 kg + 442 kg = 982 kg
  - monthly return: 39 kg - 14 kg - 8 kg = 17 kg
  - **break-even time: 982 / 17 = 58 months**
  - then: ~200 kg of Lunar lander payload mass "earned" each year

Moon ISRU Benefits: Case B

Production rate requirement: ~1419 kg of O_2 / year (118 kg / month)

- Process: carbothermal reduction
  - inputs to the process: regolith and methane
  - outputs of the process: oxygen and waste

- Features of the resulting plant:
  - Mass: 545 kg
  - Inputs: ~42 kg / month of CH_4 (+ ~1470 kg/month of regolith)
  - Power consumption: ~1.87 kW
- Required support elements:
  - Power plant, mass: 287 kg
  - Terrain management vehicle: 442 kg (conservative: sized for 4.5 t O_2 / year)

- Assumed maintenance mass: 10% of total elements (ISRU plant + support elements) mass / year (conservative)
- When the ISRU maintenance task (in EVA) is added, the LSB ECLSS O_2 needs variation is negligible due to the PLSS regenerative assumption
- Mass Savings:
  - "initial investment": 545 kg + 287 kg + 442 kg = 1247 kg
  - monthly return: 118 kg - 39 kg - 10 kg = 69 kg
  - **break-even time: 1247 / 69 = 18 months**
  - then: ~830 kg of Lunar lander payload mass "earned" each year

Main Trade-offs

Types of Mars Resources

- **Components of the atmosphere**
  - CO$_2$
  - Buffer gases
- **Components of the soil**
  - Water (if available at the site)

Uses of Mars Resources

- **Life Support**
  - On surface
  - In space
- **Energy Provision**
  - Fuel Cell Reactants
- **Construction**
  - Radiation Shielding
- **Transportation**
  - On surface
  - Surface → Orbit, ...

Assumptions done in the context of the Architecture Analysis

- **Material Produced**
  - Baseline: Oxygen and Water
  - Alternative: also Methane
- **Exploited resource**
  - Atmosphere
- **Process**
  - Baseline: Cryo-compressor + RWGS
  - Alternative: also Sabatier
- **Deployment**
  - 2 years before crew arrival
- **Uses (baseline)**
  - Life Support Consumables
  - Water for Pressurized Rover Radiation Protection
- **Uses (alternative)**
  - Also Manned Ascent Propulsion

Requirements: how much for which use

Production of Water/Oxygen only for Life Support needs

- **Main features:**
  - Mars Surface Base water needs (whole mission): ~4200kg (assumed 87% Life Support closed loop for Air Management)
  - Mars Surface Base oxygen needs (whole mission): ~140kg (assumed 90% Life Support closed loop for Air Management)
  - Pressurized Rover water needs (10 excursions): ~310kg/excursion (no Life Support System closed loop)
  - Pressurized Rover oxygen needs (10 excursions): ~165kg/excursion (no Life Support System closed loop)
  - Pressurized Rover radiation protection needs: ~3500kg
- **Total Water needs for the whole mission: ~10800kg**
- **Total O_2 needs for the whole mission: ~1790kg**

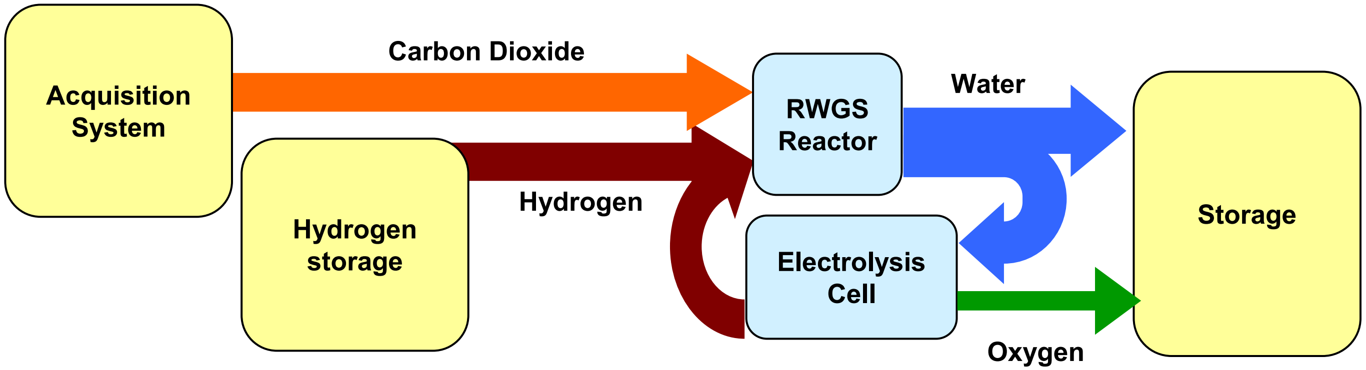
Production of Water/Oxygen for Life Support needs and ISPP

- **Main features:**
  - Water and Oxygen needs for Life Support as above
  - Additional ~21000kg of Propellant for Ascent Vehicle
- **Total Water needs for the whole mission: ~10800kg**
- **Total O_2 needs for the whole mission: ~1790kg**
- **Total Propellant needs for the Ascent Vehicle: ~21000kg**

