Abstract MOXIE is a technology demonstration that addresses the Mars 2020 (Perseverance) objective of preparing for future human exploration by demonstrating In Situ Resource Utilization (ISRU) in the form of dissociating atmospheric CO₂ into O₂. The primary goals of the MOXIE project are to verify and validate the technology of Mars ISRU as a springboard for the future, and to establish achievable performance requirements and design approaches that will lead to a full-scale ISRU system based on MOXIE technology.

MOXIE has three top-level requirements: to be capable of producing at least 6 g/hr of oxygen in the context of the Mars 2020 mission (assuming atmospheric intake at 5 Torr, typical of Jezero Crater, and 0 °C, typical of the rover interior); to produce oxygen with > 98% purity; and to meet these first two requirements for at least 10 operational cycles after delivery. Since MOXIE is expected to operate in all seasons and at all times of day and night on Mars, these requirements are intended to be satisfied under worst-case environmental conditions, including during a dust storm, if possible.

Keywords In-situ resource utilization · ISRU · Mars atmosphere · Oxygen production on Mars · Mars 2020 · MOXIE
List of Acronyms

APB  Advance Peripheral Bus
ASR  Area Specific Resistance
CAC  CO₂ Acquisition and Compression System
CSA  Ceramatec SOXE Assembly
DAC  Digital-to-Analog Converter
DRA  Design Reference Architecture
EDL  Entry, Descent, and Landing
EM   Engineering Model
FPGA Field Programmable Gate Array
FM   Flight Model
FS   Flight Spare
GUI  Graphical User Interface
HEPA High Efficiency Particulate Air filter
iASR Intrinsic Area Specific Resistance
ISRU In Situ Resource Utilization
JPL  Jet Propulsion Laboratory
JSA  JPL SOXE Assembly
LOX  Liquid Oxygen
MAV  Mars Ascent Vehicle
MEDA Mars Environmental Dynamics Analyzer
MMRTG Multi-Mission Radioisotope Thermoelectric Generator
MOXIE Mars Oxygen ISRU Experiment
MRAM Magneto-resistive Random Access Memory
MT   Metric Tons
NASA National Aeronautics and Space Administration
NDIR Non-Dispersive Infrared Radiation
OCV  Open Circuit Voltage
OC#  Operating Cycle number
PET  Polyethylene Terephthalate
PID  Proportional-Integral-Differential
PMC  Process Monitor and Control
PRT  Platinum Resistance Thermometer
PWM  Pulse Width Modulation
RAMP Rover Avionics Mounting Panel
RCE  Rover Compute Element
RCT  Run Control Table
ScSZ Scandia-Stabilized-Zirconia
SOXE Solid Oxide Electrolysis unit
SRS  Shock Response Spectrum
TVAC Thermal Vacuum
VFCD Viscous Flow Control Device

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1 How MOXIE Works

MOXIE is a Class D technology demonstration that addresses the Mars 2020 (Perseverance) objective of preparing for future human exploration by demonstrating In Situ Resource Utilization (ISRU) in the form of dissociating atmospheric CO₂ into O₂. On a future human mission, such a process will be used to autonomously provide at least 24 metric tons (MT) of liquid oxygen (LOX) for ascent vehicle propellant in the 16 months preceding launch of a human crew to Mars. Allowing for margin, no more than a 14-month production cycle should be assumed.

A mission to send a human crew to Mars has long been an important goal of planetary exploration. Numerous mission plans have been developed in the period beginning ∼ 1950 (e.g. Portree 2001; Drake 2009; Rapp 2015), as well as a series of NASA Design Reference Missions (now Design Reference Architectures) that began in the 1990s (Drake 2009).

A major challenge emerging from these studies is how to provide the large mass of cryogenic propellants needed to power a Mars Ascent Vehicle (MAV) to transport astronauts from the Mars surface to an Earth Return Vehicle waiting in Mars orbit. As an alternative to carrying the propellant from Earth, the Design Reference Architecture calls for using in situ resource utilization (ISRU) to manufacture some or all of the propellants from indigenous Mars resources. For a methane–oxygen system with rendezvous to an elongated elliptical orbit, an estimated 24 MT of O₂ would be required for a MAV sized for a crew of four. For a crew of six, this would be ∼ 36 MT.

Sending all the propellant for the MAV from the Earth would require launching hundreds of tons of payload into Earth orbit on multiple vehicles, then coordinating their delivery to a common landing site on Mars. With current propulsion technology and without any as yet untested techniques such as aerocapture, sending one ton from low Earth orbit to the surface of Mars requires anywhere from 11–30 tons in Low Earth Orbit (Rapp 2015, Chap. 4), the so-called “gear ratio”, which depends on the use of aerocapture or propulsive descent, accounting for factors such as propellant, the spacecraft and propulsion system, cryogenic tanks, and a heat shield for Mars entry, descent, and landing (EDL). Despite the reduction in launch costs resulting from new generations of reusable launch vehicles, the cost of launching all the MAV propellant from the Earth would be billions of dollars. Besides launch costs, sending large quantities of oxygen from the Earth to Mars would require a zero boil-off system, which needs insulation, refrigeration, and power, and the logistics of managing many heavy lift launches in a manner compatible with the 26-month cycle of Mars launch opportunities would also be a great challenge.

While it is known that significant amounts of water ice exist at high latitudes on Mars (Smith et al. 2009, Rapp 2015, Appendix C, Leighton and Murray 1966) and converting Martian water into rocket propellant may ultimately be possible, a more practical first step towards using local Mars resources is to produce the oxygen needed for ascent directly from the Martian atmosphere, eliminating the need to prospect, mine, and refine ice or any other resource. The oxidizer in a CH₄+O₂ propellant system comprises 78% of the total propellant mass, so producing it on Mars saves a lot, even if the fuel itself is imported from Earth (Rapp 2015).

In the vast majority of mission studies, it is argued that the safest way to get a human crew to Mars is in two steps, ∼ 26 months apart (the interval between Hohmann transfer launch opportunities), with the first establishing infrastructure and the second carrying the crew. Incorporation of ISRU into a human mission would follow the same pattern, with an ISRU plant accompanying the Mars habitat, MAV, and power system to the Martian surface on the first launch (the Earth return vehicle is also sent at that time and left
in orbit). Allowing for the time to reach Mars and commission the hardware, the ISRU system would have to load the MAV tanks with propellants over about a 14-month period. This will give sufficient time to confirm that the MAV propellant tanks are properly loaded, after which the human mission could proceed to launch. The amount of propellants required, together with the time to produce them, determines the required production rate.

In 2013, NASA took a major step toward developing Mars ISRU technology and validating its performance on Mars by issuing an Announcement of Opportunity (AO) that called for: “... demonstration of in-situ resource utilization (ISRU) technologies to enable propellant and consumable oxygen production from the Martian atmosphere for future exploration missions”. Mass, volume, and power was allocated on the Mars 2020 Rover to enable this payload to operate on the surface of Mars. A team led by the Massachusetts Institute of Technology (MIT) was subsequently selected to deliver and operate the Mars OXygen ISRU Experiment (“MOXIE”), with NASA’s Jet Propulsion Laboratory (JPL) as the technology development partner and flight system integrator.

1.1 Design Approach

The primary goals of the MOXIE project are to verify and validate the technology of Mars ISRU as a springboard for the future, and to establish achievable performance requirements and design approaches that will lead to a full-scale ISRU system based on MOXIE technology.

MOXIE has three top-level requirements: to be capable of producing at least 6 g/hr\(^1\) of oxygen in the context of the Mars 2020 mission (assuming atmospheric intake at 5 Torr, typical of Jezero Crater, and 0 °C, typical of the rover interior); to produce oxygen with > 98% purity; and to meet these first two requirements for at least 10 operational cycles after delivery. Since MOXIE is expected to operate in all seasons and at all times of day and night on Mars, these requirements are intended to be satisfied under worst-case environmental conditions, including during a dust storm, if possible.

In recognition of MOXIE’s purpose to serve as a technology pathfinder, a high priority design guideline was to select approaches and components that reasonably extrapolate to a full-scale system. For example, even though the MOXIE flight model is expected to run for no more than ~ 100 hrs, it would not be valuable to select a CO\(_2\) collection technology whose lifetime is intrinsically incompatible with the > 10000 hours of operation required of the full-scale system. We tried, where possible, to avoid such technology dead ends.

We also recognized that despite the inevitable focus on successful surface operations, MOXIE technology validation is the sum of what is learned on Mars and what is learned in the laboratory on Earth. The MOXIE project team proposed a dual-pronged approach of operating a prototype system on Mars to validate that ISRU can effectively be carried out autonomously in a hostile environment, and operating a system in the laboratory where it is possible to do experiments such as sustained, long-term operation and exploration of new control algorithms that are not possible in the context of a flagship NASA mission. Together, these results will inform the design of future scaled-up Martian atmospheric ISRU missions. MOXIE’s design approach was guided by the recognition that the achievable oxygen production rate is limited by three factors:

\(^1\)The somewhat unusual unit of g/hr reflects initial requirements on the MOXIE system and will be used consistently through descriptions of the flow system.
• The atmospheric density, which is a strong function of landing site and can vary by nearly a factor of two over annual and diurnal cycles even at a single location.
• Physical limitations of the technology, including the maximum compressor speed and the current limits for the oxygen generation plant.
• The need for prudent and robust operations, particularly with respect to avoiding carbon production, which constrains the maximum operating voltage and fractional utilization of CO₂.

Key aspects of the MOXIE design include:
• Mechanical acquisition of Martian air using a scroll compressor, developed under contract with Air Squared, Inc. The scroll compressor was sized for \( \sim 40 \text{ g/hr} \) room-temperature atmosphere intake at a minimum atmospheric pressure of 3.5 Torr (equivalent to 87 g/hr @ 7.6 Torr).
• Conversion of CO₂ to O₂ using a solid oxide electrolysis (SOXE) unit developed by Cera-ramatec, Inc. (now OxEon Energy). The SOXE is configured as a single mechanical stack of 10 cells, electrically configured as two stacks of 5 cells each.
• A power supply capable of delivering up to 4 A for SOXE conversion, sufficient to produce O₂ at a rate of up to 1.2 g/hr/cell, or 12 g/hr for the stack.
• Tolerance of the SOXE to a range of inlet pressures from \( \sim 260–760 \text{ Torr} \), relieving the need to provide active pressure regulation.
• Robust and redundant process control and telemetry, provided by a combination of traditional flight-qualified sensors (e.g. Platinum Resistance Thermometers (PRTs) for temperatures, Kulite pressure transducers) and commercial sensors, including a luminescence oxygen sensor and several NDIR gas composition sensors. In addition, a pair of pressure sensors is configured around an aperture to provide a measure of flow. MOXIE will rely on other Mars 2020 sensors (notably from the MEDA instrument) to monitor external environmental conditions.

Sharing resources with the Mars 2020 investigation constrained several aspects of the design and operation of MOXIE:
• MOXIE is expected to run at least 10 times in the primary mission of one Martian year. This necessitates that MOXIE be capable of thermal cycling to its 800 °C operating temperature at least 10 times (the driving requirement) in addition to several test cycles on Earth as part of test and validation. This degree of cycling is substantially more than is expected on a full-scale mission, particularly given the conventional qualification requirement of testing to three times the anticipated number of cycles (60 in this case). Thermal cycling is associated with subtle materials degradation processes that pose a significant challenge to meeting this requirement.
• Overall operating lifetime for MOXIE on Mars is expected to be a few tens of hours, in comparison to a need for sustained operation in excess of 10000 hours for a full-scale system.
• Mass, volume, and power constraints dictate compromises in the overall power and mass efficiency of the MOXIE design that, if extrapolated, would suggest an impractical size in a full-scale system. An optimal prototype would have been substantially larger, with a more capable power source.
• The Mars 2020 landing site is at substantially higher elevation than any past Mars lander and any likely human landing site. As a consequence, the atmospheric density is substantially lower than would be expected for a future mission, increasing the challenge of CO₂ collection and compression.
MOXIE is installed in the belly of a temperature-controlled rover, relatively insensitive to Mars environmental temperatures except for the temperature of the gas intake.

Technical resource allocations for MOXIE are 18 kg, an allocated volume of $23.9 \times 23.9 \times 30.9$ cm, and two 10-amp power switches. MOXIE is intended to be energy-neutral in operation, while using a full sol’s payload allocation of $\sim 1000$ W-hrs. In other words, the rover will begin the sol following a “MOXIE sol” with the same battery state-of-charge as at the beginning of the previous sol. MOXIE will use MOXIE sols to investigate the robustness of its technical performance (flow rate, oxygen production rate, oxygen purity, voltage–current relationship of SOXE), to learn how to optimize performance, and to understand how performance changes with environmental conditions and repeated use.

1.2 Overview

MOXIE collects Martian atmosphere, filtering and compressing it before injecting it into a Solid OXide Electrolysis reactor (SOXE) that converts CO$_2$ into oxygen and CO according to the reaction $2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2$. Numerous sensors measure the progress of the electrolysis and allow monitoring and control of the process.

Figure 1 shows the assemblies responsible for gas collection and electrolysis as they are assembled for flight. The actual SOXE stack, embedded in the SOXE assembly, uses a negligible share of the overall mass and volume resources. Operating at $\sim 800$ °C, the stack is surrounded by thermal insulation, heaters and heater blocks, a thermally controlled gas-handling manifold, and a mechanical compression apparatus driven by four springs.

A scroll compressor customized for MOXIE was chosen as the gas collection system. Some of the gas handling lines can be seen in the figure; not shown is the filter enclosure located on the exterior of the rover. The inlet filter adds an additional $23 \times 9 \times 12$ cm. The mass of the combined system is 17.8 kg.

For thermal control, the bottom plate of MOXIE dissipates the substantial rejected heat from the electronics, SOXE, and compressor to the Rover Avionics Mounting Panel (RAMP).

Figure 2 shows a simplified layout of the MOXIE gas flow system. Most sensors and flow control devices are collected on a common panel mounted behind the compressor and SOXE assemblies; since the panel is not temperature controlled, all devices need to be calibrated over the anticipated temperature range. An electronics box is mounted on the side. Thermal control of the gas stream is accomplished with 3D-printed heat exchange devices, among the first 3D-printed parts to be flown on planetary missions.

Mars atmosphere contains about 95.5% CO$_2$, with Ar and N$_2$ comprising most of the remainder. Gas is drawn in through a HEPA (High Efficiency Particulate Air) filter to the compressor inlet. The atmospheric pressure at Jezero Crater, the chosen landing site for Mars 2020, is expected to vary during the course of a year from $\sim 4.5$ to $\sim 6.0$ Torr. Note that future human landers are expected to land at significantly lower elevations than Jezero, more like the locations chosen for previous lander missions, which will result in substantially higher atmospheric pressure.

To minimize mass and volume, the outlet pressure of the MOXIE gas collection system is constrained by Viscous Flow Control Devices (VFCDs) at the outlets rather than by gas regulators. Since VFCDs are effectively temperature-compensated precision apertures, the outlet pressure will go up or down with the inlet gas density as well as the motor speed and
Fig. 1 MOXIE with front cover removed, showing compressor and SOXE assemblies. Not shown are the inlet filter, sensor and flow control panel, and electronics. The dimensions of the unit are $23.9 \times 23.9 \times 30.9$ cm

performance of the gas collection system. The throughput of the VFCDs reflects a design choice weighing optimal operating pressures for the SOXE against minimization of mass and power resources. On Mars, MOXIE will electrolyze CO$_2$ at a pressure between 400 and 760 Torr. Ar and N$_2$ pass harmlessly from the inlet to the waste stream, which is exhausted to the Mars atmosphere.

After the now-pressurized Mars atmospheric gas emerges from the scroll compressor, it is preheated in a 3D-printed Inconel heat exchanger with internal channels that provide a sufficient surface area-to-volume ratio to bring the gas into thermal equilibrium with the metal, while a back-flow gas cooler prevents hot gases from damaging the check valve during the shut-down process. The hot gas flows into a stack of ten solid oxide electrolysis cells comprising the SOXE, which converts 30–50% of the hot CO$_2$ to CO and O$_2$, depending on operating conditions.

Inside the stack of ten SOXE cells, one side of the formed and sintered interconnects separating the cells directs the inlet gas across the nickel-catalyzed cathodes, carrying CO, unreacted CO$_2$, and residual atmospheric gases to the cathode exhaust plenum. The other side of the interconnects directs the pure oxygen product away from the anodes into the oxygen plenum. From the gas-handling perspective, a single inlet stream results in two outlet streams, one for waste products and the other for the oxygen product.

