ISRU for Human Missions to Mars

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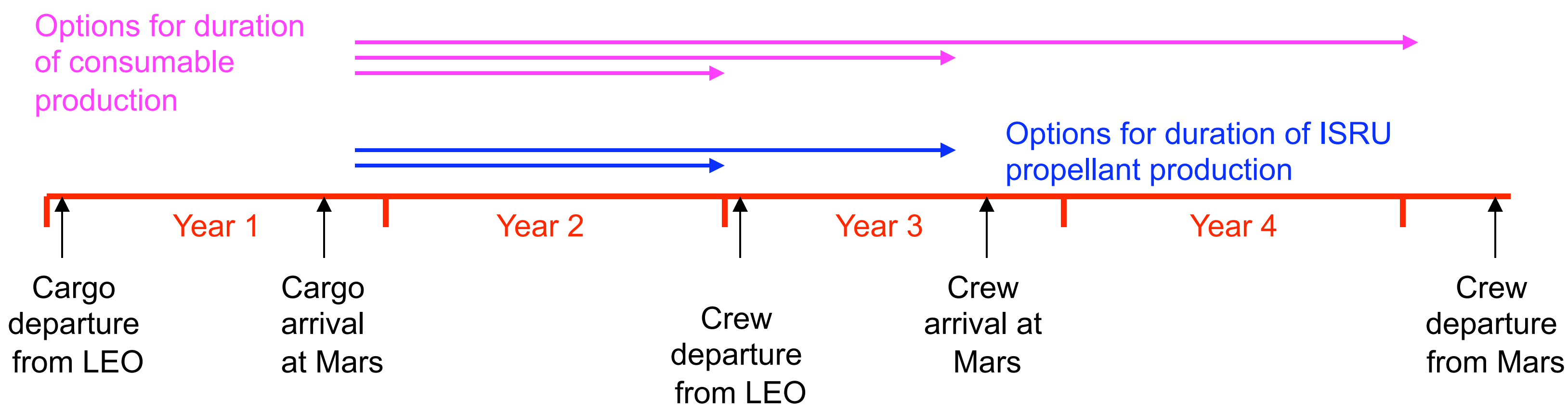
Time Sequence for Mars ISRU

