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Martian Atmospheric Dust Mitigation for ISRU Intakes via Electrostatic Precipitation

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Abstract

The Mars 2020 and Mars Sample Return missions expected to fly to Mars within the next ten years will each include an *In Situ* Resource Utilization (ISRU) system. They convert carbon dioxide in the Martian atmosphere into consumable oxygen at 1% and 20% of the rate required by a full scale human exploration Mars mission, respectively. The ISRU systems will need to draw in the surrounding atmosphere at a rate of 110L/min and 550L/min, respectively, in order to meet their oxygen production goals. Over the duration of each respective mission, a total atmospheric dust mass of 4.86g and 243g will be drawn into each system, respectively. Ingestion of large quantities of dust may interfere with ISRU operations, so a dust mitigation device will be required. The atmospheric volume and dust mass flow rates above will be utilized to simulate Martian environmental conditions in a laboratory electrostatic precipitator being developed to provide active dust mitigation support for atmospheric ISRU systems such as these.

1 Introduction

1.1 ISRU

In Situ Resource Utilization (ISRU), or living off the land, allows for mission critical consumables to be created during the mission from resources that are obtainable from the Martian environment. Such a system will allow for a reduction in mass and therefore the overall cost required for future Mars missions, as well as provide an infrastructure for a low-risk human presence on Mars.

A primary goal of the ISRU project is the production of mission consumables such as water and oxygen for life support, along with methane and oxygen for use as propellant in landing/ascent vehicles. The Martian atmosphere is a prime commodity to use for this purpose because it is composed primarily of carbon dioxide, which may be readily converted into the required mission consumables.

Oxygen needs to be produced for both life support and propellant uses, so the productivity of a Martian atmospheric ISRU system is generally categorized by its oxygen production rate. A full-scale human exploration mission on Mars will require an oxygen production rate of at least 2.2kg/hr. (Sanders et al., 2005)

1.2 Mars 2020 Mission

The Mars 2020 mission will include an instrument that will demonstrate the conversion of atmospheric carbon dioxide into oxygen for the first time on the Martian surface. It will utilize the process of solid oxide electrolysis (SOE) to reduce the carbon dioxide at the electrolyzer cathode to form oxygen ions as in Equation 1.

$$\mathrm{CO_2 + 2e^- \rightarrow O^{2-} + CO} \tag{1}$$

The oxygen ions produced in the previous reaction are then recombined in a reaction at the electrolyzer anode to produce oxygen gas as in Equation 2.

$$\mathrm{2O^{2-} \rightarrow 4e^- + O_2} \tag{2}$$

The net electrolysis reaction, Equation 3, obtained via the combination of Equation 1 and Equation 2, illustrates the overall conversion of carbon dioxide to oxygen by the system.

$$\mathrm{2CO_2 \rightarrow O_2 + 2CO} \tag{3}$$

Equation 3 indicates that two moles of carbon dioxide will need to be reacted for every mole of oxygen produced. (Hecht, Rapp, & Hoffman, 2014)

This SOE ISRU system will operate at 1% of the full scale oxygen production required for a manned mission, corresponding to an oxygen production rate of 22g/hr. If allowed to operate continuously for the entire mission length of 50sol, roughly 25.7kg of oxygen will be produced. (NASA SMD, 2013)

1.3 Mars Sample Return Mission

The Mars Sample Return (MSR) mission will include a suite of ISRU tools focused around producing methane and oxygen from consumables found in the Martian environment and will launch sometime between 2024 and 2026.

Water extracted from the Martian regolith by the Soil Processing Module (SPM) is purified by the Water Cleanup Module (WCM) and electrolyzed by the Water Processing Module (WPM) to create hydrogen and oxygen as in Equation 4.

$$2H_2O \rightarrow 2H_2 + O_2 \tag{4}$$

Carbon dioxide extracted from the Martian atmosphere is combined with the hydrogen produced in Equation 4 in the Atmospheric Processing Module (APM) to produce methane and water via the Sabatier reaction as in Equation 5.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{5}$$

The additional water produced as an output in Equation 5 is then sent back to the WPM for electrolysis as an input to Equation 4. The net reaction, Equation 6, obtained via the combination of Equation 4 and Equation 5, illustrates the overall production of methane and oxygen by the system.

$$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2 \tag{6}$$

When run in reverse, Equation 6 is the combustion reaction for methane, showing that rocket propellant can be synthesized entirely from consumables found on the Martian surface and atmosphere. Equation 6 also indicates that two moles of oxygen are produced for every mole of carbon dioxide that is reacted. (Muscatello & Santiago-Maldonado, 2012)