Composition sensors characterize the outlet gases before they exhaust through VFCDs and sintered filters into the Mars atmosphere. The sensors in the anode line verify the mass flow of oxygen (also determined by measuring the SOXE current), and the purity of the product is verified by measuring trace CO$_2$, the only plausible contaminant (any CO leaking into the oxygen stream would be immediately oxidized to CO$_2$). Sensors in the cathode line
Fig. 2  Schematic layout of MOXIE gas flow system, showing compression, electrolysis, and thermal control of the inlet, product and waste gas streams. Heat exchange devices receive cold gas from the compressor, preheat them to operating temperature, recover the heat from the outlet gases, and prevent hot gases from backflowing into the compressor when the system is being shut down. Exhaust gas heaters are vestigial from an earlier design that maintained full temperature control of the sensors. A check valve damps out pressure oscillations from the rotating scroll pump. The flow sensor is a pair of pressure sensors that measure ΔP across an orifice.

detect CO and CO₂, a critical ratio controlled by a combination of compressor speed and SOXE current to produce the maximum amount of oxygen possible while avoiding carbon formation that would result from overdriving the reaction voltage. Like the oxygen measurement, these measurements are redundant, since CO mass flow can also be determined from SOXE current, and CO₂ mass flow can be determined from pressure, temperature, and volumetric flow sensors.

As CO₂ is a mildly oxidizing gas, long-term operation with Mars inlet gas can result in oxidation of the nickel catalyst in the cathode. To prevent this, a few percent of the exhaust gas in the cathode line is tapped off by a VFCD to recirculate back to the compressor inlet, so that the gas entering the SOXE contains a few percent CO, whose reducing property counteracts potential oxidation by the CO₂.

The following sections describe the various subsystems of MOXIE in greater detail, following the gas flow from the ambient atmosphere through the gas composition monitoring at the outlet, and concluding with a system-level discussion of controls and mass flow.

1.3 Gas Flow Through MOXIE

Primary elements of the MOXIE flow system are shown schematically in Fig. 3, ignoring small pressure drops across filters and other components. The two flow restrictors at the
Fig. 3 MOXIE flow system nomenclature. $F$ refers to mass flow, typically in g/hr. Elements marked $V_a$, $V_c$, and $V_r$ are VFCD apertures for anode, cathode, and recirculation respectively. The cathode exhaust $F_{ex}$ is split into a recirculated flow stream $F_r$ and a non-recirculated stream $F_{nr}$. The flow through the SOXE consists of the intake $F_i$ from Mars ambient and the recirculated $F_r$.

Fig. 4 MOXIE pressure sensor placement. $P_1$ is downstream of the inlet filter and will read close to Mars ambient pressure. $P_2$ and $P_3$, downstream of the compressor, are separated by a small constriction to provide a measure of flow. $P_4$ measures cathode exhaust and $P_5$ measures the oxygen plenum. Elements marked $V_a$, $V_c$, and $V_r$ are VFCD apertures for anode, cathode, and recirculation respectively. Exhaust gasses are released to the Mars atmosphere at pressure $P_M$.

Far right are VFCDs for which there is a known flow resistance and, therefore, a known relationship between the upstream pressure and the mass flow rate through the VFCD. This relationship depends slightly on the composition and the temperature of the gas. The compressor combines two mass streams: $F_i$ is the intake from Mars ambient and $F_r$ is a small stream recirculated from the cathode exhaust. The compressor delivers the combined mass flow $F_s = F_i + F_r$ into the SOXE, where $F_i$ makes up a few percent of the total mass.

The gas exits the SOXE in two streams, $F_{ex}$ from the cathode (consisting of CO, unused CO$_2$, and 4–5% inert gases) and $F_{O2}$ from the anode (consisting of pure O$_2$), such that $F_s = F_{ex} + F_{O2}$. The cathode exhaust is further divided into two streams: $F_r$, which is recirculated to the compressor inlet through a third VFCD, and $F_{nr}$, which is returned to the ambient, such that $F_{ex} = F_r + F_{nr}$.

The flow system is instrumented with five pressure sensors, in locations shown in Fig. 4. $P_M$ is the pressure of the Martian atmosphere, to which the exhaust gasses are released. This measurement will be made by the MEDA experiment. Both composition and total pressure at any point in the flow stream can be determined from mass balance with knowledge of the compressor throughput $F_s$, the SOXE current $I$, and all flow resistance values. Mass balance can also be used to determine $F_s$ from pressure sensor readings. Ignoring a small drop across a sintered exit filter, the pressure at the cathode exit is:

$$P_4 = a F_s$$

where the mass balance factor $a \sim 9.60$ mbar-hr/g in the typical flow range.

1.3.1 Filtering Dust from the Mars Atmosphere

In addition to CO$_2$ and trace gases, the Martian atmosphere contains suspended dust particles (Pollack et al. 1977, 1979, 1995). Filtering out these particles before they reach the SOXE is
essential, because they can cause both physical damage from clogging and chemical damage if the particles contain sulfates (Hecht et al. 2017). MOXIE filters the atmosphere upstream of the scroll compressor to avoid potential compressor damage. An initially-assumed disadvantage of filtration at Mars ambient pressure was that even a small pressure drop across the filter would be a large proportion of the total pressure. In future systems, it may be preferable to filter only the larger particles upstream of the compressor, with High Efficiency Particulate Air (HEPA) filters operating at a high-pressure stage.

The most important properties of the suspended dust for filtration are its size distribution and number density. The size distribution is typically a modified gamma function (Korablev et al. 2005). The two parameters of the distribution, the effective radius and effective variance, are determined using optical scattering methods (Hansen and Travis 1974). The effective radius, equivalent to the surface area moment mean radius, is approximately 1.5 µm (Pollack et al. 1995; Tomasko et al. 1999; Lemmon et al. 2004; Komguem et al. 2013; Vicente-Retortillo et al. 2017), and varies throughout the Mars year (Chen-Chen et al. 2019). It should be noted, however, that optical scattering methods are only sensitive to particles in the size range 0.8 to 3 µm (Tomasko et al. 1999), whereas particles of all sizes are relevant for filtration. The number density is typically in the range 1 to 10 /cm³ (Moroz et al. 1993; Metzger et al. 1999), although this can increase during dust storms. The number density is usually retrieved by measurement of the optical depth of the atmosphere (Taylor et al. 2007; Lemmon et al. 2015).

In addition to suspended dust particles, the dust-lifting processes of saltation and dust emission must be considered. Saltation is the wind-driven lofting of particles that are too large to enter into suspension and follow semi-ballistic trajectories near the surface (Kok et al. 2012). Dust emission is the wind-driven production of particles that are small enough to enter into suspension and is subdivided into the processes of aerodynamic entrainment and saltation bombardment (Shao 2008). Aerodynamic entrainment is the direct wind-driven lofting of particles that are small enough to enter into suspension. Saltation bombardment is the fragmentation of aggregate particles into particles that are small enough to enter into suspension.

Dust-lifting processes are initiated when the wind shear, or equivalently the surface stress, exceeds a threshold that is determined by the aerodynamic lift and drag acting on a particle, particle weight, and interparticle forces. The threshold is therefore dependent on particle size, with a minimum around 100 µm. On small spatial scales, dust lifting can occur due to strong winds, convective vortices (dust devils), and descent rocket efflux. Dust devils present a particular challenge, as they combine increased dust particle number density with strong convective updrafts. On large spatial scales, dust-lifting events can combine to form local, regional and global dust storms.

Mars 2020’s landing date at $L_\circ \sim 5^\circ$, shortly after the northern hemisphere spring equinox on Mars, is compatible with an initially conservative operating strategy for MOXIE. During the first half of the Mars year, the dust particle number density is expected to be relatively low and dust storms infrequent. During the second half of the Mars year, the dust particle number density is expected to increase, and dust storms are expected to become more frequent (Martínez et al. 2017). Therefore, by distributing MOXIE runs throughout the mission, operation can first be proven in relatively benign dust conditions, followed by more challenging conditions.

The MOXIE approach to dust filtration has been described by Hecht et al. (2017) and McClean et al. (2020). To prevent dust ingestion, MOXIE is fitted with a High Efficiency Particulate Air (HEPA) filter, described in greater detail below, as well as a mechanical baffle that protects the filter from larger particles mobilized by saltation events or, during landing, by the downward-pointing retro rockets of the sky crane. The MOXIE team undertook
Fig. 5  MOXIE HEPA filter on the cm, mm and µm scale

experimental filter studies to both verify that the capacity of the filter is adequate for the anticipated conditions and to learn how the size will need to scale in the future with increasing operating time and mass flow rate. Preliminary studies suggest that the combination of the baffle and the filter housing, which acts as a bluff body, may also deflect most of the smaller entrained particles, but further fluid dynamic analysis is needed to confirm this result.

MOXIE’s filter assembly consists of a filter housing, a baffle, and a HEPA filter. The filter housing is bolted to the exterior of the rover body. The rectangular inlet faces downwards and is approximately flush with the rover belly. The HEPA filter is made of LydAll® LydAir® Micro Glass (MG) HEPA 3428 A/A media (Custom Filter LLC, Aurora, IL). The media consists of three layers: a central glass microfiber layer and two surrounding polyethylene terephthalate (PET) layers. The filter media is located between two sheets of coarse wire mesh, formed into pleats, and mounted in the filter housing using epoxy. The baffle, which contains a double-switchback flow path to prevent larger particles from damaging the filter, is bolted to the front of the filter housing. The filter assembly is connected to the compressor by a ~70 cm long tube.

Figure 5 displays the filter at 50,000, 200, and 3 µm scales.

Although HEPA filter performance has been extensively studied under terrestrial atmospheric conditions (e.g. Brown 1993; Thomas et al. 2017), there are relatively few studies relevant to Mars atmospheric conditions (Li et al. 2014; Agui 2016, 2019), where the transition and free molecular flow regimes are applicable. Moreover, most of these studies focus on particles at the limit of HEPA filtering ability, typically an order of magnitude smaller than the characteristic Martian particles.

To address this gap, three studies of the HEPA filter dust loading and pressure drop under Martian conditions were conducted over two experimental campaigns (McClean et al. 2020) at the Mars Simulation Laboratory at Aarhus University, Denmark (Merrison et al. 2008; Holstein-Rathlou et al. 2014) using MOXIE-like filters and Mars dust simulant (Nørnberg et al. 2009). These studies investigated (a) the pressure drop across the filter as a function of dust loading, (b) the rate of dust loading as carbon dioxide was drawn through the filters, and (c) dust loading from passive exposure to dusty wind.

Pressure Drop Across the Filter  In Earth atmospheric conditions, HEPA filters operate in the slip flow regime. In the slip flow regime, the pressure drop across a filter, $\Delta P$, is described by Davies (1973) with the Cunningham slip correction factor applied, and is largely independent of atmospheric pressure $P$. In contrast, under Mars atmospheric conditions the MOXIE HEPA filter will operate in the free molecular flow regime, where the pressure drop across the filter, described by Pich (1971), is proportional to atmospheric pressure. To
Fig. 6 Nine flat samples of the MOXIE HEPA filter media with levels of dust loading from 1.0 to 45.3 g/m²

To maintain effective filter performance, it is therefore only necessary to ensure that \( \Delta P / P \) is acceptably low, independent of ambient pressure fluctuations. When MOXIE is operating, the HEPA filter will produce a non-negligible pressure drop. As dust accumulates on the filter, this pressure drop will increase, reducing the mass flow rate. The magnitude of this increase was measured in the Aarhus experiments (McClean et al. 2020), in which nine sections of MOXIE filter media were preloaded with Mars dust simulant, with loading per unit filter media area varying from 0 to 45.3 g/m² (Fig. 6).

The pressure drop across each filter was then measured in simulated Mars atmosphere at filtration speeds between 0 and 10 cm/s. The pressure drop was found to increase linearly with dust loading such that \( \Delta P = (am + b)v \), where \( \Delta P \) is the pressure drop in mbar, \( a = 0.0012(1) \text{ mbar/(g/m}^2\text{/cm/s)} \), \( m \) is the dust loading per unit filter media area in g/m², \( b = 0.063(1) \text{ mbar/cm/s} \), and \( v \) is the filtration speed (not inlet flow speed) in cm/s (Fig. 7). Pressure drop was directly proportional to filtration speed and increased with wind tunnel pressure.

Inlet flow speeds on Mars are expected to be approximately 6 cm/s. At such flow speeds, the pressure drop across the clean filter is expected to be approximately 0.5 mbar (0.37 Torr). The experimental result shows that the pressure drop across the clean filter doubles at a dust loading per unit filter media area of approximately 50 g/m². Since MOXIE’s HEPA filter is expected to reach dust loadings of 0.1 g/m², the increase in pressure drop across the filter is expected to be small.

**Dust Accumulation During Compressor Operation**  The dust loading rate can be estimated as follows. MOXIE is expected to run for a total of at least 10 hours during the nominal mission duration of one Mars year. During this time, MOXIE will produce approximately 100 g of oxygen from \( 5 \times 10^7 \text{ cm}^3 \) of Mars atmosphere with a mass of 830 g. Assuming an optical depth of 0.5, corresponding to 4 dust particles per cm³, MOXIE will have to reject \( 2 \times 10^8 \) dust particles. Assuming a volume moment mean radius of 2.1 µm and

\(^2\)When discussing instrumentation, pressure is generally expressed in Torr, while in atmospheric studies it is typically expressed in mbar.
Fig. 7 Measured pressure drops for clean and dusty filter samples as a function of inlet flow speed. The line labeled “No Filter” reflects the pressure drop due to the pumping manifold.

Density of 1.5 g/cm³, the mean particle mass is $6 \times 10^{-11}$ g, and the total mass of the ingested dust will be 0.01 g. Note that the density is an estimate. For example, the density could be as low as 0.25 g/cm³ if the particles are aggregates of finer nanophase iron oxide, and as large as 5 g/cm³ if the particles are bulk iron oxide. The dust mass per unit filter face area will be 0.7 g/m², corresponding to a dust loading rate per unit filter face area of 0.07 g/m²/h. This value compares to an estimate of 0.02 g/m²/h by Phillips et al. (2016). However, MOXIE uses a pleated filter, in which the filter media area is ten times that of the filter face area. Therefore, the dust loading rate per unit filter media area will be 0.007 g/m²/h.

The dust loading rate was also investigated experimentally. A flight-representative MOXIE filter assembly was mounted in a wind tunnel in the Mars Simulation Laboratory at Aarhus University (Merrison et al. 2008; Holstein-Rathlou et al. 2014). A simulated Mars atmosphere of carbon dioxide at 10.3 mbar, horizontal wind speed of 3 m/s, and dust simulant (Nørnberg et al. 2009), was produced. To keep the duration of the experiment practical (6 3/4 hours), the number density of the dust particles was much higher, approximately 1000 /cm³, than is typical on Mars. A vacuum pump was used to draw carbon dioxide through the filter assembly at an inlet face speed of 7 cm/s.

The resulting dust loading rate per unit filter media area, linearly scaled to a typical dust particle number density of 4 /cm³, was $\sim 2 \times 10^{-4}$ g/m³/h. Other filter configurations and particle size distributions were tested, as listed in Table 1. The dust loading rate was reduced for larger dust particles; reduced by an order of magnitude for a pleated filter relative to a flat filter; reduced to negligible when carbon dioxide was not being drawn through the filter; reduced by 15–25% for filters fitted with baffles; and not affected by filter face rotation about the vertical axis.

Capture fraction is defined as the number of particles captured by the filter per unit time divided by the product of the particle number density and filter volumetric flow rate. The number of particles captured by the filter per unit time is found by dividing the measured filter mass increase by an assumed particle mass and the exposure duration. Since the size distribution of the captured particles cannot be determined by weighing, an assumed volume moment mean particle radius and density are used to calculate the particle mass. The capture fraction is therefore a mass-weighted capture fraction.
Table 1  Measured filter dust loading rates (McClean et al. 2020)

| Filter configuration | Dust loading rate per unit filter media area (mg/m²/h) scaled to dust particle number density of 4 /cm³ |
|----------------------|----------------------------------------------------------------------------------------------------------------|
| Filter media geometry | Salten Skov (2 µm) | Soda-lime glass (4 µm) | Soda-lime glass (10 µm) |
| Flat Pump on Baffle Parallel | 2.7 ± 0.4 | 1.8 ± 0.4 | 0.45 ± 0.4 |
| Flat Pump on No baffle Parallel | 3.6 ± 0.4 | 2.3 ± 0.4 | 0.45 ± 0.4 |
| Flat Pump off Baffle Parallel | < 0.4 | < 0.4 | < 0.4 |
| Flat Pump off No baffle Parallel | < 0.4 | < 0.4 | < 0.4 |
| Pleated Pump on Baffle Parallel | 0.18 ± 0.04 | 0.18 ± 0.05 | 0.088 ± 0.04 |
| Pleated Pump on Baffle 45° | 0.13 ± 0.03 | Not tested | Not tested |
| Pleated Pump on Baffle 90° | 0.22 ± 0.04 | Not tested | Not tested |

The measured dust loading rate for the flight-representative filter configuration suggests a capture fraction of ∼ 20%, assuming Salten Skov has a density of 2.7 g/cm³ and a volume moment mean radius of 1 µm. This low capture efficiency may be caused by two factors: deflection of dust particles around the inlet with the filter housing acting as a bluff body in the horizontal wind, and reduction of particle ingress due to the baffle. Fluid dynamic analyses are underway to confirm this result. At this capture efficiency, 10 hours of MOXIE operation would result in a dust loading per unit filter face area of 0.14 g/m² rather than the expected 0.7 g/m² if 100% of the dust were captured.