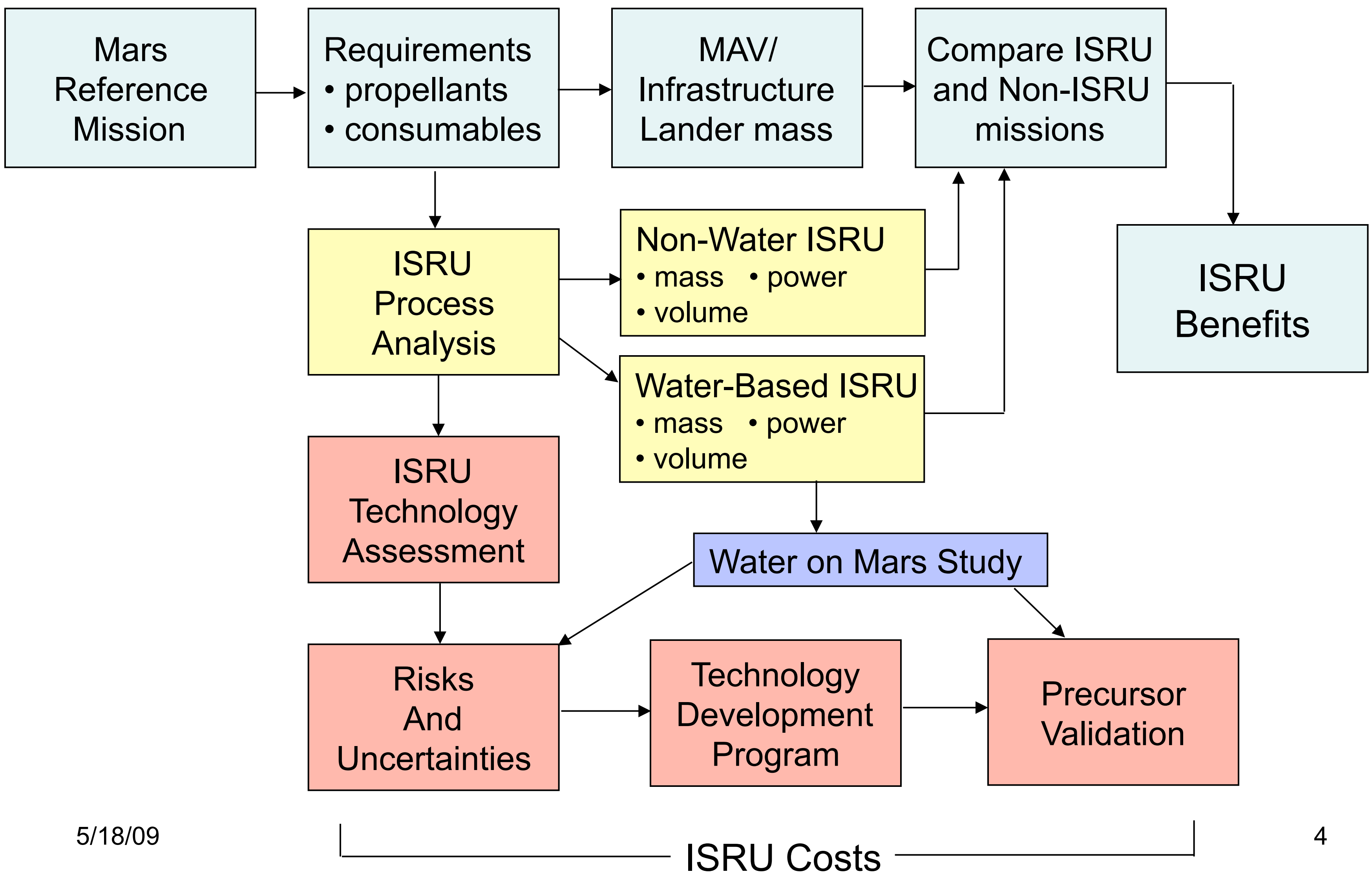


- The MAV and the nuclear reactor power system (NRPS) arrive at the same time as the ISRU system.
- The NRPS is deployed behind a berm at some distance from the main landing site and connected by cables to the main site.
- ISRU system is connected to the (adjacent) MAV via cryogenic connecting tubes.
- The ISRU system begins operating soon after landing and set-up
- ISRU will gradually fill the propellant tanks of the MAV and will either partly or fully fill life-support consumable tanks
- The ISRU system can be sized to fill the tanks prior to crew departure or prior to crew arrival - power system is larger in former case
- When the crew arrives, the power system will be used for crew support - not for ISRU

ISRU Operational Period

- Propellant Production
  - No problem with storage - use MAV Tanks
  - Lower power requirement if MAV tanks filled prior to crew arrival (rather than departure)
- Consumable Production
  - Mainly water, also oxygen
  - Water storage may be problematic if stored in advance of crew arrival: 120 mT = 120 m^3 = 5-m cube (inflatable?)
  - Oxygen requires cryogenic storage but volumes are ~1/8 of those in MAV
  - One could continue consumable production after crew arrival

ISRU System Analysis



Power System

- Does the mass of the nuclear reactor power system count against the ISRU system?
  - If the ISRU system has completed its job prior to crew arrival
  - And the power requirement for ISRU is comparable to that needed to support the crew
  - And the same power system serves both purposes
- Then the mass of the power system can be treated as a constant for both ISRU and non-ISRU missions
  - But it must operate two years longer with ISRU

ISRU Processes

Water is accessible for propellant production and life support

- Electrolyze water:
  Produce:
  $H_2 + O_2$
  Hydrogen storage is a major problem
- Sabatier/ Electrolysis
  Produce:
  $CH_4 + O_2$
  Relatively mature technologies