This Sabatier ISRU system will operate at 20% of the full scale oxygen production required for a manned mission, corresponding to an oxygen production rate of 440g/hr. If allowed to operate continuously for the entire mission length of 500sol, roughly 5140kg of oxygen will be produced. (NASA SMD, 2013)

2 ISRU System Intakes

2.1 Required Martian Atmosphere

The input mass flow rate of carbon dioxide, $\dot{m}_{\mathrm{CO}_2}$, required to generate the target output mass flow rate of oxygen, $\dot{m}_{\mathrm{O2}}$, for an ISRU system is given by

$$\dot{m}_{\mathrm{CO}_2} = \dot{m}_{\mathrm{O}_2} \frac{M_{\mathrm{CO}_2}}{M_{\mathrm{O}_2}} \frac{n_{\mathrm{CO}_2}}{n_{\mathrm{O}_2}} \tag{7}$$

where M is molecular mass and n is number of moles. Subscripts of O_2 and CO_2 indicate whether the quantity refers to oxygen or carbon dioxide, respectively. The mass flow rate calculated in Equation 7 assumes an atmosphere composed completely of carbon dioxide is undergoing a perfectly efficient conversion to oxygen. After compensating for these poor assumptions, a more reasonable estimate of the true Martian atmospheric mass flow rate, $\dot{m}_{\mathrm{mars}}$, is given by

$$\dot{m}_{\mathrm{mars}} = \dot{m}_{\mathrm{CO}_2} \frac{1}{\eta} \frac{1}{w_{\mathrm{CO}_2}} = \dot{m}_{\mathrm{O2}} \frac{M_{\mathrm{CO}_2}}{M_{\mathrm{O}_2}} \frac{n_{\mathrm{CO}_2}}{n_{\mathrm{O}_2}} \frac{1}{\eta} \frac{1}{w_{\mathrm{CO}_2}} \tag{8}$$

where η is reaction conversion efficiency and w_{CO2} is the mass fraction of carbon dioxide in the atmosphere. Since the actual conversion efficiency for each of the ISRU systems is unknown, a value of 60% ($\eta = 0.60$) will be assumed for the purposes of this document. The carbon dioxide composition of the Martian atmosphere is 95.32% (Williams, 2015), so a value of $w_{CO2} = 0.9532$ will be used throughout the remainder of this document. The corresponding volumetric flow rate, $\dot{V}_{\mathrm{mars}}$, required to accommodate this mass flow rate at Martian environmental conditions is given by

$$\dot{V}_{\mathrm{mars}} = \frac{\dot{m}_{\mathrm{mars}}}{M_{\mathrm{CO}_2}} R \frac{T}{P} = \frac{\dot{m}_{\mathrm{O}_2}}{M_{\mathrm{O}_2}} \frac{n_{\mathrm{CO}_2}}{n_{\mathrm{O}_2}} \frac{1}{\eta} \frac{1}{w_{\mathrm{CO}_2}} R \frac{T}{P} \tag{9}$$

where R is the universal gas constant, T is the atmospheric temperature, and P is the atmospheric pressure. Mean values for temperature and pressure on the Martian surface are $T = 210\mathrm{K}$ and $P = 6.36\mathrm{mbar}$ (Williams, 2015).

2.1.1 Relation to the Mars 2020 Mission

Given that the net reaction in Equation 3 consumes $n_{\mathrm{CO2}} = 2\mathrm{mol}$ of carbon dioxide for every $n_{\mathrm{O2}} = 1\mathrm{mol}$ of oxygen produced and that the SOE ISRU system must produce oxygen at a rate of $\dot{m}_{\mathrm{O2}} = 22\mathrm{g/hr}$, the required Martian atmospheric mass flow rate into the system must be $\dot{m}_{\mathrm{mars}} = 106\mathrm{g/hr}$ as calculated via Equation 8. This mass flow rate resolves into an atmospheric volume flow rate of $\dot{V}_{\mathrm{mars}} = 110\mathrm{L/min}$ as calculated via Equation 9.