The measured dust loading rates for the three particle size distributions, and preliminary CFD modeling results, also suggest that capture fraction decreases as particle size increases. The modeling suggests that this is caused by inertial size separation, in which larger particles respond more slowly to changes in flow speed and direction. The effective radius of particles in the Martian atmosphere is thought to range up to about 2 µm (Lemmon et al. 2019). The corresponding capture fraction, which is found to fall off dramatically with increasing particle size, may be as small as a few percent, and it presumably can be further lowered by optimizing the filter intake geometry. This has profound implications for the design of future filtration systems.

Dust Accumulation Due to Long-Term Exposure to Mars Winds  A unique feature of MOXIE compared to a future full-scale system is that for the vast majority of the time the MOXIE compressor will not be operating. During this time wind will continuously impinge on the MOXIE filter housing at speeds (∼ 3 m/s) greatly exceeding the flow speed through the filter inlet when the compressor is operating (∼ 1 cm/s). Surprisingly, studies in Aarhus indicated that a negligible mass of dust was captured when carbon dioxide was not being drawn through the filter by the vacuum pump and the wind was parallel to the filter inlet area. Note that wind normal to the filter inlet area was not studied in that effort, which was focused on validating the MOXIE design. While of interest for MOXIE, this result is of limited relevance to future systems, which would typically be in continuous operation.
1.3.2 Acquisition and Compression of the Mars Atmosphere

Acquisition and pressurization of Mars atmosphere gas is simple in concept but challenging in practice. Three possibilities have been proposed: a sorption process, a cryogenic process, and a mechanical pump. The mechanical compressor would be the obvious choice in any terrestrial application but, despite the relative inefficiency and complexity of sorption cycle and cryogenic cycle collection, those technologies were investigated out of concern about the expected overall size and anticipated lifetime of a mechanical compressor in a Mars environment. With the evolution of Mars-compatible motor technology coming out of the rover programs and the development of mass-efficient mechanical pumps such as the Air Squared scroll compressor, the mechanical approach was the most attractive for MOXIE and may well be preferred for any scaled-up system. The other two technologies are briefly reviewed below, and the remainder of the discussion is devoted to scale-up of the mechanical compressor.

**Batch Sorption**  In the sorption process (Rapp et al. 1997), as was used in the Mars ISPP Prototype (Sanders and Kaplan 1998) developed for the subsequently cancelled Mars 2001 Surveyor Lander mission, a sorbent with interstices chosen to match the CO₂ molecule is passively cooled at night and exposed to the Mars atmosphere, from which it adsorbs and accumulates the gas. The sorption bed is then passively or electrically heated during the day to release high-pressure gas. The linkage to the diurnal cycle requires significant storage of gas if oxygen production is to operate continuously.

**Cryogenic Cycling**  A cryogenic system for acquisition and compression of CO₂ from the Mars atmosphere was pioneered by Clark et al. (2001) in a proof-of-concept demonstration. Since then, Muscatello et al. (2014) evaluated several designs for a cryogenic accumulation chamber. In each collection cycle a “cold finger” in the accumulation chamber is exposed to the Mars atmosphere, condensing a ball of solid CO₂. After closing the inlet to the atmosphere, the accumulated “dry ice” is warmed in a pressure chamber, possibly going through a liquid phase before ending up as pressurized gaseous CO₂. Unlike the sorption system, multiple compressors can be run out of phase to provide a continuous supply of oxygen. A drawback of this approach is the build-up in the accumulation chamber of the non-condensable gases Ar and N₂, which constitute up to 5% of the Martian atmosphere. In order to maintain the differential pressure that draws atmosphere into the condensation chamber, it is necessary to use a mechanical pump to periodically vent these non-condensable gases. In this sense the cryogenic approach retains a dependence on a mechanical compressor while adding the complexity and inefficiency of a cycling cryogenic system. It is also energy intensive; a cryogenic batch process was estimated to consume nearly 6 times as much energy as the MOXIE mechanical compressor for the same amount of oxygen production.

**Mechanical Compression**  Mechanical compression is a simple, mature, and ubiquitous technology on Earth. From a thermodynamic perspective mechanical movement of gases should utilize significantly less energy than a cryogenic system requiring phase changes, and a mechanical compressor should be substantially simpler in a flow-through architecture than a batch sorption system requiring high pressure gas storage. Of the available mechanical compression technologies, the oil-free scroll compressor was the most mechanically robust, mature, clean, mass efficient, and resilient system for a MOXIE-scale application. The MOXIE compressor takes in a fixed volume of gas with each rotation and compresses it to a substantially smaller fixed volume. It then releases the compressed gas into the downstream plenum leading toward the SOXE. Assuming a constant volumetric efficiency, the
output mass flow rate scales linearly with the rotation rate and the input gas density. While a different mechanical configuration may be optimal for a scaled-up system, the fundamental functionality will be similar.

The MOXIE compressor is a scroll pump provided by Air Squared (Broomfield, CO) driven by a motor provided by Avior Control Technologies (Longmont, CO). A scroll compressor functions by rotating a movable scroll past a fixed scroll so that a suction volume of inlet gas is sealed off, compressed, and pushed out into the compressor exhaust with each rotation (Fig. 8). As a result, the flow of gas into the downstream plenum oscillates at the frequency of rotation. A check valve at the compressor outlet reduces the downstream pressure oscillations to an acceptable level.

MOXIE’s scroll compressor is driven by a controller that adjusts the power input to the compressor to achieve a commanded rotational speed \( \omega \). Figure 9 shows the interior of the MOXIE scroll pump.

The MOXIE scroll compressor takes in 30.1 cm\(^3\) of gas per rotation and efficiently compresses it to 5.19 cm\(^3\), a 5.8:1 compression ratio. This volume is then forced into the downstream plenum, compressing it at an energy cost of approximately \( V \Delta P \), to a pressure determined by the ambient gas density, the rotation rate \( \omega \), and the VFCD at the cathode exit, but typically in the range 400–600 Torr. Operating the SOXE at lower pressure therefore would offer a significant energy advantage.

The mass flow rate through the compressor, \( F_s \), is proportional to \( \omega \) and to the density of the intake air. The intake gas density is reduced relative to the Mars ambient density as the gas warms in the inlet system, whose temperature is estimated to be \( \sim 20 \) °C. Pressure drops
Fig. 10  Mass flow rate through the compressor vs. inlet gas pressure at various values of rotation rate for the flight model (FM) and flight spare (FS). Labels indicate $\omega$ in RPM. Measurements at 2500 RPM used the Engineering Model (EM).

across the HEPA filter and the inlet tube also reduce the gas density entering the scroll pump compressor. Finite backflow through the compressor reduces the nominal volumetric flow rate (the product of the intake volume and the rotation rate) by a factor captured by the volumetric efficiency $\eta$, which varies with exhaust pressure. Under typical MOXIE operating conditions $\eta$ is typically $\sim 0.86$, indicating that 14% of the gas is lost to backflow.

Three flight-equivalent compressors were delivered to JPL by Air Squared: the Flight Model (FM), the Engineering Model (EM) and a Flight Spare (FS). These were subjected to acceptance tests to determine their power dissipation and mass flow rate as a function of inlet pressure and $\omega$. The compressor was placed in a pressure-controlled chamber that provided inlet gas at a selectable temperature between $-55$ °C to $+70$ °C. The output was routed through a calibrated VFCD with flow resistance 5000 lohms and then exhausted by a vacuum pump. The flow rate was calculated from the pressure measured at the VFCD (Fig. 4). The volumetric efficiency was determined using a quasi-isothermal test setup.

The mass flow rate through the compressor vs. inlet pressure in the JPL tests is shown in Fig. 10.

The mass flow rate is expected to be:

$$F_s = \rho_i V \omega \eta$$  

(1.1)

where $\rho_i$ is the density of the intake air and $V$ is the volume taken in per revolution (30.1 cm$^3$).

In practice, $\eta$ was found to vary slowly with flow rate. At a typical rate of 60 g/hr the volumetric efficiency was found to be $\eta = 0.86 \pm 0.02$. When the 5.19 cm$^3$ volume containing pressurized gas is being sealed by pushing the 5.19 cm$^3$ volume into the plenum, the amount of pressurized gas leaking backward through the compressor to the Mars atmosphere at low pressure causes $\sim 14\%$ loss of compression.

The measured power consumption of the compressors is shown in Fig. 11 as a function of mass flow rate (determined by varying inlet pressure) at two motor rotation rates. MOXIE
uses VFCDs with combined 3745 lohm flow resistance, compared to 5000 lohms in the test configuration, and as a result the required power for thermodynamic compression is slightly lower for the same mass flow rate.

The total measured power dissipated by the compressor is considerably greater than the thermodynamic power as a result of tip and bearing friction, controller losses and motor losses. Compressor power dissipation has been observed to drop with each successive test, suggesting wear on the tip seals, and differences from compressor to compressor are presumably due to differences in tip seal friction. The long-term impact of this wear on time scales greater than anticipated MOXIE usage has not yet been determined, but experience with this family of pumps suggests that they are long-lived and power consumption will approach an asymptote.

### 1.3.3 Measuring Mass Flow

Referring to Fig. 10, the total flow into the SOXE, $F_s$, is partitioned between the cathode $F_{ex}$ and anode $F_{O2}$ flows, in a ratio that can be determined by the SOXE current $I$. The cathode exhaust $F_{ex}$ is further partitioned into two streams, an outlet stream $F_{nr}$ and a recirculation stream $F_t$, such that $F_{ex} = F_t + F_{nr}$. The corresponding VFCD flow resistances are 58.8 klohm for the recirculation line and 4.0 klohm for the outlet, with net resistance of $L_{tot} = 3.745$ klohm. Hence:

$$F_t = 0.064F_{ex} \quad (1.2)$$

$$F_{nr} = 0.936F_{ex} \quad (1.3)$$

The VFCD flow resistance on the anode side is 31.22 klohm.

With the assumption of a starting composition of the ambient gas and knowledge of the gas temperature, the partial pressure of component gases everywhere in the flow path can be uniquely determined.
In practice, the various flow terms are derived from the pressure and temperature sensors shown in Fig. 10. Note that in the following numerical examples the pressure terms \( P_x \) are in Torr, the flow terms \( F_x \) are in g/hr, and temperatures are in Kelvin.

\( F_{ex} \) is derived from the pressure measured at \( P_4 \) using the equation for sonic flow through the pair of VFCDs:

\[
P_4 = F_{ex} L_{tot} / 0.00268 MKT_n \tag{1.4}
\]

where:

\[ K = \text{composition-weighted flow constant} \left(= 4289 \text{ for 50:50 mix of CO/CO}_2 \right) \]

\[ M = \text{composition-weighted molecular weight} \left(= 36 \text{ for 50:50 mix of CO/CO}_2 \right) \]

\[ T_n = \text{normalized VFCD temperature} \left(\frac{T}{273} \sim 1.02\right) \]

The relationship between \( F_s \) and \( P_4 \) is nearly independent of \( F_{O2} \):

\[
P_4 \sim 7.46 F_s \tag{1.5}
\]

The mass flow rate through the compressor \( F_s \) is

\[
F_s = \rho_i \omega V_0 \varepsilon \tag{1.6}
\]

where the sealed volume per rotation \( V_0 = 30.1 \text{ cm}^3 \), \( \omega \) is the commanded compressor rotation rate, and the volumetric efficiency \( \varepsilon \sim 0.85 \). The gas density \( \rho_i \) and pressure \( P_i \) at the compressor inlet will be determined from external measurements of the ambient temperature \( T_M \) and pressure \( P_M \) by the MEDA instrument. The pressure drop across the inlet filter depends on the product \( F_s T_M / P_M \). Here we take \( T_1 \sim T_M + 20 \text{ K} \) as an estimate of the warming of the inlet gas during its transit through the filter and inlet tube.

The volumetric efficiency \( \varepsilon \) of the compressor is weakly dependent on \( P_2 \), the pressure at the compressor exhaust, which drives backflow through the compressor:

\[
\varepsilon = 0.944 - 0.000113 P_2 \tag{1.7}
\]

Knowledge of internal resistances allow proportionality constants to be determined for relating \( P_2 \), \( P_3 \), and \( P_4 \) to \( F_s \):

\[
P_4 = 7.46 F_s \tag{1.8}
\]

\[
P_2 = 8.53 F_s \tag{1.9}
\]

\[
P_3 = 8.32 F_s \tag{1.10}
\]

Most of the pressure drop from \( P_3 \) to \( P_4 \) occurs across the SOXE.

Finally, it can be shown that:

\[
F_s = 28.4x + 3.2xy + 2.0y + 9.3 \tag{1.11}
\]

where,

\[
x = 100(P_M / T_M) \tag{1.12}
\]

\[
y = (\omega - 3000) / 500 \tag{1.13}
\]

and \( \omega \) is in RPM. Representative values are shown in Fig. 12, and typical values for MOXIE operation are shown in Table 2.
Ceramatec (now OxEon Energy; Salt Lake City, UT) developed SOXE technology from 2015 through 2018 through a series of gradually upgraded prototypes, resulting in final production of eleven flight-equivalent stacks. Zirconia (ZrO$_2$) is a ceramic that can exist in several crystal arrangements. The cubic crystal is unstable, because the Zr$^{4+}$ ions are too small to fit within the ideal lattice structure. This crystal structure is stabilized by replacing some of the Zr$^{4+}$ ions with a larger ion such as Sc$^{3+}$. The resulting “doped” zirconia is called ScSZ – Scandia-Stabilized-Zirconia. Other dopants have also been used. The Sc$^{3+}$ ions form the equivalent of Sc$_2$O$_3$ in the lattice; that is, each Sc atom acquires 1.5 oxygen ions, whereas each Zr atom would have acquired two oxygen ions. Therefore, the presence of Sc$^{3+}$ in the ZrO$_2$ lattice takes oxygen ions away from the Zr$^{4+}$ ions, producing oxygen vacancies within the lattice at Zr$^{4+}$ sites.

These materials have a unique property. When an electric field is applied across a sheet of ScSZ, oxygen ions can flow from the cathode, through the ScSZ lattice, jumping from vacancy to vacancy until they arrive at the other side of the ScSZ (anode), whereupon the oxygen ions give up their electrons, and oxygen gas forms. These ScSZ ceramic materials can be electrically conductive at high temperatures, but the current is carried by O$^{2-}$ ions rather than by electrons. This property offers the possibility for use as a fuel cell or an electrolysis cell, with porous, electrically conducting electrodes bounding both sides of a sheet of ScSZ.

The scandia stabilized zirconia (ScSZ) electrolyte is prepared by tape-casting a slurry of ScSZ powder with appropriate mix of organic binder, plasticizer, and solvent. The dried tape
is then laser cut to the desired dimensions accounting for lateral shrinkage during sintering. The resulting sintered ceramic is non-porous and thus forms a gas impermeable layer to separate the incoming CO/CO$_2$ and the produced O$_2$. A doped lanthanum cobalt ferrite oxygen evolution electrode (anode) is applied to one side of the ScSZ electrolyte with a nickel-ceria cermet CO/CO$_2$ electrode (cathode) applied on the opposite side. The electrode layers are screen printed on sintered electrolyte and fired at high temperature to achieve appropriate interfacial bonding, thickness and porosity. Additional current collection layers including higher conductivity perovskite (doped lanthanum cobalt ferrite) over the anode and nickel over the cathode are also applied to complete the cell prior to stack assembly. Glass seal material is applied around the cell perimeter and around gas ports, melted and devitrified to join each cell with an adjacent interconnect to complete the stack assembly.

A critical decision point is the selection of the cathode material. Very early in the development of solid oxide cell technology, the SOXE team used the traditional nickel cermet electrode, Ni-YSZ (yttria stabilized zirconia). Later, an advanced Ni-ceria (ceria is rare earth doped) cermet was developed and used for both fuel cell (for three decades) and steam electrolysis or steam – CO$_2$ electrolysis (approaching two decades) operation. Much of the prior work (Minh et al. 1998; Sridhar and Vaniman 1997; Tao et al. 2004) investigating dry CO$_2$ electrolysis used Pt or Pt-YSZ as the cathode material. In all cases, the cathode overpotential losses were much higher than either type of Ni-cermet, which resulted in high overall cell resistance. Further, early work by the SOXE team lead scientist showed that Pt coarsening and dewetting of YSZ was a significant degradation mechanism that had been overcome with the Ni-cermet formulations. Given the MOXIE timeline and the need to meet oxygen production target with the volume and mass constraints, higher performance Ni-ceria cermet was selected recognizing the challenges in using a nickel-based electrode, namely the oxidation of nickel in CO$_2$.
Figure 13 shows a schematic of a single solid oxide electrolysis (SOXE) cell layer. When heated CO$_2$ flows over the nickel-catalyzed cathode surface under an applied electric potential, a fraction of the CO$_2$ can be electrolyzed according to the reaction:

$$\text{CO}_2 + 2e^- \rightarrow \text{CO} + \text{O}_2^-$$

The CO and any unreacted CO$_2$ are exhausted through an outlet tube, while the oxygen ions are electrochemically driven through the solid oxide electrolyte to the anode, where the O$^{2-}$ ions combine to produce the gaseous O$_2$ that is released from the anode cavity at a rate proportional to the current.