Mars ISRU : Water and O_2 Production Process

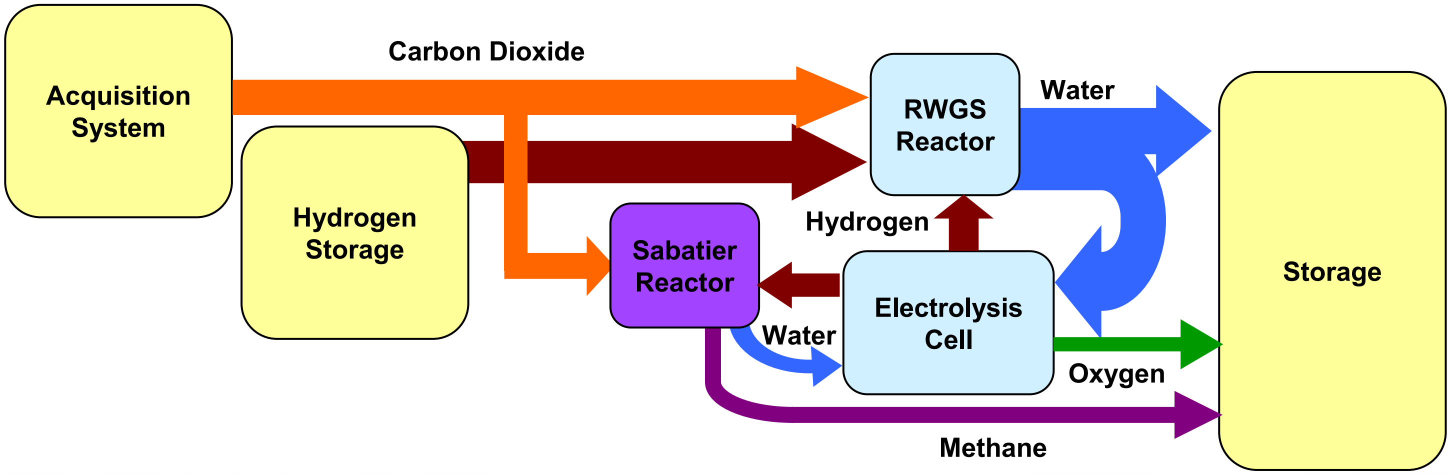
Baseline process (ECLSS only)

- Key component: **RWGS Reactor**: endothermic catalytic reaction. $CO_2 + H_2 \rightarrow CO + H_2O$, T>400°C; simple low mass and low power demand reactor



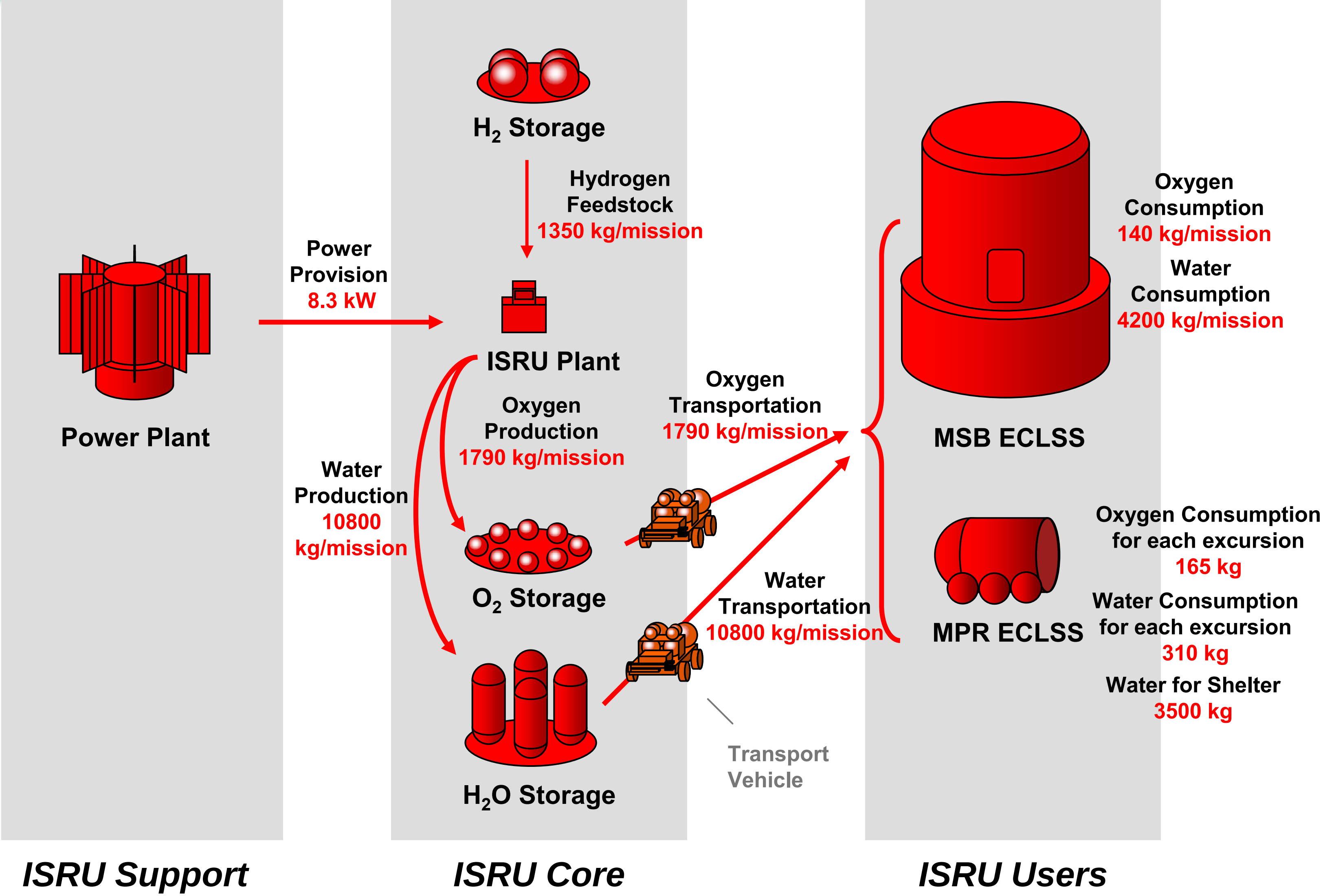
Acquisition System
Carbon Dioxide
RWGS Reactor
Water
Storage
Hydrogen storage
Hydrogen
Electrolysis Cell
Oxygen