2.1.2 Relation to the MSR Mission

Given that the net reaction in Equation 6 consumes $n_{\mathrm{CO2}} = 1\mathrm{mol}$ of carbon dioxide for every $n_{\mathrm{O2}} = 2\mathrm{mol}$ of oxygen produced and that the Sabatier ISRU system must produce oxygen at a rate of $\dot{m}_{\mathrm{O2}} = 440\mathrm{g/hr}$, the required Martian atmospheric mass flow rate into the system must be $\dot{m}_{\mathrm{mars}} = 529\mathrm{g/hr}$ as calculated via Equation 8. This mass flow rate resolves into an atmospheric volume flow rate of $\dot{V}_{\mathrm{mars}} = 550\mathrm{L/min}$ as calculated via Equation 9.

2.2 Martian Atmospheric Dust Properties

Martian dust storms cause the regolith on the surface of Mars to become suspended in the Martian atmosphere and continuous winds allow the entrained dust to remain airborne indefinitely. The size distribution of these dust particles may be integrated to provide weighting coefficients to determine the mean radius for a specific physical property of the dust particles.

The weighting coefficient values of $w_{\mathrm{a}} = 6.875$ and $w_{\mathrm{m}} = 9.75$ correspond to the cross-sectional area and mass weighted mean radii, respectively (Landis, 1996). The cross-sectional area weighted mean radius of an atmospheric dust particle was measured to be $r_{\mathrm{a}} = 1.6\mu\mathrm{m}$ (Tomasko et al., 1999). The mass weighted mean radius, r_{m}, may be determined by scaling the area weighted mean radius by the weighting ratio of mass to area; this yields a value of $r_{\mathrm{m}} = 2.27\mu\mathrm{m}$.

The cross-sectional area of a single atmospheric dust particle, A_{d}, is calculated using the cross-sectional area weighted mean radius, r_{a}, as in Equation 10.

$$A_{\mathrm{d}} = \pi r_{\mathrm{a}}^2 \tag{10}$$

The volume of a single atmospheric dust particle, V_{d}, is calculated using the mass weighted mean radius, r_{m}, as in Equation 11.

$$V_{\mathrm{d}} = \frac{4}{3}\pi r_{\mathrm{m}}^3 \tag{11}$$

The mean mass of a single atmospheric dust particle, m_{d}, is given by

$$m_{\mathrm{d}} = \rho_{\mathrm{d}} V_{\mathrm{d}} \tag{12}$$

where ρ_{d} is the mean density of an atmospheric dust particle. This density was determined from data collected by Mars Pathfinder to be $\rho_{\mathrm{d}} = 1.52\mathrm{g/cm}^3$ (Hviid et al., 1997). The mean dust particle cross-sectional area, volume, and mass were calculated to be $A_{\mathrm{d}} = 8.04\mu\mathrm{m}^2$, $V_{\mathrm{d}} = 48.9\mu\mathrm{m}^3$, and $m_{\mathrm{d}} = 74.4\mathrm{pg}$ via Equation 10, Equation 11, and Equation 12, respectively.

2.3 Martian Atmospheric Dust Concentration

The concentration of dust particles in the Martian atmosphere may be derived via the optical properties of the dust measured by surface rovers. The optical depth of the Martian atmosphere, τ, is given by

$$\tau = \frac{N_\mathrm{c} A_\mathrm{d}}{A_\mathrm{c}} \tag{13}$$

where N_c is the total number of dust particles in a vertical column of atmosphere, A_d is the mean cross-sectional area of an atmospheric dust particle as calculated via Equation 10 and A_c is the cross-sectional area of the atmosphere column. The volume of the column of atmosphere is given by

$$V_\mathrm{c} = A_\mathrm{c} H_\mathrm{c} \tag{14}$$

where H_c is the scale height of the atmosphere column. Solving Equation 13 for the total number of dust particles in the atmosphere column, N_c, and dividing by the volume of the atmosphere column, Equation 14, yields an expression for the mean atmospheric dust concentration, C_d, given by Equation 15.

$$C_\mathrm{d} = \frac{N_\mathrm{c}}{V_\mathrm{c}} = \frac{\tau}{A_\mathrm{d} H_\mathrm{c}} \tag{15}$$

This method of calculating the atmospheric dust concentration assumes a homogeneous vertical distribution of dust particles, but a more accurate model follows an exponential decay with increasing distance from the planet surface (Haberle et al., 1993). This redistribution of particles may be done by equating the integral of the unweighted particle concentration, C_d, to the integral of a generalized exponential function with a coefficient that is equivalent to the weighted particle concentration, C'_d, at the Martian surface as given by

$$\int_0^{H_\mathrm{c}} C_\mathrm{d} \mathrm{d}z = \int_0^{H_\mathrm{c}} \frac{\tau}{A_\mathrm{d} H_\mathrm{c}} \mathrm{d}z = \int_0^{H_\mathrm{c}} C'_\mathrm{d} e^{-z/H_\mathrm{c}} \mathrm{d}z \tag{16}$$

where z is the vertical height off of the Martian surface. Evaluating the integrals in Equation 16 yields the relation found in Equation 17.