The two principal reactions of interest in a cell are:

1. CO$_2$ + electricity $\Rightarrow$ CO + 0.5O$_2$. (This is the desired oxygen-producing reaction.)
2. CO + electricity $\Rightarrow$ C + 0.5O$_2$. (This oxygen-producing reaction also produces carbon, which is undesirable. There are also other ways carbon can form, see Sect. 1.4.4.)

If carbon is produced, it will coat the electrodes, interfering with the electrolysis process. Nickel in the cathode is a well-known catalyst for carbon formation, which not only coats the cathode but damages it structurally. Figure 14 shows the deleterious effect of carbon coking. Successful operation of a SOXE, discussed below, thus involves maintaining the voltage and gas supply within a regime that allows reaction (1) but not reaction (2).

### 1.4.1 MOXIE Stack Configuration

MOXIE’s SOXE electrolysis stack, shown schematically in Fig. 15, utilizes a set of ten electrolysis cells arranged in two groups of five cells each, electrically connected in series, with a plenum to admit Mars atmosphere to the cathode entry of each cell, a plenum to remove oxygen from the anode of each cell, and a plenum to remove CO and unreacted CO$_2$ from the cathode exhaust of each cell. The cells are flat and multi-layered, with the electrolyte in the middle, bordered on both sides by porous electrodes. The typical operating temperature of the stack is 800 °C.

A pattern of indentations in each layer (shown only conceptually, near the input and exhaust holes in Fig. 15) spreads the gas over the entire level as it flows from the input...
Fig. 14 SOXE cells without coking (left) and with significant coking (right) (Meyen 2017)

Fig. 15 Simplified view of the SOXE stack

To the exhaust. Since the pressure inside the SOXE is much higher than the external Mars atmosphere, the layers must be sealed together to prevent leakage of hot gas. Traditional rubber O-rings cannot be used at the $800 \, ^\circ C$ temperature, so the sealing is done with thin glass gaskets running around the outside of each layer, fused to the layers as part of the high-temperature curing process.

1.4.2 SOXE Assembly

The SOXE assembly was designed and developed at NASA’s Jet Propulsion Lab, which had overall responsibility for delivering the MOXIE instrument. Primary functions of the assembly include thermal control and insulation, mechanical compression, gas handling, sensing, and structural support.

Thermal Insulation  Minimizing heat leakage from the $800 \, ^\circ C$ SOXE stack is a high priority, given the power-limited nature of the mission. This was accomplished with high
quality insulation (Aerogel and Min-K™) and selection of Inconel to minimize losses along wires that penetrate the insulation. The wire design was a trade, since the fine Inconel wires add series electrical resistance. Wire-wrap around the taps on the stack, needed to strain-relieve the connection, introduces ambiguity as to where the electrical connection is actually made, resulting in uncertainty in the total wire resistance and introducing the possibility that it may change with age or temperature. This in turn causes uncertainty in the measurement of applied voltage across the stack, which, as will be explained below, is a critical value for operating MOXIE.

A significant finding from the EM test campaign (see Sect. 4 – “Ground Testing”) was the appearance of a conductive pyrolyzed residue on one of the insulating materials used in the SOXE assembly when heating in a Mars-like (i.e. non-oxidizing) environment. The residue resulted in a short across the top and bottom electrical terminals of the SOXE stack. The problem was mitigated for the flight SOXE assembly by first burning off the residue in an ambient air environment at \( \sim 500 \, ^\circ\text{C} \) prior to first \( \text{O}_2 \) production.

**Gas Thermal Control**  The exhausting of hot gases represents a source of heat loss that was intentionally accepted in the design. In principle, a heat exchanger could efficiently heat the gases going into the SOXE and cool the exiting gases with little net loss of energy. In practice such a heat exchanger would have to be placed outside the hot zone, and the hot side of the exchanger would have to be pre-heated to initiate oxygen production. While this would be beneficial in a continuously operating system, the energy investment in pre-heating does not turn out to be advantageous for the short MOXIE operating cycles. Instead, preheating is performed in the hot zone, and the outlet gas is cooled by a heat exchanger outside the assembly that dumps the heat to the RAMP. The power loss associated with this approach is \( \sim 20 \, \text{W} \).

MOXIE’s six heat exchangers were fabricated with additive manufacturing and are among the first 3D-printed parts to be flown on JPL missions. One, mounted inside the hot zone, preheats the gas to the 800 \( ^\circ\text{C} \) operating temperature. Two more, outside the hot zone, cool the product and exhaust gas streams to a temperature compatible with the composition sensors. These heat exchangers are bolted to the MOXIE baseplate, which is in turn thermally connected to the RAMP. Two additional heat exchangers are mounted on the sensor panel itself to further equilibrate the gases to the sensor panel temperature. Finally, a “backflow cooler” is inserted between the compressor and the SOXE to avoid damage from backflow of hot gases when the compressor is turned off at the end of a production run.

**SOXE Thermal Control**  Tests and models show that for the SOXE to operate efficiently it should be held at a temperature of at least 770 \( ^\circ\text{C} \). For it to operate safely, without material damage, tests show that it should operate below \( \sim 835 \, ^\circ\text{C} \). MOXIE has adopted a nominal operating temperature of 800 \( ^\circ\text{C} \) in consideration of gradients and measurement errors that might result in exceeding the safe temperature range. Internal temperature gradients will occur even under isothermal external conditions because of the endothermic reaction taking place within the stack, which is mitigated only partially by the flow of hot gas through the system.

A uniform-temperature oven provides the optimal thermal control for a stack, and initial characterization of SOXE stacks at Ceramatec all took place under oven conditions. The limited space available in the flight configuration did not allow a complete oven and instead dictated heating from the two ends, with “heater carriers” providing thermal contact to the ends and “skirts” covering part of the sides to approximate an oven. As a consequence, comparing performance data from the initial tests at Ceramatec and JPL (see Sect. 4, “Ground
Testing”) with tests of both engineering and flight stacks needs to recognize the two distinct thermal configurations.

A trade study of heater carrier materials favored Inconel 600 over silicon carbide, which performed well thermally but was prone to cracking, and over pure chromium, which performed well thermally and mechanically but was determined to be sensitive to small impurities that were not consistently characterized by the vendors. Even though Inconel 600 has poor thermal conductivity, its mechanical and thermal robustness made it the favored choice. This choice was validated in testing with the prototype SOXE assembly which showed acceptable thermal gradients of $\sim 10^\circ C$ on the exterior of the stack.

Among the candidate materials for the skirts, Inconel steel was chosen for its well-known and reproducible properties at high temperature, including both strength and plasticity. Inconel has relatively poor thermal conductivity compared to other possible choices such as silicon carbide or chromium, resulting in disparities of $\sim 50^\circ C$ between the stack side of the carrier and the heater side, where the platinum resistance thermometers (PRTs) are located. The poor conductivity also results in a relatively long time constant in response to changing stack thermal conditions as the rate of endothermic oxygen production changes. Inconel also has high density compared to other choices, and thus overall mass limitations dictated relatively short skirts. The collective result of this trade was a highly reliable and reproducible system from a mechanical perspective, at the expense of relatively steep thermal gradients, large measurement offsets, and slow response from a performance perspective, while still meeting all performance requirements.

**Mechanical Compression** In addition to its perimeter glass seal, the SOXE stack must be pressed together by a set of external springs. This is in part to reduce stress on the seals, but also to ensure a good contact between anode and interconnect across the cell and to prevent lateral motion of the stack within the insulation as a result of vibration during launch and landing. The springs can be seen in Fig. 1, and two of the four are shown schematically in Fig. 16, a schematic cutaway view of half of the SOXE assembly. Figure 16 also shows the heaters at the top and bottom of the stack, as well as part of the thermal insulating layer consisting of a combination of aerogel in unstressed locations and Min-K™ elements that bear the compressive force of the springs. The Min-K insulation is gradually compressed as a result and, to mitigate this effect, the Min-K is pre-compressed before installation. While the Min-K will continue to compress slightly over time, tests over many months have shown that it will remain within the performance specifications of the uncompressed material indefinitely. The original design featured snubbers to limit the range of possible motion, but since they proved unnecessary, they were removed in favor of additional thermal insulation.

**Instrumentation** Selected laboratory versions of the SOXE assembly are instrumented with voltage measurement leads to allow cell-by-cell characterization of performance. This approach has provided, and continues to provide, valuable characterization of cell nonuniformity, and degradation processes. In particular, cell-to-cell uniformity was the primary criterion for selection of the flight stack.

The individual leads and connections required to perform such monitoring are generally incompatible with the dynamic stresses associated with launch and landing and can cause significant faults if shorts occur. They are also a non-negligible contribution to thermal leakage through the insulation. As a result, monitoring of the flight stack is limited to measurement of the temperature at the top and bottom heater, and separate measurements of current and voltage through the top half and bottom half of the stack (5 cells each). Troubleshooting
and monitoring of MOXIE will continue to be informed by tests of fully instrumented lab models.

1.4.3 $O_2$ Production and Electrical Current

Since it takes exactly 4 electrons to produce an $O_2$ molecule, the mass flow of oxygen $F_{O2}$ can be determined from the relationship:

$$F_{O2} = nI/4F$$

(1.14)

where $I$ is the ion current across the membrane (identically equal to the electron current in the circuit), $F$ is Faraday’s constant, and $n$ is the number of cells wired in series (10 for MOXIE). Thus, for MOXIE:

$$F_{O2} = I/0.335 \text{ (g/hr)}$$

(1.15)

where $I$ is in amps and $I = 2$ A is sufficient to meet the MOXIE requirement to produce oxygen at a minimum rate of 6 g/hr. Since each oxygen atom produced corresponds to one molecule of CO, the mass flow rate of CO can be trivially calculated from:

$$F_{CO} = F_i + (28/16)F_{O2}$$

(1.16)

where $F_i$ is the amount of CO in the SOXE inlet stream (see discussion of recirculation) and 28/16 represents the mass ratio of CO to O.
1.4.4 Nernst Potentials

The electrolysis reaction is initiated when the voltage is increased above the Nernst potential $V_N$. For oxygen production via the reaction $2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2$ (Hartvigsen et al. 2015; Ni 2010):

$$V_N(\text{O}_2) = V_{\text{rev}} + \left(\frac{RT}{4F}\right) \ln \left(\frac{p\text{CO}^2 p\text{O}_2}{p\text{CO}_2^2}\right)$$ (1.17)

where:

- $T$ = temperature in Kelvin.
- $p\text{CO}$ and $p\text{CO}_2$ = partial pressures of the respective gases on the cathode side of the membrane in standard units (see below).
- $p\text{O}_2$ = partial pressure of oxygen on the anode side of the membrane in standard units.
- $R = 8.314$ J/mol-K is the universal gas constant.
- $F = 96485.3$ C/mol is the Faraday constant.
- $V_{\text{rev}} = -\Delta G_f^{\text{rev}} / 4F$ is the voltage below which the reaction proceeds in the opposite direction as a fuel cell, potentially resulting in degradation due to oxidation of anode material. At a partial pressure of 1 bar, $V_{\text{rev}} = 1.4227 - 4.4924 \times 10^{-4}T$.

At the nominal operating temperature of 1073 K with a pressure standard of 1 bar, the voltage threshold for oxygen production is:

$$V_N(\text{O}_2) = 0.9809 + 0.02312 \ln \left(\frac{p\text{CO}^2 p\text{O}_2}{p\text{CO}_2^2}\right)$$ (1.18)

Note that a change in the standard pressure units inside the logarithm would introduce an additive constant (for example, if the standard changed from $P_1$ to $P_2$ there would be an additional voltage term $\Delta V = \left(\frac{RT}{4F}\right) \ln \left(\frac{P_2}{P_1}\right)$), but that constant would be equal and opposite to a term in $V_{\text{rev}}$ and would not alter $V_N$. The choice of standard units should ideally be consistent with the conditions under which $V_{\text{rev}}$ is to be measured (i.e. such that the logarithmic term goes to zero under those conditions). In practice 1 bar is generally used, since the differences are small.

For MOXIE, the minimum voltage $V_N(\text{O}_2)$ for producing oxygen depends on operating temperature, inlet flow (affecting $p\text{CO}_2$), and the choices of the outlet apertures (VFCDs), which affect the pressure and hence molar concentrations at the anode and cathode. All molar concentrations can then be calculated with knowledge of the reaction rate, which is determined by the current–voltage relationship (discussed below).

It is also important to note that $p\text{CO}$ and $p\text{CO}_2$ will vary across the cell. The quantities used for MOXIE calculations always refer to the outlet of the cell where $p\text{CO}_2$ is lowest and $p\text{CO}$ is highest, which are the most favorable conditions for destructive carbon formation (see Sect. 1.4).

The safe operating voltage for the SOXE is constrained by the need to stay below the threshold for carbon production via the reaction $\text{CO} \rightarrow \text{C} + 0.5\text{O}_2$. The Nernst potential for that reaction, following Hartvigsen et al. (2015) and Ni (2010), is:

$$V_N(\text{C}) = V_{\text{rev}} + \left(\frac{RT}{4F}\right) \ln \left(\frac{p\text{O}_2}{p\text{CO}}\right)$$ (1.19)
Fig. 17 Nernst free energy curves for carbon formation and oxygen production vs. mole fraction of CO in the cathode exhaust. These curves apply to the case where the anode and the cathode are both at the same operational pressure of 0.868 bar, typical atmospheric pressure at Salt Lake City. For any given voltage and mole fraction the oxygen production rate is determined by the area specific resistance (ASR). These curves show general trends but do not apply directly to MOXIE, where the anode and cathode pressures vary with operating conditions.

At 1073 K, the threshold for carbon formation is thus:

$$V_N(C) = 1.0713 + 0.02312 \ln \left( \frac{pO_2}{pCO_2} \right)$$

Note that carbon can also be produced directly by the electrochemical reaction \( \text{CO}_2 \rightarrow \text{C} + 0.5 \text{O}_2 \), which has a similar Nernst threshold but is less kinetically favorable, and it can be produced indirectly by the thermochemical Boudouard reaction \( 2\text{CO} \rightarrow \text{C} + \text{CO}_2 \) (Skafte et al. 2019), but the chosen threshold is believed to be the most likely in the MOXIE stack.

The Nernst potential curves for the two primary reactions described above are shown in Fig. 17, plotted vs. CO mole fraction \( u = p\text{CO}/(p\text{CO} + p\text{CO}_2) \) in the cathode exhaust, and showing temperature dependence near the nominal 800 °C operating temperature. The Boudouard Boundary is the point at which the Nernst potentials for the two reactions are equal. To produce oxygen without producing carbon, the local cathode potential must be greater than the lower curve and below the upper curve. Since measurements of the local cathode potential are not available, the cell voltage is used for comparison with this threshold, which is on the safe side and effectively assumes that all of the cell voltage drop is only across the cathode. Operation between the curves in Fig. 17 is the “safe voltage zone”, which applies to the most CO-rich part of the flow field at the flow outlet of the cells.
Comparing the two Nernst potentials above, an interesting dependence on anode and cathode pressure emerges. Both $V_N(O_2)$ and $V_N(C)$ have the same dependence on anode pressure $p_{O_2}$, so they will go up and down together as anode pressure is changed. For example, if the anode pressure changes from $P_1$ to $P_2$ without changing the cathode pressure, then the difference in both $V_N(C)$ and $V_N(O_2)$ will be:

$$\Delta V_{\text{comp}} = \left(\frac{RT}{4F}\right) \ln\left(\frac{P_2}{P_1}\right)$$

(1.21)

reflecting the additional power needed for the cell to compress the gas in the anode. The only impact on MOXIE operation will be that some additional energy will be applied to gas compression, as reflected in the higher voltages. If the objective is to ultimately compress the oxygen product, then the increased power needed for the higher anode pressure may nonetheless be advantageous. There will also be some difference in the start-up profile, since when MOXIE oxygen production commences, the anode is at Mars ambient pressure. If operated in constant current mode, this will be observed as a transient increase in voltage as the anode pressure builds up to its equilibrium value.

The situation with respect to cathode pressure is distinctly different. If the VFCD controlling cathode pressure were enlarged, reducing cathode pressure from $P_1$ to $P_2$ without changing mass flow (i.e. the gas moves at higher velocity) then $V_N(O_2)$ will also be unchanged because the reduction in $p_{CO}$ and $p_{CO_2}$ will cancel. $V_N(C)$, however, will increase by:

$$\Delta V_c = \left(\frac{RT}{2F}\right) \ln\left(\frac{P_1}{P_2}\right)$$

(1.22)

(note the change by a factor of 2 in the denominator, coming from the $(p_{CO_2})^2$ exponent in the logarithm). This means that the SOXE can operate at higher voltage without risk of C deposition. This means that, all else being equal, lower cathode pressure is distinctly advantageous for MOXIE. The lower limit of cathode pressure possible without negatively impacting SOXE performance has not yet been determined but is planned to be explored in the laboratory.