Water is not accessible
Produce only oxygen

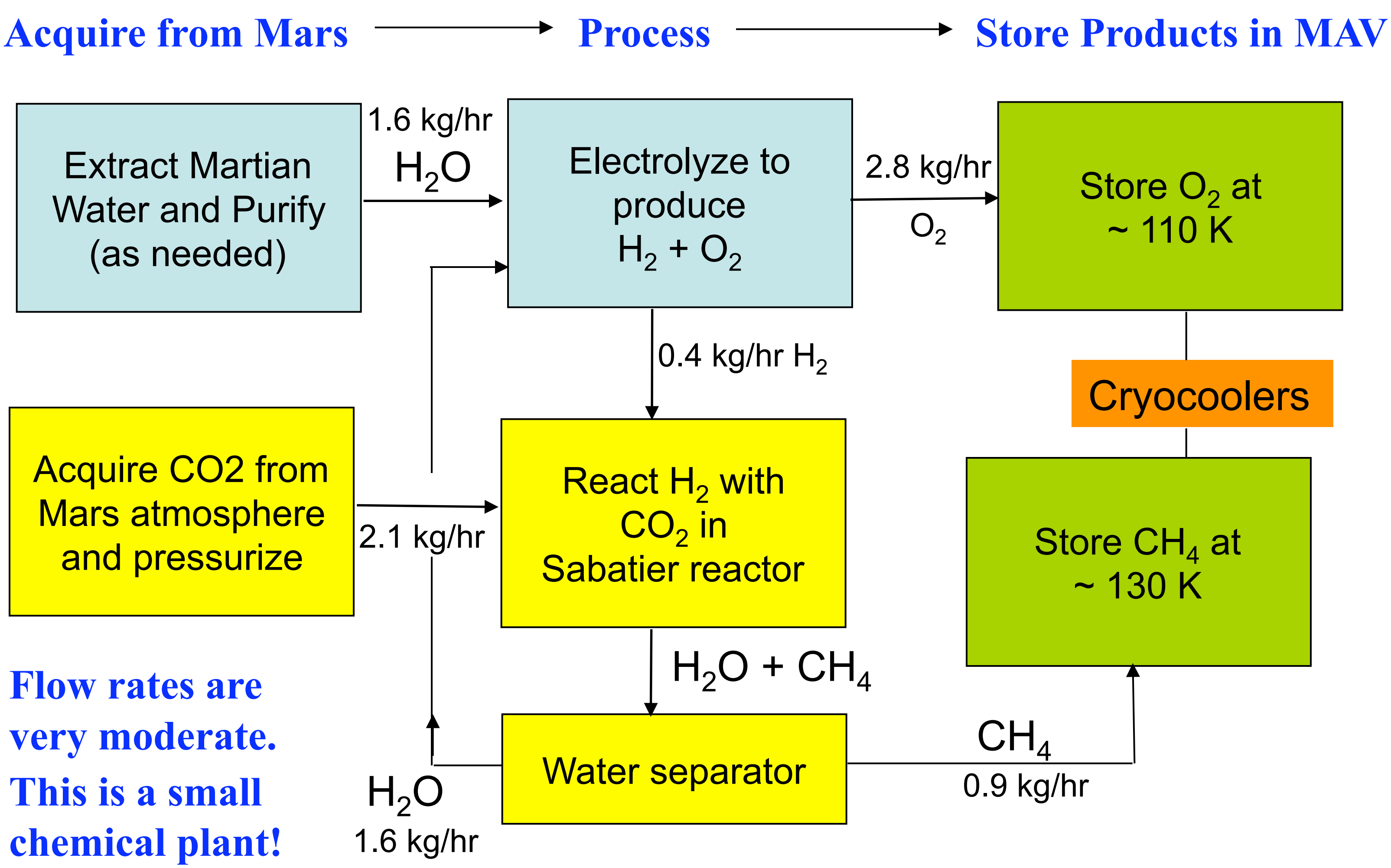
- Solid oxide Electrolysis
  Produce only O_2
  Bring fuel and water from Earth
  Immature technology
- Reverse Water Gas Shift
  Produce only O_2
  Bring fuel and water from Earth
  Immature technology

FAVORED APPROACH (we use for remainder of presentation)

Backup Approaches if water is not accessible

Propellant Production

Propellant Requirement Based on DRM-3 (ascent to elliptical orbit)



Flow rates are very moderate. This is a small chemical plant!