Alternative process (also ISPP)



Acquisition System
Carbon Dioxide
RWGS Reactor
Water
Storage
Hydrogen Storage
Hydrogen
Sabatier Reactor
Electrolysis Cell
Water
Oxygen
Methane

Mars ISRU Operational Scenario - ECLSS only



Power Plant

Power Provision
8.3 kW

H$_2$ Storage

Hydrogen Feedstock
1350 kg/mission

ISRU Plant

Oxygen Production
1790 kg/mission

Water Production
10800 kg/mission

O$_2$ Storage

H$_2$O Storage

Oxygen Transportation
1790 kg/mission

Water Transportation
10800 kg/mission

Transport Vehicle

MSB ECLSS

Oxygen Consumption
140 kg/mission

Water Consumption
4200 kg/mission

MPR ECLSS

Oxygen Consumption for each excursion
165 kg

Water Consumption for each excursion
310 kg

Water for Shelter
3500 kg

ISRU Support

ISRU Core

ISRU Users

Mars ISRU Benefits

Production requirement: 1790 kg of O_2 and 10800 kg of H_2O

- Process: Cryo-compressor + RWGS
  - inputs to the process: martian atmosphere
  - outputs of the process: oxygen and water

- Features of the resulting plant:
  - Mass: 1090 kg
  - H2 Storage Mass: 405 kg
  - Inputs (total): 1350 kg of H_2
  - Power consumption: 8.3 kW
- Required support elements:
  - Power plant (mass not considered for the mass savings estimation since this element is shared with the Habitat)

- *Mass Savings for ECLSS consumables only*:

  12590 kg (mass without ISRU) – 2845 kg (mass with ISRU) = 9745 kg

- *Mass Savings with ascent ISPP*:

  33590 kg (w/o ISRU) – 11450 kg (ISRU) = **22140 kg**

Note: both the Mass savings are referred to the whole Mars mission

ISRU Demo Missions

Moon: ISRU Demo mission

Demonstrator for a full-scale ISRU Plant, using the Carbothermal Reduction Process in the South Pole area:

- **Input**: lunar regolith + CH_4 feedstock
- **Output**: oxygen + waste slags

The Demonstrator is placed on a Rover platform in order to test different lunar soils.

Rover platform (adaptable for other P/Ls)

- **Payload support robotics,** for delivering regolith to the plant (scoop) and removing waste
- **Mobility** for accessing different sites

Mission Duration: 3 months

Oxygen Production Rate: 5kg/month

Total Mass: ~725kg	**Total Volume (stowed configuration):** 2m x 2m x 1.8m

ISRU Roadmap

Step 1: Resource Mapping and ISRU Demo missions

- Resource mapping with orbital and surface systems
- Demonstration of ISRU capabilities – **production of small amounts of material**
- In situ analysis of produced materials or sample return missions

Step 2: Pilot Plants

- Production range from **hundreds of kg up to a few tons per year**
- Pilot plants developed to:
  - test and validate procedures and operations
  - generate information about the behavior of the system for use in design of larger plants
  - reduce the risks associated with the construction of larger systems

Step 3: Large Production Infrastructure

- Production range from a **few tons up to tens or hundred of tons**
- Global production requirements can be obtained exploiting multiple plants with medium-large production capability

- **Moon: all the steps are typically present - in a long/very long term scenario**
- **Mars: steps 2 and 3 may be merged (e.g. production of the entire required quantity for a Manned Mars Mission, by predeploying the plant)**