Gas pressure in the cathode and anode is a design choice. Ideally both would be regulated, but for MOXIE it was decided to reduce mass, volume, and complexity by throttling the output flow with a precision aperture in the form of a VFCD. Even with the VFCD, the range of operating pressures can be selected by an appropriate choice of aperture size. In view of these Nernst potential relationships, the MOXIE design reflects the largest cathode aperture consistent with tested performance range.

### 1.4.5 Current–Voltage Relationships

SOXE performance characteristics are best captured in the form of the relationship between current $I$ and operating voltage $V_{op}$ for a particular value of gas injection rate, temperature, and anode and cathode pressure. This curve is predominantly linear, like an ohmic resistor, with an offset representing the voltage required to initiate current flow (the open circuit voltage $V_{oc}$) and an additional potential drop reflecting the nonlinear portion of the curve near threshold.

The operating voltage $V_{op}$ is determined from three potentials $V_N(O_2)$, $V_{\text{ohm}}$, and $V_{\text{add}}$ (Sridhar and Vaniman 1997; Ni et al. 2006; Nehrir and Wang 2009; Ni 2010):

$$V_{op} = V_N + V_{\text{ohm}} + V_{\text{act}}$$

(1.23)
The Nernst potential, $V_N$, which ranges from 790 to 950 mV as an integral average across the cell as CO$_2$ is converted to CO, is the largest component and is a function of the partial pressure of the O$_2$ in the anode, the CO$_2$ and CO in the cathode, and the temperature of the cell.

An additional empirical potential $V_{\text{add}}$, defined as the difference between the intercept of the linear part of the $I$–$V$ curve and the Nernst potential averages 21.55 mV for a representative SOXE stack (Meyen 2017), with no statistically significant temperature dependence. This apparent overvoltage likely arises from large changes in Nernst potential near open-circuit when close to 100% reactant supply is used (as is the case here with $\sim$ 98% CO$_2$ due to product gas recycling to the inlet), and/or from electrode activation overvoltage contributions (which, however, have strong temperature dependence, and are often negligible in high-temperature solid oxide cells).

The term $V_{\text{ohm}}$ represents the voltage drop from the intrinsic area specific resistance of the cell ($\text{ASR}_{\text{int}}$) which comes from the ohmic resistance of ion conduction through the solid scandia-stabilized zirconia (ScSZ) electrolyte, with minor additional ohmic contributions from electron conduction through the electrical interconnect and electrodes, and from the electrochemical reaction resistance in both anode and cathode. $V_{\text{ohm}}$ is a function of $\text{ASR}_{\text{int}}$, the current through the cell, the area of the cell, and the temperature. The temperature dependence of $\text{ASR}_{\text{int}}$ is a function of the composition of the electrolyte and the two electrodes, and can be represented as an Arrhenius relationship.

$\text{ASR}_{\text{int}}$ thus corresponds to slope of the linear portion of the $I$–$V$ curve. In analogy to a simple ohmic circuit the relationship can be written in the general form:

$$ (V_{\text{op}} - V_0) = I \left( \frac{\text{ASR}_{\text{int}}}{A_{\text{cell}}} \right) $$

where $V_0 = V_N + V_{\text{add}}$, current $I$ is proportional to the oxygen production rate, and $A_{\text{cell}}$ describes the cell area (for MOXIE, $A = 22.7$ cm$^2$). For a stack of cells in series, as implemented for MOXIE, $V_{\text{op}}$ will also be proportional to the number of cells. Figure 18 shows the measured $I$–$V$ relationship for the MOXIE flight stack, where the current passes through all ten cells, and the voltage is the average voltage per cell.

Note that when no current is passing through the cell, the only observed voltage is $V_N(O_2)$. This special case is called the open-circuit voltage, $V_{\text{oc}}$. For non-zero current both $V_N(O_2)$ and $V_{\text{ohm}}$, and thus the slope of the $I$–$V$ curve, increase with cell current as a result of the higher ratio of CO to CO$_2$ in the cathode.

In practice, any measurement of ASR is an average value since it varies across the cell, and the measured $I$–$V$ relationship may also incorporate ohmic terms associated with resistive layers in the cell stack or impedances between the measurement contacts and the cells. The latter are particularly large for MOXIE due to the use of thin Inconel wire to provide compatibility with the high temperature environment while minimizing heat leakage.

ASR will vary in a known way with gas flow rate, gas temperature, and anode or cathode pressure, and it is useful to define other formulations of ASR to compensate for this dependence. In particular, a significant portion of the slope of the $I$–$V$ relationship in MOXIE is due to the changing Nernst potential $V_N(O_2)$ as CO$_2$ utilization increases. It is therefore convenient to define a conversion-corrected voltage $V_{\text{cc}} = V_{\text{op}} - V_N$. The remaining voltage should comprise only the additional offset potential, ohmic potential, and other minor potential losses such as diffusion effects through the cathode. $\text{ASR}_{\text{int}}$ can thus be expressed in terms of $V_{\text{cc}}$ as:

$$ \text{ASR}_{\text{int}} = \frac{dV_{\text{cc}}}{di} $$

(1.25)
**Fig. 18** Average voltage per cell vs. current $I$ for the pristine SOXE flight stack, prior to thermal cycling, for various rates of flow $F_s$ (g/hr).

**Fig. 19** Measured voltage and average Nernst potential (left) and the observed voltage after subtracting the average Nernst potential (right).

Figure 19 shows the result of removing the average Nernst potential from the observed voltages of SOXE stack CSA-005 at all 800 °C at 12 flow conditions.
Solid oxide electrolysis is a high-temperature process, and both the conductivity of the electrolyte and the reaction rates at the electrodes increase significantly with increasing temperatures, resulting in lower ASR\(_{\text{int}}\) (see Table 3).

The relationship can be described by an Arrhenius equation:

$$\frac{k}{k_0} = A e^{-\frac{E_A}{RT}}$$

where \(k\) is the measured intrinsic cell conductivity per unit area (inverse of ASR\(_{\text{int}}\), in \(\Omega\)-cm\(^2\)) at each flow condition and \(k_0\) is the reference conductivity measured at 800 °C. \(A\) is the pre-exponential term and intercept of the linear fit of the natural log of \(k/k_0\) vs \(-1/T\). The activation energy, \(E_A\), is calculated by multiplying the slope of that linear fit, \(E_A/R\), by the universal gas constant. The results are shown in Fig. 20.

The activation energy \(E_A\) of the SOXE cells at 800 °C with 100 g/hr input flow is 82.6 kJ/mol, with a pre-exponential term of 10300. A fully temperature-corrected current–voltage relationship for the SOXE can thus be written as:

$$V_{\text{op}} = V_{\text{add}} + V_{\text{Nernst}} + I \left( \frac{1}{A_{\text{cell}}} * \text{ASR}_{\text{temp}} \right)$$

where \(A_{\text{cell}}\) is the cell area and the temperature-corrected ASR is defined as:

$$\text{ASR}_{\text{temp}} = \frac{\text{ASR}_{\text{cc@1073 K}}}{10300e^{\frac{82556}{RT}}}$$

For CSA 005 at 800 °C, \(\text{ASR}_{\text{temp}} = 0.9922\ \Omega\text{-cm}^2\).
Fig. 21 Voltage per cell vs. mass flow rate through the SOXE ($F_s$) at constant O$_2$ production rates of 4, 6, and 8 g/hr (dashed lines). Corresponding values of $V_N$(O$_2$) (lower solid curves) and $V_N$(C) (upper solid curves) follow the same color scheme. The error bars refer only to the typical cell-to-cell variation within the stack.

1.4.6 Flow and Temperature Considerations

Since MOXIE is often run in a constant current mode (i.e. constant oxygen production), it is useful to replot the data in Fig. 17 for various oxygen generation rates, since $F_s$, the flow of gas through the SOXE, changes due to variations in ambient atmospheric density and intentional changes to the compressor rotation rate. Such curves are shown in Fig. 21.

It can be seen that higher flow, which reduces the utilization factor $u = p_{CO}/(p_{CO_2} + p_{CO})$, results in lower ASR, lower $V_N$(O$_2$), and more efficient oxygen production. Note that utilization can also be written in terms of the controllable factors $F_{O2}$ (determined by SOXE current $I$) and $F_s$ (determined by compressor speed and ambient density), as:

$$u = (m_{CO_2}/m_O)F_{O2}/F_s = (44/16)F_{O2}/F_s \quad (1.29)$$

Figure 21 also demonstrates how the minimum potential for $V_N$(O$_2$) changes with both flow rate $F_s$ and with oxygen production rate $F_{O2}$, both of which affect the utilization factor $u$. The actual voltage needed to produce O$_2$ at a particular rate is determined by the ASR of the cell but will always exceed $V_N$(O$_2$). On the other hand, the minimum potential for carbon formation $V_N$(C) is only dependent on $p_{O2}$ and $p_{CO}$, both of which are determined only by $F_{O2}$, and are independent of $F_s$.

For MOXIE to produce a particular amount of oxygen, both $V_N$(O$_2$) and the ASR must be such that the operating voltage can be set sufficiently high without getting too close to $V_N$(C), i.e. without initiating carbon formation (see Sect. 1.4.4). Even without knowing the
ASR, the voltage gap between the two Nernst potentials is a guide to how likely this will be. Figure 21 shows how that gap shrinks as the oxygen production rate is increased and how it grows as CO₂ flow rates from the compressor increase. A moderate flow rate of \( F_s = 60 \text{ g/hr} \) will comfortably meet the instrument minimum requirement of 6 g/hr for foreseeable values of ASR.

As discussed in a previous section, MOXIE temperature can be increased within a limited range, up to \( \sim 830 ^\circ C \) with increasing risk of damage, as performance demands may dictate. Motivating such increases is the highly favorable scaling of ASR with temperature. Also, since Nernst potentials scale with temperature, higher temperature will slightly increase the voltage gap between oxygen production and carbon formation.

### 1.4.7 Thermal Balance

The thermal neutral voltage \( V_{\text{tn}} \), where the reaction is neither endothermic nor exothermic, can be calculated from:

\[
V_{\text{tn}} = \frac{\Delta H}{4F}
\]  

Where \( \Delta H_f \) is the enthalpy of reaction and \( 4F \) is the charge transferred in the reaction. The heat generated or consumed by a particular cell is determined by:

\[
\dot{Q}_{\text{gen,cell}} = (V_{\text{op}} - V_{\text{tn}})I
\]

The sum of the heat generated or consumed by all cells is the total heat generated by the stack. Voltages exceeding the thermal neutral voltage result in a net exothermic reaction. For MOXIE at 800 °C, \( V_{\text{tn}} = 1.463 \) for the desired oxygen-producing reaction (\( \text{CO}_2 + \text{electricity} \Rightarrow \text{CO} + 0.5\text{O}_2 \)) exceeds \( V_{\text{N}}(\text{C}) \), and therefore MOXIE is always run in an endothermic mode, with additional heat provided to maintain the reaction.

### 1.4.8 Power Considerations

From the perspective of total system energy, it is desirable to utilize as much of the incoming CO₂ as possible (i.e. to maximize \( u \)) without risking carbon formation. Figure 22 shows how \( u \) maps onto this parameter space. With anticipated ASR values, MOXIE can expect to operate safely at 40% utilization if \( F_{\text{O}_2} = 8 \text{ g/hr} \) and \( F_s \geq 55 \text{ g/hr} \).

While it seems reasonable to tune a SOXE system to operate at the maximum safe voltage, it is important to note that the electrochemical power requirement is independent of both operating voltage and ASR, and can be calculated from the simple formula \( P = IV_{\text{TN}} \) where \( V_{\text{TN}} = 1.46 \text{ V} \) is the thermal neutral voltage for the reaction. Any reduction of the power product \( P = IV \) simply makes the reaction more endothermic and must be compensated for by a corresponding increase in external joule heating. The advantage of lower ASR thus lies solely in allowing more oxygen to be produced (i.e. higher current \( I \)) without exceeding \( V_{\text{N}}(\text{C}) \), a result that might also be accomplished by a design that reduces the overall cathode pressure or increases the net cell area. Note also that \( V_{\text{TN}} \) is greater than \( V_{\text{N}}(\text{C}) \) for all practical operating conditions, and the reaction is therefore always endothermic (see Sect. 1.4.7).

As noted previously, an additional voltage \( \Delta V_c = \left( \frac{RT}{P} \right) \ln \left( \frac{P_a}{P_c} \right) \) must be applied when the anode pressure exceeds the cathode pressure. When multiplied by the current \( I \), the factor of \( \Delta V_c \) corresponds to the thermodynamic power required to mechanically compress the gas to higher pressure, and amounts to 53 mV per decade increase in \( p_{\text{O}_2} \) at 800 °C. From the system perspective, the additional power invested in SOXE corresponds to a reduction in the power requirement for the compressor.
Degradation and Failure Modes

The challenge of enabling vigorous oxygen production without triggering carbon formation has been discussed above. In this section other failure mechanisms and their mitigation are discussed.

Cathode Oxidation As a common practice in electrolysis stack testing, the nickel-based cathode is always exposed to reducing conditions in order to avoid oxidation of nickel. In steam electrolysis mode of operation, for example, the inlet steam contains approximately 10% H₂ gas. At the system level, this hydrogen is recirculated from the electrolysis product. Given the dry conditions on Mars, stacks for MOXIE were tested from the start using dry CO₂. As expected, the nickel electrode oxidized near the inlet port, and the oxidation front progressed downstream with each operational cycle (heat up, 2 hr CO₂ electrolysis run, cool down) as evidenced by post-test analysis. It was also seen that the stack resistance increased progressively with each operational cycle as the oxidation front caused a loss of active electrode area. This resulted in doubling the area specific resistance (ASR) after one operational cycle with continued increases in ASR with every cycle, resulting in a 7-fold increase in ASR after ten cycles. Simulating CO recycling by adding ~10% CO in the CO₂ feed stream eliminated cathode oxidation, and operational cycles no longer caused a large increase in stack resistance. This recycle strategy was implemented in MOXIE to avoid the nickel cathode oxidation problem.

The current MOXIE system baseline design incorporates a cathode exhaust gas recycle loop, wherein a nominal 19:1 flow split allows 5% of the cathode exhaust gas to be drawn

![Fig. 22](image-url) Vₙ(O₂) vs. Fₛ for various oxygen production rates. Upper horizontal lines indicate Vₙ(C), which is essentially independent of MC (elsewhere referred to as FS, the mass flow through the compressor). Dotted lines indicate constant values of the utilization factor u.
into the suction of the scroll compressor along with fresh Mars atmosphere. At anticipated CO₂ utilization values, the cathode inlet feed will contain about 2% CO. Tests with a 3-cell stack with some improvements to the current distribution layers showed no degradation over 10 cycles while operating with a 3% CO added to the CO₂ input stream. Stack operation was limited to 4 A, based on the flight power supply limits, which gave \( \sim 1.2 \) V/cell, based on a semi-conservative consideration of the expected \( V_N(C) \) threshold after losses (see Sect. 1.4.4).

### Power Supply Leakage Current

Following cycle 10, the stack was cooled and reheated with the stack shorted through a resistor to simulate power supply leakage current in the power-off state. Cycles 11–14 used a 115 ohm resistor (\( \sim 22 \) mA leakage), which resulted in significant degradation in subsequent cycles. Cycles 15–18 used a 2.4 kohm resistor (\( \sim 1 \) mA leakage), after which the stack showed a recovery in performance at each cycle, as shown in Fig. 23. The leakage current allows an equilibration of anode and cathode chamber \( pO_2 \), which results in oxidation of the nickel cermet cathode and reduction of the perovskite anode. The flight system power supply design was modified to reduce this leakage current to less than 1 mA.

### Cell-to-Cell Variability

While the ten SOXE cells are fabricated in exactly the same way, small differences in cell resistances nonetheless occur. Since cells in the stack are electrically connected in series, the voltage drop will therefore vary from cell to cell. The cell with the highest voltage (the “weakest” cell) comes nearest to \( V_N(C) \), the Nernst potential for carbon deposition (see Sect. 1.4.4).

While no practical method was found to individually monitor voltage across each cell in a fully packaged SOXE assembly, the distribution of voltages was measured for the eleven candidate flight stacks prior to packaging, and the stack with the minimum voltage spread was selected for flight. The spread of cell voltages for that stack was \( \pm 0.008 \) V about the average at 6 g/hr oxygen production, as indicated by the error bars in Fig. 21. Other stacks had significantly greater cell-to-cell variation.