2.8 kg/hr x 24 hrs/day x 600 days = 40 metric tons oxygen

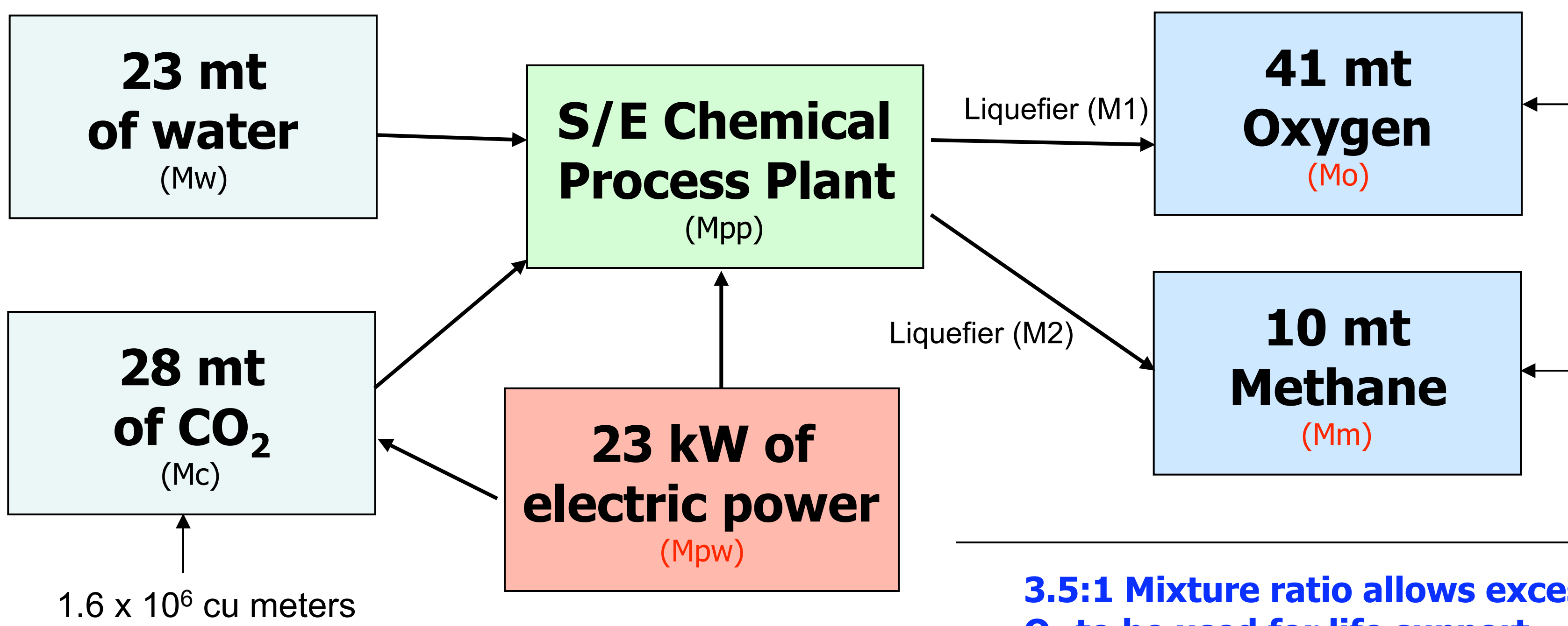
Propellants from Water-Based ISRU

Small ISRU Plant plus Power System (already there) provide large amounts of propellants (and consumables)

ISRU plant mass = Mw + Mc + Mpp + M1 + M2

Mpw + Mo + Mm are attributed to the Mission - independent of ISRU

Acquire from Mars **Process for ~600 sols** **Store Products in MAV**



3.5:1 Mixture ratio allows excess O_2 to be used for life support

Additional water (~ 100 mT) can be used for life support

Water Acquisition for Propellants

- Assume ice field is located from precursor missions
  - 10% water content by weight below 0.4 m desiccated upper layer
- Each square meter excavated to depth 1.4 m yields:
  - 2.8 mT of dry regolith
  - 0.3 mT = 300 kg of water
- Equipment must acquire 38 kg water per day
  - Requires excavation of 38/300 = 0.13 square meter per day (0.36 m x 0.36 m) = 400 kg of regolith excavated per day
- Regolith must be carted to heater that raises T > 273 K to melt ice
  - Energy requirement for heating and melting: ~ 3.85×10^7 J/day = 10.6 kW-hr per day
- Water must be recovered and piped to main process unit
- Spent regolith must be dumped
- **Rough WAG:**
  - **Total mass of water acquisition ~ 4 mT**
  - **Power requirement ~ 5 kW continuous (Mainly for charging vehicles)**