$$\frac{\tau}{A_\mathrm{d}} = C'_\mathrm{d} H_\mathrm{c} (1 - e^{-1}) \tag{17}$$

Upon rearranging Equation 17, the weighted atmospheric dust particle concentation at the surface of Mars, C'_d, is given by

$$C'_\mathrm{d} = \left(\frac{e}{e-1}\right) \left(\frac{\tau}{A_\mathrm{d} H_\mathrm{c}}\right) = \left(\frac{e}{e-1}\right) C_\mathrm{d} \tag{18}$$

which shows that there are approximately 58% more dust particles accounted for in the exponential versus the homogeneous model. Data collected by the Mars Exploration Rovers was used to determine the mean Martian atmosphere optical depth to be $\tau = 0.5$ and the scale height of the Martian atmosphere to be $H_{\mathrm{c}} = 11.6\mathrm{km}$ (Lemmon et al., 2004). The unweighted and weighted Martian atmospheric dust particle concentrations were calculated to be $C_{\mathrm{d}} = 5.36\mathrm{particles/cm}^3$ and $C'_{\mathrm{d}} = 8.48\mathrm{particles/cm}^3$ via Equation 15 and Equation 18, respectively.

2.4 Martian Atmospheric Dust Ingestion

The flux of atmospheric dust particles, $\dot{N}$, into an ISRU system is given by

$$\dot{N} = C_{\mathrm{d}}\dot{V}_{\mathrm{mars}} \tag{19}$$

where C_{d} is the weighted atmospheric dust particle concentration as calculated via Equation 18 and $\dot{V}_{\mathrm{mars}}$ is the volume flow rate of atmosphere into the system as calculated via Equation 9. The total number of atmospheric dust particles ingested, N, by an ISRU system is given by

$$N = \dot{N}t \tag{20}$$

where $\dot{N}$ is the atmospheric dust particle flux as calculated via Equation 19 and t is the total operational time of the system. The total volume of the dust particles ingested, V_{t}, by an ISRU system is given by

$$V_{\mathrm{t}} = NV_{\mathrm{d}} \tag{21}$$

where N is the total number of atmospheric dust particles ingested by the system as calculated via Equation 20 and V_{d} is the mean volume of a single atmospheric dust particle as calculated via Equation 11. The total mass of the dust particles ingested, m_{t}, by an ISRU system is given by

$$m_{\mathrm{t}} = Nm_{\mathrm{d}} \tag{22}$$

where N is the total number of atmospheric dust particles ingested by the system as calculated via Equation 20 and m_{d} is the mean mass of a single atmospheric dust particle as calculated via Equation 12.

2.4.1 Relation to the Mars 2020 Mission

Given that the SOE ISRU system requires an atmospheric volume flow rate of $\dot{V}_{\mathrm{mars}} = 110\mathrm{L/min}$ as calculated via Equation 9, the flux of dust particles into the system will be $\dot{N} = 9.33 \times 10^5\mathrm{particles/s}$ as calculated via Equation 19. Since the system will operate for a total time of $t = 50\mathrm{sol}$, the number of dust particles ingested over its lifetime will be $N = 6.54 \times 10^{10}\mathrm{particles}$ as calculated via Equation 20.

Given that the mean volume of a single atmospheric dust particle is $V_{\mathrm{d}} = 48.9\mu\mathrm{m}^3$ as calculated via Equation 11 and the mean mass of a single atmospheric dust particle is $m_{\mathrm{d}} = 74.4\mathrm{pg}$ as calculated via Equation 12, the total volume of the ingested dust particles will be $V_{\mathrm{t}} = 3.20\mathrm{cm}^3$ as calculated via Equation 21 and the total mass of the ingested dust particles will be $m_{\mathrm{t}} = 4.86\mathrm{g}$ as calculated via Equation 22.