![Fig. 23 STX-013 effect of power supply leakage current on cycling](image-url)
Compounding the intrinsic cell-to-cell variability is the expectation of thermal gradients across the cells due to the placement of the heaters on the top and bottom. Cells in the center of the stack may be as much as 10 °C cooler than the top and bottom cells, which has the effect of both raising their ASR and lowering $V_N(C)$. These cooler cells are therefore at significantly greater risk of coking.

Since the immediate effect of carbon deposition (coking) is to raise the resistance of a cell (typically by reducing the active area rather than increasing the ASR), the series electrical configuration serves to exacerbate the effect by raising the voltage across the damaged cell at the expense of the unaffected cells. To continue to produce oxygen at a constant rate (constant current mode) then requires an increase in total applied voltage, further accelerating the coking process.

**Effects of Thermal Cycling** For a complex materials system like solid oxide fuel cells and electrolyzers, it is not surprising that repeated cycling between room temperature and operating temperature might cause degradation. Such degradation is generally mitigated to the extent possible in the design and fabrication, and ultimately by minimizing the cycling of the system. For MOXIE, however, such cycling is intrinsic to the nature of Mars 2020 mission operations, which allow only intermittent operation of MOXIE.

MOXIE was developed with an expectation of being able to fully meet performance requirements after 20 such cycles (at least 10 on Mars and up to 10 in testing prior to launch). Following conventional protocol, the assemblies were successfully exercised for at least 60 cycles. Encouragingly, the only ill effect of such cycling was a modest increase in the voltage required to maintain a 2 A oxygen production current (i.e. increased ASR). While the voltage increase seems to follow a power law over a large number of cycles, the increase was surprisingly linear over many cycles, making it amenable to further study. In practice it amounts to 1–2 mV per cycle, which is small compared to the margin of hundreds of mV between operating voltages and $V_N(C)$ discussed earlier in this section. Importantly, there was no indication of any changes that would preclude continued operation at lower production rates. No tests or analysis predict a time when MOXIE ceases to be able to produce oxygen, albeit possibly at progressively lower rates. Extended measurement of MOXIE’s performance as it gradually ages in a real Mars environment will provide valuable guidance for future solid oxide electrolysis ISRU designs.

While the specific mechanism of the degradation cannot be determined from existing test data, preliminary indications supported the presumption that it was due to thermal cycling rather than to the oxygen generation process. Repeated startup and shutdown of oxygen production in a single heating cycle had no apparent effect on the magnitude of the degradation. Future testing will attempt to confirm that repeated thermal cycling causes the same 1–2 mV degradation per cycle even without oxygen production.

Understanding the nature of the observed degradation is critical in determining safe operating parameters for MOXIE. While an increase in operating voltage suggests an increase in ASR (i.e. the required voltage across the cell membrane), it is also possible that it is caused by an increase of series resistance elsewhere in the system. This could be in the form, for example, of degraded contacts between the interconnect and the anode or of increase in the Inconel wire resistance. It is also possible that the observed increase derives from small changes in the thermal gradients in the stack and heater carriers, or even in the fidelity of the PRT measurement controlling the stack temperature. Each of these possibilities carries different implications for safe operation. In particular, if the change is in series resistance, then the voltage margin with respect to the onset of carbon formation will not change and the voltage can be increased with impunity to compensate for the degradation. This will be the subject of further study in the laboratory.
Cell-to-cell variation has been observed to increase with thermal cycling, posing additional danger of exceeding safe conditions on individual cells. This, too, will be the subject of further study.

**Measurement Uncertainty** Preliminary, conservative specifications for the MOXIE sensor system indicate accuracy of no better than a few percent, which compares unfavorably with the narrow temperature and voltage control required for MOXIE operation. It is not yet clear to what extent this uncertainty has been overstated or whether it can be improved with calibration, averaging, and the combination of redundant measurements. An additional complication was encountered with the SOXE temperature measurement as a result of temperature-dependent electrical resistance of the insulation around the platinum resistance thermometer (PRT) wiring. The insulation became increasingly conductive at high temperature, providing an alternate current path within the grounding scheme and skewing the SOXE temperature measurement. Mitigation involved repurposing two other PRT circuits ($T_5$ and $T_6$ in Fig. 24) to perform the measurement with a different applied current value, then extrapolating the results to eliminate the perturbing factor.

**1.5 Monitoring and Control**

In order to inform and control its operation, MOXIE is monitored by the array of sensors and transducers shown in Fig. 24.

The system includes 5 pressure transducers, 4 commercial-off-the-shelf (COTS) gas composition sensors, 16 ambient temperature sensors, 2 SOXE high-temperature sensors, 2 SOXE voltage and current measurement circuits, and a Hall sensor to measure compressor motor speed. All sensor readings are read once per second and recorded in telemetry along with various computations based upon those sensor readings.
1.5.1 Temperature

The temperature sensors are all platinum resistance thermometers (PRT) of a type used routinely in space applications. Of particular importance are \( T_3 \) and \( T_4 \), which monitor temperatures in the compressor; \( T_4 \) monitors the motor Hall effect sensor, which provides motor commutation signals to the motor controller electronics and has the lowest temperature rating of all the components inside the compressor assembly. The \( T_3 \) and \( T_6 \) sensor circuits have been repurposed to support a dual-current measurement of SOXE temperature, with the result that there is no longer a temperature measurement of the gas as it passes through the volumetric flow sensor. \( T_7 \) is the baseplate temperature; \( T_8 \) and \( T_9 \) are located on the SOXE assembly CO₂ outlet cooler. The remainder of the numbered PRTs monitor components on the sensor panel, with the exception of \( T_2 \) in the gas inlet.

Temperature sensors \( T_T \) and \( T_B \) are located adjacent to the top and bottom SOXE heaters respectively, as discussed in the SOXE assembly section. Calibration during lab testing of fully instrumented SOXE stacks indicated that setting \( T_T \) and \( T_B \) to nominal read-out values of \( \sim 850 \) °C produces a temperature of 800 °C at the mid-point of the SOXE stack. Those studies also indicated a temperature drop of \( \sim 10 \) °C between the center cell and the end cell. Voltage measurements of the individual cells, however, were not consistent with such a steep gradient and it is speculated that it may be an edge effect only. Ultimately the best indication that temperatures are within the desired range is the consistency of stack performance with the values recorded in a temperature-controlled oven prior to packaging. MOXIE temperatures are expected to be isothermal at the start of operation, providing a single-point calibration opportunity relative to RAMP sensors.

1.5.2 Pressure

MOXIE’s Kulite pressure transducers utilize fully active, four-arm Wheatstone bridge dielectrically isolated silicon-on-silicon patented leadless technology. Note that \( P_1 \) (upstream of the compressor) is a model optimized for Mars ambient pressures, typically in the range 5 to 10 mb, while sensors downstream of the compressor are optimized for the anticipated range 400 mb to 1000 mb. Sensor \( P_4 \) measures the pressure at the cathode exhaust and can optionally be used to actively control the compressor speed. All sensors should be equilibrated at Mars ambient pressure, providing a single-point calibration relative to external measurements by the MEDA instrument.

1.5.3 Gas Composition

Four gas composition sensors are physically located on the sensor panel, as are all VFCDs. Two composition sensors in the anode exhaust verify the amount and purity of the output oxygen stream. A fiber optic luminescence oxygen sensor from PyroScience measures the \( O_2 \) density, which can be converted to partial pressure with knowledge of \( T_{15} \), a result that should be consistent with \( P_5 \). Oxygen flow rate \( F_{O_2} \) can be derived from either result as described previously. The intrinsic accuracy of the oxygen sensor is specified by the vendor as \( \pm 2\% \) full-scale (0.012 bar). Sensor output is reported digitally to the MOXIE processor.

The other anode-side sensor is one of three non-dispersive infrared radiation (NDIR) sensors from SmartGas. This one measures small quantities of CO₂, the only candidate gas present in sufficient quantities to be detectable in the event of a leak (CO would rapidly oxidize to CO₂ in the anode line). The sensor output can be converted to \( pCO_2 \) using the \( T_{13} \) temperature readout. Sensor range corresponds to 0–50 mbar \( pCO_2 \) at room temperature,
with a stated accuracy of ±2% of full-scale. Like the O\textsubscript{2} sensor, it reports this information digitally to the MOXIE controller.

Two additional SmartGas NDIR sensors in the same family are placed in the cathode line, one tuned to the CO spectral line and the second tuned to CO\textsubscript{2} at significantly higher densities than its anode counterpart. Both sensors have a range of 0–1000 mbar (assuming room temperature), with a stated accuracy of ±8% full-scale. The sum of the outputs should be compatible with the $P_4$ measurement. There is known cross-sensitivity between the CO and CO\textsubscript{2} sensors that is corrected in post-processing.

The NDIR sensors work by measuring the attenuation of an infrared source as it passes through the gas volume, filtering it for the characteristic absorption line of the target gas and for a non-absorbing portion of the spectrum that services as a reference intensity. An embedded processor applies internal algorithms to the measured intensity, reference beam, and temperature data. These algorithms normalize the detector output against the reference, linearize the ratio according to the Beers–Lambert equation, correct for temperature dependence of the components and other nonlinear factors in the signal, and uses the ideal gas law to report the result in the form of partial pressure of the gas relative to a hypothetical 1 bar atmosphere. Post-processing on the ground corrects this algorithm to represent the actual measured quantity, the target gas density.

To augment calibration of the flight sensors, controlled laboratory tests over a range of temperature, pressure and gas composition expected during operations on Mars are being conducted to characterize sensors of the same type. Single point in situ calibration against the Mars ambient will be performed every run immediately after MOXIE startup, with reference to external pressure and temperature measurements from MEDA. Consistency checks relative to measured pressures and temperatures at the sensor panel will complete the in situ calibration.

### 1.5.4 Compressor Speed

The compressor is driven by a three-phase brushless DC motor. A set of commutation control magnets on the rotor support three Hall sensors, one for each electrical phase, which are required for the motor to spin. The Hall sensor outputs are digital in the sense that they have two states, corresponding to which polarity magnetic pole has passed most recently.

Telemetry from the Hall sensors indicates the actual, measured rotation rate. Motor speed is controlled by a separate analog signal derived from the Hall sensor edge transitions that has a known temperature dependence. As a result, the reported rotation rate may not be identical to the commanded rate, and the flow $F_4$ may be slightly dependent on compressor temperature if the motor is not feedback-controlled (see Sect. 1.5.6 – Controls).

### 1.5.5 Current and Voltage

MOXIE electronics measure and report various currents and voltages associated with the power management system, sensors, SOXE heaters, and SOXE stack. Only the SOXE stack measurements are discussed here.

The SOXE power system consists of two separate voltage regulators, where the regulation is implemented in hardware via op-amp-controlled feedback. The voltage of each regulator is set using a digital-to-analog converter (DAC). One supply supports the top half-stack of the SOXE, the other supports the bottom half-stack. Each can be commanded to output up to 8.7 V, with a maximum current 4 A (corresponding to 6 g/hr O\textsubscript{2} production per half-stack or 12 g/hr total).
Fig. 25  The MOXIE current control system specifies both a current setpoint and a voltage offset, allowing the SOXE to be operated at either fixed current or fixed voltage. The same strategy is applied to the compressor speed, with $P_4$ as the optional sense parameter.

Telemetry reports the measured current and voltage going into each stack. The voltage measurement can be compared to the commanded voltage, which is reported once per second even when it is under current feedback control. In theory, the difference reflects the resistive drop between the supply and the measurement point. In practice, the measurement point is on the supply side of the largest known resistive drop, the Inconel wiring to the SOXE, and it is also subject to uncertainties in the analog to digital conversion (ADC) step. The relative fidelity of the commanded and measured information will be assessed in the laboratory.

As discussed earlier, qualification models of the SOXE assembly are also instrumented to monitor cell-to-cell variations in the applied voltages.

### 1.5.6 Controls

In addition to internal regulation of supply voltage and motor speed, MOXIE software uses digital control loops with 1 Hz feedback to control (a) two zones of SOXE current and voltage, (b) two zones of SOXE temperature, and (c) compressor motor speed and outlet pressure. Setpoints for these loops are varied stepwise during MOXIE operation as part of a Run Control Table (RCT), while gains and safety limits are specified in parameter tables that govern the entire run. Violation of a safety limit for longer than a time specified by a persistence parameter causes a return to the IDLE state, effectively aborting the run.

**Voltage Control**  As is shown in Fig. 25, the control loops use a conventional proportional-integral-differential (PID) scheme to relate the control parameter (voltage in this case) to the sense signal (current), though in practice the differential mode is not implemented.

An important variant to the conventional scheme is indicated as a “voltage offset” in Fig. 25. The offset ($V_0$) defines the voltage setting when the loop is initiated. In the allowed case where feedback gains are set to zero, the control simply remains at $V_0$ and the circuit operates in a constant voltage rather than a constant current mode. When the gains are non-zero the loop operates as a constant current controller with a current setpoint. Both modes have been used, but the constant current setpoint is the more common.
**Compressor Control**  
The same strategy is employed for compressor speed control, where the sense signal is the pressure sensor $P_4$. When the gains are non-zero, the loop controls the motor speed to achieve a pressure setpoint. In most testing to date the gains have been set to zero and the offset defines the motor speed setpoint, typically 1500 to 3500 RPM. In either case the sense signal is a digital conversion of an analog voltage derived from filtering of the Hall sensor edge transitions, which is different from the raw count of edge transitions reported in telemetry. Both the motor rotation rate and the pressure measured by $P_4$ are related to the volumetric flow of the gas, not the mass flow. The two control schemes will have a different relationship to $F_s$ since the temperature of the gas measured by $P_4$ may be different from the temperature of the gas emerging from the compressor. The compressor sense signal and the $P_4$ sensor itself may also be weakly dependent on temperature, but this is expected to be an insignificant effect.

Even though $P_4$ only samples the cathode side of the flow, the molar flow rate (as distinct from mass flow rate) is insensitive to whether the molecules are CO or CO$_2$ and the pressure sensor itself is independent of gas composition. Under the ideal gas law, therefore, $P_4$ should depend only on compressor output $F_s$ and be independent of oxygen production $F_{O_2}$. One minor caveat accompanies that statement, however. The viscosity of CO and CO$_2$ are different, and hence the resistance of the VFCD will change slightly as the gas mixture changes.

Thus, the relationship between $P_4$ and $F_s$ may vary slightly with gas composition, although analysis has shown this effect to be small.

**Temperature Control**  
SOXE temperature is controlled by heaters at the top and bottom of the stack. To control the temperature, the sense signal comes from the PRT adjacent to the top or bottom heater ($T_T$ and $T_B$). In principle, the loop could be operated with zero gain as a constant heater voltage controller. In practice the gain is always non-zero, and the heater carrier is controlled to a temperature setpoint.

### 1.5.7 Scanning (Voltage–Current Sweeps)

Characterization of SOXE performance typically involves stepwise variation of voltage, current, temperature, or compressor speed. Voltage changes are essentially instantaneous, and both the inlet flow rate $F_i$ and anode pressure $pO_2$ will equilibrate in a matter of seconds. However, each such change affects the energy balance of the reaction, making it more or less endothermic. This factor, as well as changes in the flow of gas through the cathode, can affect the temperature gradient, which itself affects the ASR and $V_N$. Thermal equilibration, as a result, can be a matter of several minutes.

Two strategies have been adopted for performing characterization “sweeps” of $V$ vs. $I$ or $V$ vs. $F_s$. The first is to allow the thermal balance of the system to equilibrate at each step, a process that is typically allocated 15 minutes, but in practice could likely be done in 5–10 minutes per step. The second method is to scan quickly, allowing ~ 30 seconds per step, too short a time to allow significant thermal equilibration. Hysteresis during fast scanning can be assessed by scanning first in one direction and then another or can be mitigated by alternating settings above and below a reference current or flow. The fast and slow scans reveal different types of information; the slow scan is more indicative of how MOXIE will operate in any one configuration, while the fast scan is more immediately relatable to how voltage varies with current or flow. The fast scan can be completed in 6 minutes or less and is therefore less likely to be influenced by changes in external conditions. Time and energy resource limitations on Mars will generally restrict characterization to fast scan modalities.
1.6 Electronics Subsystem

MOXIE Electronics implement the electrical power and data interfaces to the M2020 Rover and operates the equipment of the MOXIE Oxygen Plant. An electronics block diagram is shown in Fig. 26. On the right are external interfaces, including the Rover power and data interfaces. The left are the elements of the MOXIE Oxygen Plant: the SOXE, heaters, the compressor motor and various sensors. In the center is a functional representation of the FPGA with its embedded 8051 microcontroller where monitor and control logic are implemented.

MOXIE Electronics are implemented on two boards integrated into a 305 mm × 290 mm chassis, as shown in Fig. 27. The chassis width, including its mounting feet, is 50 mm.

Functionally, the Power board implements Rover power interfaces, secondary voltage generation, power switching and high-power functions such as compressor motor, heater and SOXE drive circuits. The Control Board implements the Rover data interface and MOXIE’s monitor and control functions.