Mass and Power - Propellant Production Reference: LMSC - JPL Study of 2004

- Includes:
  - Cryogenic CO_2 acquisition
  - Electrolysis of Water
  - Sabatier Conversion to methane
  - Liquefaction of product O_2 and CH_4
- Does **NOT** include mass of power system
- **Mass ~ 500 kg**
- **Power ~ 23 kW**
- Based on 600 days of operation at
  - Water flow rate = 1.6 kg/hr
  - CO_2 flow rate = 2.1 kg/hr

ISRU Mass and Power for propellant production

Duration of ISRU ops	600 days (tanks full prior to crew arrival)	14 months* (tanks full prior to crew departure)	30 days* (Sortie short stay mission)
Water Acquisition Mass (mT)	4	5.3	30
Process Mass	0.5	0.7	7
Total Mass (kg)	**4.5**	**6.0**	**37**
Water Acquisition Power (kW)	5	7	40
Process Power	23	29	300
Total Power (kW)	**28**	**36**	**340**

* Note: Scale-ups are assumed to be non-linear because larger systems are more efficient. Wild guesses made as to scale-up requirements.

Consumable Production (~ 100 mT)

- Oxygen comes "free" as byproduct from propellant production
  - Process produces O_2/CH_4 = 4:1
  - Mixture ratio for propulsion is in range 3 to 3.5:1
- About 5X as much water needed for consumables as is needed for propellant production
  - Scale-up from propellant production assumed to be non-linear due to efficiency of scale; WAGs for 600 days are:
  - Additional mass of consumable water system ~ 8 mT
  - Additional power for consumable water system ~ 10 kW

System to supply propellants (~40 mT) and consumables (~100 mT)