2.4.2 Relation to the MSR Mission

Given that the Sabatier ISRU system requires an atmospheric volume flow rate of $\dot{V}_{\mathrm{mars}} = 550\mathrm{L/min}$ as calculated via Equation 9, the flux of dust particles into the system will be $\dot{N} = 4.66 \times 10^6 \mathrm{particles/s}$ as calculated via Equation 19. Since the system will operate for a total time of $t = 500\mathrm{sol}$, the number of dust particles ingested over its lifetime will be $N = 3.27 \times 10^{12} \mathrm{particles}$ as calculated via Equation 20.

Given that the mean volume of a single atmospheric dust particle is $V_{\mathrm{d}} = 48.9\mu\mathrm{m}^3$ as calculated via Equation 11 and the mean mass of a single atmospheric dust particle is $m_{\mathrm{d}} = 74.4\mathrm{pg}$ as calculated via Equation 12, the total volume of the ingested dust particles will be $V_{\mathrm{t}} = 160\mathrm{cm}^3$ as calculated via Equation 21 and the total mass of the ingested dust particles will be $m_{\mathrm{t}} = 243\mathrm{g}$ as calculated via Equation 22.

3 Electrostatic Precipitator

3.1 Background

A typical electrostatic precipitator consists of a cylindrical high voltage electrode installed along the central axis of a grounded metal cylindrical shell into which a gas infused with dust may flow. The corona emanating from the high voltage electrode charges the dust particles within the gas and allows an electrostatic force generated between the high voltage electrode and grounded chassis to deflect the charged particles into the wall of the chamber and remove them from the gas stream. Additional supporting equipment is required to simulate the Martian environment inside the chamber.

3.2 Laboratory Setup

A gas source is connected, regulated, and protected from overpressure events by a relief valve that vents when the system pressure rises above atmospheric pressure. The flow into the chamber is regulated via an upstream flow controller and the pressure within the chamber is regulated via a downstream pressure controller that throttles the effectiveness of the vacuum pump. A vent valve is included between the chamber and the pressure controller to quickly return the system to ambient laboratory conditions. The pressure of the gas is measured before the flow controller to detect overpressure events and after the flow controller to verify the pressure of the simulated atmosphere. Two laser particle counters sample the atmosphere upstream and downstream of the filtering element located within the chamber in order to quantify dust removal efficiency. The block diagram of the laboratory setup is shown in Figure 1.

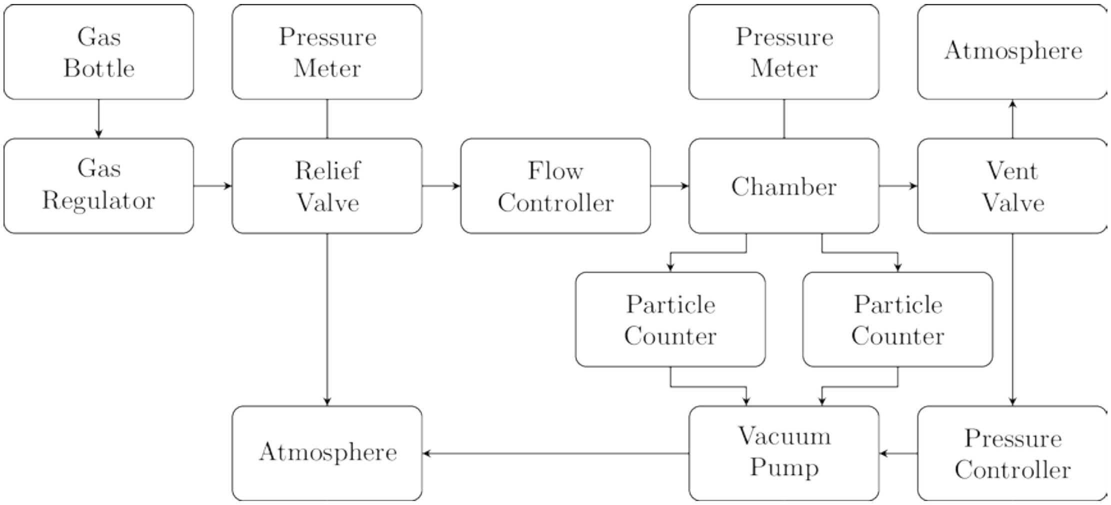

Figure 1: Block diagram of the electrostatic precipitator laboratory setup with arrows marking the flow of gas through the system.