The Rover provides power to MOXIE via two switches, each capable of handling 10 amps continuously. Each switch is also protected by a fuse. The purpose of the fuse is to protect the Flight System from overcurrent conditions (i.e. short circuits) in the switch, wiring harness or MOXIE.

The first power input, referred to as Primary Bus MAIN, powers all the digital electronics, sensors and the compressor motor drive electronics. The second power input, referred to as Primary Bus SOXE, drives the SOXE Heaters and the SOXE Electrolysis Stack.
Nominal electrical currents based on test results on both the EM and FM MOXIE are shown in Table 4.

Operating MOXIE on a Rover drove key aspects of the electronics design. The electronics must operate over an input voltage range of 22 to 36 volts and not be damaged over the range 0 to 40 volts. MOXIE is also required to be tolerant of an unannounced loss of power and no guaranteed order of sequencing the MAIN and SOXE switches during power up or power down.

To achieve high efficiency on MOXIE’s highest power loads, the SOXE Heaters and Compressor Motor are regulated with PWM circuits driven directly from the Rover’s Primary Power Bus. The SOXE electrolysis, on the other hand, is driven with a two-stage regulation system. The first stage is a commercial, space qualified Crane/Interpoint DC-DC converter that is adjustable from 6.1 to 7.8 volts with 72% minimum specified efficiency. As SOXE technology matured its planned operation required lower voltage than the capability of the DC-DC converter, so a second adjustable linear stage was added to the design to reduce the SOXE operating voltages further. Consequently, lower SOXE stack operating voltages have lower power efficiency due to additional power dissipation in the linear stage.
Electrical limits on SOXE electrolysis are established by the Crane/Interpoint power converter’s capability. Its current and power limits are 4 amps and 35 watts, respectively. Four amps will support an oxygen production rate of 12 grams/hour. At a system level, MOXIE’s oxygen production will be limited by environmental conditions. Specifically, Mars atmospheric density dictates the maximum amount of CO₂ available for electrolysis and will limit oxygen production to less than the capability of the electrical system.

MOXIE’s high current PWM switching loads, the SOXE Heaters and the Compressor, generate electrical noise. The compressor is the greatest source of electrical noise in the system. Not surprisingly, measurement noise is strongly affected by compressor and heater operations. This is illustrated in the various telemetry channels shown in the plots Figs. 28 and 29, which show representative telemetry of MOXIE’s various current and temperature measurements recorded during the FM MOXIE Thermal Vacuum Test of 3/3/2019. Through ∼9000 seconds the SOXE was heating to its operating temperature. Noise dependence on duty cycle is visible in the change in noise characteristics on the current measurements as the heater duty cycle changed at ∼6000 seconds. Compressor operation and electrolysis started at ∼9000 seconds. The noise each measurement experiences varies due to different coupling to the compressor and heaters. Due to real estate constraints, analog telemetry has very little filtering, so PWM induced noise is aliased in the 1 Hz telemetry measurement.

1.7 Flight Software

MOXIE software executes on a 8051 microcontroller core that is instantiated in the MOXIE Field Programmable Gate Array (FPGA) state logic. There is no operating system, and it is a single thread with deterministic execution. The only external interface is the RS-422 UART serial communication port to the rover and two discrete lines, a Reset, and a Status Out. The capability for patches and updates to the software exists, although at this time no updates are planned for the software once it is loaded.
The software executes a fixed set of activities, including (a) setting the initial conditions for oxygen production, (b) controlling the oxygen production, (c) shutting down the oxygen production, and (d) reporting process metrics. As part of this scope, it manages the Process Monitor and Control (PMC) functions including temperature and gas flow control, SOXE current and voltage management, and gas composition measurement. A small set of fault monitors are associated with the preparation and proper function of the process control.

At the lowest level, MOXIE software commands the voltage to the SOXE stacks, controls the compressor motor speed, and applies variable voltage to the SOXE through a pulse width modulation (PWM) circuit. During operation, it reads sensors on a 1 second cadence and stores the results for upload. It accepts upload of secondary operational software and allows selection of software image at boot-up. It further accepts upload of configuration tables and can download the currently active configuration table. MOXIE software also controls the feedback loops that maintain the temperature of the two SOXE stacks, two SOXE setpoint voltages with constraints on the corresponding current draw, and the inlet pressure as determined by the compressor speed.

Data is acquired at a rate of \(\sim 0.5\) MB/hr (136 bytes/s) and is stored in an 8 MB buffer. Only one run can be stored at a time, and the data is retained until it is confirmed from the ground that it has successfully been transferred to rover memory. The maximum time period of data that can be stored is therefore 16 hours, compared to the typical run of 2–4 hrs, though additional hours may be allocated to extended monitoring during cooldown.

The specific settings defining the sequence of MOXIE operations is governed by a Run Control Table (RCT), which breaks down the activities into a series of steps of predetermined duration and a specific performance objective. For example, one step might heat the SOXE at a predetermined power level until it reaches a temperature setpoint, then maintain it at that setpoint until the time duration expires. The structure of the RCT is discussed elsewhere.

Anomalous conditions such as exceeding a sensor limit or failing to meet a prerequisite for a RCT operation trigger the only internal MOXIE instrument failure mode available – an orderly shutdown of all systems other than electronics, and a return to the IDLE state.
The RCT persists in MOXIE magneto-resistive random access memory (MRAM) until overwritten and will hence serve as the default until a new RCT is uplinked to the spacecraft and sent to MOXIE by the Rover Compute Element (RCE) using the SET_RCT command. The new RCT may be uploaded from the ground in advance, or as part of the actual run sequence.

Additional detail on specific software subsystems follow:

**Processor**  MOXIE is commanded by an 8-bit 8051 processor, implemented in a ProASIC3 FPGA as a core8051s cell and extended to support modern programming practices and processor architecture. It uses the Harvard architecture, which separates the code and address space, and extends the address space by 64 kB for code, local data, and external data. The extensions include floating point hardware. A Microsemi SoftConsole programmer’s toolset provides the C language, including floating point as a C data type, and adds assembly code keywords for initialization, external data, and interrupt declaration.

The 8051 communicates with the FPGA via an Advance Peripheral Bus (APB) interface. The bottom 60 kB are exposed to the external memory interface, and the top 4 kB are mapped to peripherals on the APB. The 8051 accesses the MOXIE hardware and the rover interface through memory mapped I/O space via the FPGA.

**FPGA Architecture**  The field programmable gate array (FPGA) is the state machine where most of the logic resides, including all the interactions with the rover computer and the hardware interfaces to MOXIE. It provides memory banks for the 8051 for program, data, and telemetry buffering; a UART to communicate with the Rover; access to MOXIE’s temperature, pressure, voltage and current sensors, motor control, heaters, clocks and timers, including the watchdog timer and the interface between the telemetry data buffer and the Mars rover. It clocks data out to the rover interface that has been written to its memory buffer by the 8051 processor, and it provides the 200 Hz interrupt to the 8051 processor as well as the system reset.

Prior to providing temperature and pressure sensor readings to the 8051, the FPGA reads ten consecutive samples from the analog-to-digital converters (ADCs), excludes the largest and smallest value, computes the average, and rounds down. The composition sensors are intelligent sensors with digital outputs that are queried via protocol. The FPGA also commands the pulse width modulation (PWM) signal to drive the SOXE heater, commands the compressor motor speed, and detects over-current conditions.

**Memory**  Four banks of nonvolatile magneto-resistive random access memory (MRAM) are available for the four flight software slots. Two memory banks are provided for two instances of the boot loader. The bootloader memory spaces are read-only and were preloaded with identical copies of the boot loader software.

Four 2-Mbyte memory spaces are available for telemetry. Telemetry buffer memory is selectable, persistent between power cycles, and visible to the 8051 through a 56 kB window of the 64 kB memory mapped I/O space via the FPGA.

Persistent memory contains certain predefined areas that hold parameter tables, allowing them to be reused after power cycles. This memory is reset, however, when the flight software slot select is commanded to change to a different slot from the previous selection.

**Time**  The FPGA generates interrupts at 200 Hz (0.005 seconds) to the 8051, which maintains a one-second clock for scheduling. Time is relative to power-up, counting up in seconds from zero. The scheduler software is driven at the interrupt rate. The run control table is driven by seconds per step, but the time-keeping slips 1/10 of a second at the execution of the first step due to the initialization taken during the transition from idle to run state.
Software Architecture  On startup or power reset the MOXIE electronics vectors to one of two identical boot loaders resident on the 8051. The loader is commanded by the rover to select one of four slots (0 to 3) containing separate copies of the flight software. The first two copies are identical and not overwritable but contain a copy of the flight software with a known bug affecting run control table execution. The latest version of the FSW, v5_5 has been preloaded into slot 3, is fully functional, and should not be overwritten. Slot 4, which has also been preloaded with FSW v5_5, is available for reprogramming.

MOXIE commands come in through the rover interface via a RS-422 UART and are parsed by command, the number of parameters, data, and checksum. If the command is recognized as valid, it is vectored to the appropriate handler, and the protocol handshake is executed. If the command is not recognized as valid, the appropriate error message is generated and the handshake protocol with the rover is completed to set the appropriate error bits.

Tasks  The flight software consists of six task-oriented and schedule-driven programs. There are two flight software states, IDLE and RUN. The flight software is in the IDLE state whenever it is not running a Run Control Table (RCT). In IDLE it executes tasks to: enable and disable sensors; handle science data telemetry; receive, implement, and respond to commands; implement diagnostics and test; load and initiate the Run Control Table; load parameter tables (safety, control algorithm, and run parameters); manage the current and thermal control and fault algorithms; and manage the watchdog timer.

The five control loops are active in RUN mode: Motor speed, SOXE current (top and bottom), and SOXE temperature (top and bottom). These loops receive and pass values between the 8051 and the FPGA using algorithms driven by the parameter tables. Other FSW tasks run fault algorithms to monitor SOXE current and pressure, and will declare a fault, safe the system, and transition the state from RUN to IDLE as needed, turning off power to MOXIE components in a prescribed sequence.

Other flight software commands are used for real-time diagnostics and testing. There are no direct commands for driving or reading sensors internal to MOXIE except by the telemetry task and through loading and running tables and parameter sets.

Boot Software  From power-up, the bootloader is selected from slot 0. A software reset after power-up will cause the bootloader to toggle between slot 0 and slot 1, and a power cycle will force the slot selection to slot 0. The boot software architecture is similar to the flight software in that it is organized as scheduled tasks but is limited as to the commands it accepts. While in boot mode, no telemetry is generated; its functions include receiving and handling commands and sending responses and selecting the flight software slot. New flight software can also be uploaded 4081 bytes at a time, requiring many iterations to load a full 65536-byte program. Debugging and diagnostic functions can also be commanded.

Data Handling  MOXIE sensors are read by the 8051 at a one second cadence and written to dedicated memory space within the FPGA. The FPGA performs a handshake with the Mars rover to transfer the telemetry data for transmission to Earth.

2 Modeling MOXIE

MOXIE has been modeled analytically for steady state operation and numerically, using Simulink®.3 to visualize dynamic performance, including feedback loops and step tran-

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3MathWorks®, Simulink®, Release R2020a, March, 2020.
sients. The steady state model is sufficient for resource estimation when developing operational sequences and for determining the overall effects of changing flow rates, currents, voltages, pressures, etc. The dynamic model is useful for tasks such as validating tuning of the control loop gains or detecting transients that could trigger fault protection.

### 2.1 Steady State Model

The steady state model incorporates a flow model and a SOXE model. The flow model (Fig. 3) is used to calculate flow rates, pressures, composition of gases, and partial pressures within MOXIE. The Nernst voltages for oxygen production and carbon formation, $V_{N(O_2)}$ and $V_{N(C)}$, can then be calculated from $pCO_2$ and $pCO$.

The steady state model takes two forms: (1) with SOXE current assigned a fixed value and maintained with a voltage control loop, and (2) with fixed voltage. The fixed current configuration is straightforward, because all the flows are defined ($1$ amp = $3$ g/hr of oxygen), while the fixed voltage case requires a model for the SOXE to estimate $F_{O_2}$ from that voltage. Both have been implemented in Excel and in MATLAB® for integration into various planning tools.

The SOXE model establishes the current–voltage ($I–V$) relationship for the “worst” cell in the stack in order to conservatively determine the proximity to $V_{N(C)}$. It starts with an estimate of the average cell voltage ($V_{avg}$) and the spread of cell voltages about the average $\Delta V$ as a function of current. A secondary model determines how $V_{avg}$ and $\Delta V$ change with thermal cycling, an intrinsically approximate process that should be calibrated with data from the most recent operational cycle. For the $n$th cycle, the voltage on the worst cell is taken as:

$$V_{max} = V_{avg}(n) + 0.5\Delta V(n)$$  \hspace{1cm} (2.1)

For the fixed current case (Fig. 30) the inlet gas density is specified first, which determines the inlet mass flow rate $F_s$ as a function of the compressor rotation rate $\omega$ and the volumetric efficiency $\eta$ (typically $\sim$ 0.86 but weakly inversely proportional to $P_2$).

The dependence of $F_s$ on Mars pressure $P_M$ and temperature $T_M$ is shown in Fig. 31. Flow rate, pressure and gas composition are then determined at all points in the cathode line, including $P_2$, $P_3$, and $P_4$, $F_{ex}$, $F_{nr}$ and $F_r$. The composition and pressure at the cathode exhaust determine $V_{N(O_2)}$ and $V_{N(C)}$, which provide a guide to the allowable range of SOXE settings for safe operation.

In the fixed voltage case, the SOXE model is invoked to estimate the area specific resistance of the SOXE, which then determines the current, $I$. After that step, the flowchart is the same as the fixed current case.

#### Utility and Limitations of Steady State Model

The steady state model predicts overall power usage, based on electrochemical characteristics of the reaction and a power inventory of the subsystems derived from testing at JPL. This is a critical parameter in planning the MOXIE operating profile on Mars, where electrical energy is a strictly metered resource. Power usage of certain subsystems, notably the compressor, can change over time but can be measured in situ, and model parameters can be updated.

The steady state model predicts the safe operating voltage range, given knowledge or assumptions about the spread of ASR from cell to cell. This capability is pending validation.

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4MathWorks®, MATLAB®, Release R2020a, March, 2020.
as it can only be performed on a test article instrumented for cell-by-cell voltage measurements, and it requires careful measurement of the onset of degradation without inflicting significant damage to the unit. These tests are planned at MIT.
Finally, the steady state model includes a parametrized prediction of cycle-to-cycle ASR degradation, based on empirical data. While this is expected to be only approximate and will be regularly updated, it is included to emulate the trend from one cycle to the next.

2.2 Dynamic Model

MOXIEsim is a tunable, multi-domain, dynamic model that demonstrates system behavior in response to various command sequences and environmental conditions. It simulates all MOXIE control modalities, including operational steps from the Run Control Tables. The following domains define the model:

1. SOXE electrical subsystem
2. SOXE thermal subsystem
3. Flow subsystem
4. Control subsystems

All four subsystems are modeled in Simulink® and Simscape™ software and enclosed in a self-contained MATLAB app with a graphical user interface (GUI) that is used to initiate test scenarios, alter test parameters, and export simulation results. Each subsystem is a “gray” model, combining physical and thermodynamic relationships with empirical laboratory or environmental parameters. A fault detection system monitors limits for critical parameters.

**SOXE Electrical Subsystem** As discussed in Sect. 1.4.4, the SOXE operating voltage ($V_{op}$) is determined from three potentials $V_N$, $V_{ohm}$, and $V_{add}$. An equivalent circuit model of these potentials is replicated in Simulink for each cell in a stack, allowing each cell to have a distinct voltage based on a cell-specific ASR and thermal conditions. The cells are then grouped into a top and bottom portion of the SOXE stack as shown in Fig. 32 below. $V_N$ is determined as described in Sect. 1.4.4, and the reversible potential $V_{rev}$ is approximated as a function of temperature using a linear fit of tabular data for $\Delta G^o_f$ for the reaction (Barin et al. 1977).

In contrast to the static model, which calculates the worst-case $V_N$ at the cathode exit, an integral average Nernst potential is used for the dynamic model:

$$V_N = \frac{1}{x_{CO, out} - x_{CO, in}} \int_{x_{CO, in}}^{x_{CO, out}} \left( V_{rev} + \frac{RT}{4F} \ln \left( \frac{(P_{\text{Cathode}} \cdot x_{CO})^2 \cdot P_0^2}{(P_{\text{Cathode}} \cdot (1 - x_{CO}))^2} \right) \right) dx_{CO} \quad (2.2)$$

where $x_{CO} = \frac{p_{CO}}{(p_{CO} + p_{CO_2})}$ is the local CO$_2$ utilization in the stream and $P_{\text{Cathode}} = p_{CO} + p_{CO_2}$ is the total pressure over the cathode excluding inert gas contributions. Equation (2.2) is then integrated by assuming a linear variation of gas composition across the cell.