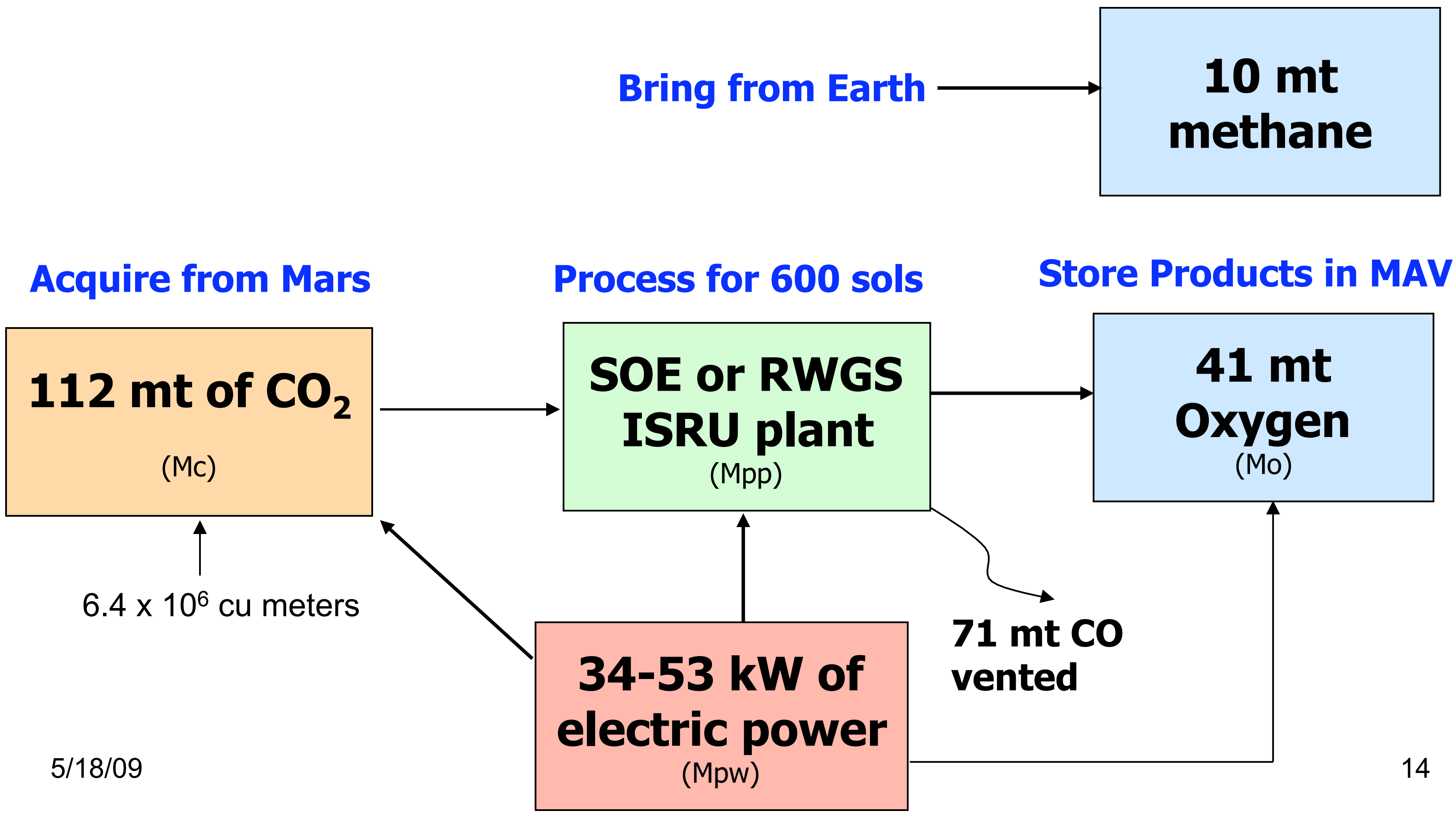
Duration of ISRU ops	**600 days (tanks full prior to crew arrival)**	**14 months* (tanks full prior to crew departure)**	**30 days* (Sortie short stay mission)**
Water Acquisition Mass (mT)	12	16	70
Process Mass	0.5	0.7	7
Total Mass (kg)	**12.5**	**15.6**	**77**
Water Acquisition Power (kW)	15	19	90
Process Power	23	29	300
Total Power (kW)	**38**	**48**	**390**

* Note: Scale-ups are assumed to be non-linear because larger systems are more efficient. Wild guesses made as to scale-up requirements.

Propellants from Atmosphere ISRU

ISRU Plant produces up to 78% of MAV propellants

(However SOE and RWGS technologies are immature)



Oxygen Production Only

- Solid-Oxide Electrolysis
  - Involves multi-cell device operating at 900-1000°C
  - Uses Pt-coated zirconia wafer to transfer O2 across membrane from CO2 + CO +O2 mixture
  - Serious technical challenges remain
- Reverse Water Gas Shift Reaction
  - One of Zubrin's best ideas
  - $CO_2 + H_2$ --> $CO + H_2O$ --> electrolyze water for O2
  - Equilibrium favors left side
  - Shift equilibrium by removing H2O and recycling products
  - Demonstrated as simple breadboard - no funding in ten years
- Both processes require acquisition of huge amount of CO2

Estimates based on 600 days operation

	Mars H2O Consumables + propellants	Mars H2O Propellants only	H2 from Earth	RWGS	SOE
Feedstocks	Mars H_2O + CO_2	Mars H_2O + CO_2	H_2 (Earth) + Mars CO_2	Mars CO_2	Mars CO_2 + small amt H_2
product water (mT)	100	0	0	0	0
product CH_4 (mT)	10	10	20(*)	0	0
product O_2 (mT)	41	41	41	41	41
Mass (mT)	12.5	4.5	1(#)	1	1
Power (kW)	38	28	15	34	53

* Extra methane produced - half must be vented (H_2 requirement is 5 mT)

Does not include mass of H_2 storage