3.3 System Operation

3.3.1 Flow Control

The flow control subsystem of the electrostatic precipitator runs at the ambient temperature, $T = 295\mathrm{K}$, and pressure, $P = 1013.25\mathrm{mbar}$, of the laboratory, rather than the Martian surface temperature, $T = 210\mathrm{K}$, and pressure, $P = 6.36\mathrm{mbar}$. Substituting these laboratory conditions into Equation 9 indicate that volume flow rates of $\dot{V}_{\mathrm{lab}} = 970\mathrm{cm}^3/\mathrm{min}$ and $\dot{V}_{\mathrm{lab}} = 4.85\mathrm{L}/\mathrm{min}$ will be required to simulate the ISRU systems on the Mars 2020 and MSR missions, respectively. These two setpoints for the flow control subsystem will correspond to the respective atmospheric flow rates of $\dot{V}_{\mathrm{mars}} = 110\mathrm{L}/\mathrm{min}$ and $\dot{V}_{\mathrm{mars}} = 550\mathrm{L}/\mathrm{min}$ calculated in Section 2.1 for the Martian environment.

3.3.2 Pressure Control

Should the pressure within the chamber diverge from the setpoint, the flow rate of the gas exiting the chamber will be set to a value higher or lower than the flow rate of the gas entering the chamber in order to decrease or increase the chamber pressure such that it converges to the desired value. Both ISRU systems will run at the mean Martian surface pressure of $P = 6.36\mathrm{mbar}$, so this will be the setpoint for the pressure control subsystem.

3.3.3 Dust Entrainment

Dust entrainment into the gas flowing through the system is controlled via a mechanical feedthrough placed immediately after the flow controller. Given that the ISRU systems operate over a lifetime of $t = 50\mathrm{sol}$ and $t = 500\mathrm{sol}$, respectively, and ingest a total dust particle mass of $m_\mathrm{t} = 4.86\mathrm{g}$ and $m_\mathrm{t} = 243\mathrm{g}$, respectively, a dust mass flow rate of $\dot{m}_\mathrm{d} = 69.4\mathrm{\mu g/min}$ and $\dot{m}_\mathrm{d} = 347\mathrm{\mu g/min}$ will be required to simulate their respective ISRU system in the laboratory.

3.3.4 Collection Efficiency

Upstream and downstream laser particle counters measure the number of dust particles before and after the filtering electrode in the electrostatic precipitator. The collection efficiency of the system is described by the ratio of the number of removed dust particles, given by the difference between upstream and downstream counts, to the total number of dust particles entering the system, given by the upstream count. The specific particle counters being used may measure collection efficiencies at the $0.5\mathrm{\mu m}$ and $5.0\mathrm{\mu m}$ scale simultaneously.

4 Conclusions

Full scale ISRU oxygen production for a human exploration mission to Mars requires an oxygen mass flow rate of 2.2kg/hr. Assuming carbon dioxide is converted to oxygen with an efficiency of 60%, Martian conditions are $T = 210\mathrm{K}$ and $P = 6.36\mathrm{mbar}$, and laboratory conditions are $T = 295\mathrm{K}$ and $P = 1013.25\mathrm{mbar}$, the setpoints for the electrostatic precipitator setup were determined.

The ISRU system included in the Mars 2020 mission will run at 1% of full scale oxygen production by producing 22g/hr over a total operational time of 50sol. The SOE reaction produces 1mol of oxygen for every 2mol of carbon dioxide consumed. To produce the target amount of oxygen, an atmospheric volume flow rate of 110L/min is required on Mars, but only $970\mathrm{cm}^3/\mathrm{min}$ is required in the laboratory. During the lifetime of the experiment, 4.86g of dust will be ingested at a rate of $69.4\mathrm{\mu g/min}$.

The ISRU system included in the MSR mission will run at 20% of full scale oxygen production by producing 440g/hr over a total operational time of 500sol. The Sabatier reaction produces 2mol of oxygen for every 1mol of carbon dioxide consumed. To produce the target amount of oxygen, an atmospheric volume flow rate of 550L/min is required on Mars, but only 4.85L/min is required in the laboratory. During the lifetime of the experiment, 243g of dust will be ingested at a rate of $347\mathrm{\mu g/min}$.

After converting the operational requirements for the planned ISRU missions into setpoints for the laboratory electrostatic precipitator setup, investigations examining the effects of varying parameters of electrode geometry such as diameter, length, and rigidity on collection efficiency may be carried out. These results will allow for the maximum operating voltages to be quantified as a function of electrode geometry in an effort to decrease the size and mass of the system for inclusion on a future mission to

Mars.

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