MOXIEsim then determines intrinsic ASR from:

$$\text{ASR}_{\text{int}} = \left( \frac{V_{op} - (V_{add} + V_N)}{I} \right) \cdot A_{\text{cell}} \quad (2.3)$$

where $I$ is the current, the additional offset potential $V_{add} = 0.02155$ V (typically independent of cycling), the cell area $A_{\text{cell}} = 22.74$ cm$^2$, and $V_{op}$ is the operating voltage.

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5MathWorks®, Simscape™, Release R2020a, March, 2020.
In a temperature range from 800 K to 1400 K, the thermal neutral voltage is calculated by the second-order polynomial fit of the temperature-dependent enthalpy of reaction divided by $4F$:

$$V_{\text{tn}} = -8.655 \times 10^{-9} T^2 - 1.496 \times 10^{-6} T + 1.475$$

(2.4)

Unlike the static model, dynamic degradation of the SOXE stack is not modeled and must be manually entered. Some SOXE dynamics and variation are not captured, including the effects of flow differences between individual cells, local gas dynamics within cells, and lateral variation in cell performance.

**SOXE Thermal Subsystem** The thermal model has both a high-fidelity version and a simplified version for fast iteration. MOXIEsim captures portions of the thermal model with a Simscape Thermal Domain Block that consists of an equivalent thermal circuit for each cell, connected in series and anchored to the surrounding environment. Sources of heat include the energy provided by the stack heaters, the heat consumed by the endothermic reaction, heat transported by flowing gases, and heat losses due to conduction. The SOXE electrolyte and interconnects are represented as thermal masses. Heat can conduct through the cell and through the insulation of the hot zone of the SOXE. Heat consumed or generated by the reaction begins in the thermal mass of the cell. The heat from the heaters enters the network from the top or the bottom of the equivalent circuit. Surface areas and material properties define the thermal mass and conductivity of the materials. Heat transfer in the SOXE stack
Section of Simscape™ thermal model that represents a cell in the SOXE Stack

is modeled using laws of conduction only; radiation and convection are not included. The model is primarily two-dimensional, and three-dimensional components of flow and heat transfer are significantly simplified.

The simplified model is shown schematically in Fig. 33.

Flow Subsystem MOXIESim calculates flow characteristics of the gas passing through the system from Mars entry to VFCD exhaust. Ambient pressure, temperature, composition, and density of the Martian atmosphere is either an input parameter or is drawn from the Mars Climate Database for a specified time and location. The flow model is primarily two-dimensional.

Pressure drop across the MOXIE HEPA filter is calculated as a function of inlet flow velocity, volumetric flow rate, and filter dimensions, with temperature and composition assumed constant across the filter. The scroll compressor model then determines the mass flow rate of gas passing into the system as a function of compressor speed and inlet gas characteristics. Subsequent pressure drops are calculated from the known pipe diameters and lengths, as well as the orifice size of the flowmeter and the properties of the VFCDs. The gases are divided into cathode exhaust, anode exhaust, and recirculation as in the static model.

Control Subsystem MOXIEsim uses Simulink to model the proportional-integral (PI) control loops and run control tables as described in Sect. 1. An example of the PI control for the heater is shown in Fig. 34 below.

Validation of Dynamic Model Each component of the dynamic model was developed and validated with results from laboratory experiments on MOXIE development models and components. Electrochemical models were developed and compared to SOXE stacks in

Fig. 33  Section of Simscape™ thermal model that represents a cell in the SOXE Stack
controlled environments (Meyen 2017) at JPL. Examples are shown in Figs. 35 and 36. The modeled SOXE stack current is shown in Fig. 35 left, and the actual JSA-006 run at JPL is shown on the right. Figure 36 similarly shows modeled and experimental results for the stack temperature heating cycle.
Table 5  MOXIE design requirements, compared to goals and demonstrated performance

| Requirement                          | Threshold | Demonstrated performance |
|--------------------------------------|-----------|--------------------------|
| Oxygen Production Rate (g/hr at 5 Torr, 0 °C) | 6         | 12                       |
| Oxygen Purity (%)                    | 98%       | > 99.9%                  |
| Number of Cycles (on Mars)           | 10        | > 60 total               |

3 Operating MOXIE

As a technology demonstration, MOXIE’s overriding objective is to inform future implementations of ISRU for the purpose of producing oxygen from the Martian atmosphere. The rigor of operating a flight instantiation of this technology on Mars is a crucial facet of the implementation strategy, but it explicitly complements a more versatile laboratory effort. Threefold broad goals therefore underlie MOXIE’s operational strategy on Mars:

- Demonstrate that MOXIE performance meets or exceeds design expectations.
- Continue to characterize the instrument and explore improved modes of operation.
- Determine the robustness of the MOXIE implementation with respect to environmental conditions, repeated operations, and long-term operation.

Performance Expectations  MOXIE design was guided by three minimal performance requirements (Table 5). The intent of specifying the cycling requirement relative to operation on Mars was to make clear that the instrument must also be capable of surviving any expected acceptance testing and integration on Earth. The process of verifying that these requirements were met allows for margin, following JPL guidelines; thus, for example, assuming 10 cycles on Earth in addition to the required capability to operate for 10 cycles on Mars requires qualification to $20 \times 3 = 60$ cycles for a laboratory model of the SOXE, after which time it is still required to satisfy performance thresholds for production rate and purity.

The final column of Table 5, which represents the raw performance of test units in the laboratory, establishes an expectation of performance that will inform operations on Mars. The oxygen production rate of 12 g/hr is strictly limited by the 4 A capacity of the flight power supply. Under typical operation, however, production is constrained by considerations of safe operating conditions (e.g. no carbon deposition) and is limited by the ability of the compressor to deliver sufficient CO₂ from the rarified Mars atmosphere. This ability is in turn proportional to the inlet atmospheric density, which varies with landing site, season, weather, and time of day. In warmer seasons, performance may also be limited by MOXIE temperature.

Characterization  Both the performance and the health of MOXIE are dependent not only on a predetermined configuration, but on (1) the condition of the SOXE stacks, captured in the broadest sense by the ASR, and (2) the ability of the CO₂ Acquisition and Compression system (CAC) to deliver CO₂, a function of both the condition of the compressor and the density of the inlet gas, which could change by as much as 50% with seasonal (pressure) and weather (temperature) variations. In addition to requirements, 10 Figures of Merit (FOMs) were tracked through most of the development period. These are shown in Table 6.

Robustness  Since the objective of MOXIE is to learn as much as possible about the performance and capability of the system in support of what has been termed “extensibility,”
Table 6  MOXIE Figures of Merit

| ID    | Title                                      |
|-------|--------------------------------------------|
| EFOM-1 | SOXE production efficiency                 |
| EFOM-2 | SOXE CO₂ utilization efficiency            |
| FOM-1  | Oxygen purity                              |
| FOM-2  | Total O₂ production rate                   |
| FOM-3  | Pump efficiency                            |
| FOM-4  | SOXE reproducibility                       |
| FOM-5  | SOXE heat loss                             |
| FOM-6  | SOXE robustness against failure            |
| FOM-7  | Thermal constraints on operability         |
| FOM-8  | Tolerance to dust                          |

i.e. learning how to design, build and operate a next-generation, scaled-up system, it is not the objective to simply find a safe operating regime and produce as much oxygen as possible throughout the mission. Rather, it is desirable to test the limits of production under different environmental conditions, to maximize the use of self-regulation and autonomy, and to map out as much of the operating parameter space as possible. In this sense MOXIE operations differ significantly from those of instruments whose objective is to study Mars itself.

Taken together, the variable performance and the need to learn about the system point to an operational plan that will allow the MOXIE team to test operation over a range of times of day, seasons, and weather conditions. For example, MOXIE will seek out, not avoid, operation in dust storm conditions.

### 3.1 Operating Strategy

On the ground, sophisticated plant models built in Simulink® will allow the MOXIE team to both predict and evaluate the performance of MOXIE based on its most recent known status. An Engineering Model (EM), which is a form, fit, and functional replica of the MOXIE Flight Model (FM), will allow the team to evaluate command sequences prior to sending them to the spacecraft and will serve in part as a “fleet follower” to experience the same general patterns of use and operational lifetime of the FM. A separate “FlatSat” consisting of free-standing SOXE assembly, compressor, and sensor assembly will allow more aggressive experimentation with operating modes, dust mitigation, etc.

While MOXIE operations follow a strategic arc through the M2020 mission, that arc is only loosely related to the process of Rover path planning and sample selection. Broadly, the strategy is as follows:

**Early mission (characterization) – at least 2 run cycles**
- Initialize, checkout, and commission MOXIE
- Determine stable and effective operating parameters
- Characterize performance, degradation rates, etc.

**Middle mission (operation) – at least 5 run cycles**
- Operate over a range of seasons and time of day
- Operate in dust events (if the opportunity presents itself)
- Pursue Level 1 Success Criteria
- Monitor long-term degradation, dust effects, etc.
Late mission (exploration) – at least 3 run cycles

- Explore improved and more robust performance, e.g. at higher temperature
- Explore improved autonomy and fault response (requires software upload)
- Intentionally test graceful fault response by operating near or at limits

Operations on Mars will proceed through Surface Checkout, Surface Commissioning, and then full oxygen production stages.

The first opportunity to run MOXIE on Mars, the Surface Checkout, will verify that the overall condition of MOXIE has not changed since the Cruise Phase checkout. It will be performed at the earliest opportunity after landing (current plans show it occurring on Sol 5) and will include an electronics aliveness test, command function test, sensor panel functionality test, stack heater test, SOXE aliveness test, and a compressor aliveness test.

Full Surface Commissioning will verify the functionality of components that require an atmosphere to operate and will establish an operational baseline under Martian conditions. Surface Commissioning will include powering up, loading a Run Control Table (RCT) to initiate execution, booting up gas sensors, running the compressor through a range of compressor speeds, and bringing the SOXE up to working temperature without producing oxygen. The compressor tests must be completed before the SOXE heating test is run, since it is desired not to have gas flowing through the heated SOXE at this stage of testing.

Once Surface Conditioning is complete, MOXIE will be ready for full oxygen-producing operation. MOXIE runs will be spaced over the course of the M2020 mission, in order to sample a variety of atmospheric conditions (all seasons and all times of day).

3.2 Modes and Tables

The MOXIE Instrument State Diagram is shown in Fig. 37. There are three operating modes: BOOT, IDLE, and RUN. Transitions are initiated by commands or by fault detections. A fault during RUN returns the system to IDLE.

In the absence of faults, operation proceeds as follows:

1. Upon power-up, MOXIE enters BOOT mode, and the power distribution system is activated. The FPGA, 8051 processor, and power distribution electronics are turned on. MOXIE waits for a Rover command to select a software slot, upload tables, upload new software, or initiate a run.
2. An oxygen production RUN is initiated by rover command. The operational sequence is driven by a Run Control Table (RCT) and supporting parameter tables that define a time series of operating parameters including SOXE temperature, CO₂ feed rate, O₂ production rate, duration, fault limits, etc. Data is collected at a 1 second cadence.
3. On completion of the RCT, MOXIE transitions to IDLE, power is turned off to MOXIE subsystems and data is sent to the rover computer. When the final data set has been transferred, MOXIE is powered off.

In RUN mode, operation is specified by four tables that are either uploaded as part of the command sequence or inherited from the prior run. Three of these tables (Safety, Algorithm, and Run parameters) specify settings that are in effect throughout the run, as shown in Table 7. The fourth is the Run Control Table (RCT), Table 8, which defines a series of time steps and specifies the value of parameters that are to be set or controlled, such as SOXE temperature, SOXE voltage, or gas flow rate.
Table 7 Three MOXIE parameter tables provide for overall safety, specify control parameters, and protect the composition sensors

| Algorithm Parameters |   |
|----------------------|---|
| Persistence on/off   | Logical flag indicating if persistence is specified |
| Proportional Gain    | $T_{SOXE}$ (2), $P_4$ (compressor), $I_{SOXE}$ (2) |
| Integral Gain        | $T_{SOXE}$ (2), $P_4$ (compressor), $I_{SOXE}$ (2) |
| Limiter, minimum     | $P_4$ (compressor), $I_{SOXE}$ (2) |
| Limiter, maximum     | $P_4$ (compressor), $T_{SOXE}$ w/V enabled (2), $T_{SOXE}$ w/V disabled (2), $I_{SOXE}$ (2) |
| Persistence          | $T_{SOXE}$ (2), $P_4$ (compressor), Utilization $I_{SOXE}/P_4$ (2) |

Safety Limits

| Persistence on/off   | Logical flag indicating if persistence is specified |
| Pressure             | Max pressure in $P_{2,3}$ (flow), $P_4$ (cathode exhaust), $P_5$ (anode exhaust) |
| $V_{SOXE}$ (2)       | Max SOXE Voltage |
| $V_{28}$ v supply (4)| Max and min for Main & SOXE 28 V supplies |
| $I_{SOXE}$ (2)       | Max SOXE Current |
| $T_{SOXE}$ (2)       | Max SOXE Temperature |
| Temperature (6)      | Max $T_1$ (sensors), $T_{3,4}$ (compressor), $T_{22}$ (power board); $T_7$ max, min (baseplate) |
| Persistence (17)     | $P_{2,3,4,5, V_{SOXE}}$ (2), $V_{28}$ v (2), $I_{SOXE}$ (2), $T_{SOXE}$ (2), $T_{1,3,4,7,22}$ |

Run Parameters

| Persistence on/off   | Logical flag indicating if persistence is specified |
| CO$_2$ + CO current limit | Combined maximum for SmartGas sensors |
| O$_2$ current limit  | Maximum for Pyroscience sensor |
| Persistence (2)      | For two items above |
Table 8 The MOXIE RCT specifies up to 64 steps of operation, each containing the information below the first row

| # of Steps     | Up to 64 |
|---------------|----------|
| Step #        | (0–63)   |
| Duration      | Seconds  |
| $T_{SOXE}$ setpoints (2) | SOXE Temperatures, Top and bottom |
| $T_{SOXE}$ limits (4) | Max, min limits, Top & Bottom (abort if exceeded) |
| $P_4$ setpoint | Controls compressor speed. |
| $P_4$ offset  | Allows fixed compressor speed to be set |
| $P_4$ limits (2) | Max, min limits (abort if exceeded) |
| $I_{SOXE}$ setpoints | SOXE current(s), Top & Bottom |
| $I_{SOXE}$ offset | Allows fixed voltage to be set |
| Utilization limits (4) | Max, min limits, $I_{SOXE}/P_4$: Top & Bottom (abort if exceeded) |
| Enable flags (6) | SOXE heaters; CO₂ & CO sensors; O₂ sensor; Compressor; $V_{SOXE}$ (2) |

The Safety Parameter Table defines operational limits to voltage, current, pressure, and temperature sensors in order to protect the hardware. Persistence parameters indicate the maximum number of seconds that a parameter may exceed these limits before triggering a fault response, returning to IDLE and effectively aborting the run. (Due to a known bug in the software, the actual persistence exceeds the commanded setting by two seconds).

The Algorithm Parameter Table defines gain for proportional and integral terms of the various control loops as well as duty cycle limits and persistence for the PWM-control of the SOXE heaters.

The Run Parameters Table is specific to the composition sensors, which are deemed non-essential for MOXIE operations. The table specifies temperature and current limits for the sensors and invokes a non-fatal fault response if they are exceeded.

The RCT specifies operational settings that are each in effect for a fixed period of time. Steps are executed in a strict time sequence, with a 0.1 second delay between steps. In addition to step duration, each row in the RCT defines setpoints and limits for the five control loops: current/voltage and temperature loops for the top and bottom halves of the SOXE stack, and a single pressure/compressor speed loop. Each step also specifies limits on the ratio of SOXE current to cathode pressure, which is proportional to CO₂ utilization, and the state of enable flags for all commandable actuators and sensors. Operation proceeds stepwise and synchronously through the table. Typically, each MOXIE run will use a unique RCT, which is uploaded to the rover as part of the current sol’s operational sequence and then transferred to MOXIE.

3.3 Typical Operation

To operate MOXIE, the rover issues a boot instruction and designates a software slice to load. Once boot is complete MOXIE transitions to IDLE, turning on all sensors and initiating data logging. Tables are transferred from the rover to MOXIE as necessary and any other business is transacted prior to the rover initiating a transition to the RUN mode. Once in RUN mode the rover does not interact with MOXIE again until the time allocated to MOXIE has elapsed, at which point it executes a full data upload and removes MOXIE power.

The essential steps in a MOXIE run are shown in Table 9. After completing the boot sequence, the SOXE is preheated to its nominal 800 °C temperature at the center of the
Table 9  Basic steps in a MOXIE run. Additional steps might walk through the $I-V$ curve or determine performance as a function of flow or temperature

| RCT step   | Step Description                              | Duration (minutes) | Comments                                                                 |
|------------|------------------------------------------------|--------------------|--------------------------------------------------------------------------|
| BOOT       | Turn on electronics and select software slice  | ∼ 1                | Turn on electronics and select software slice                          |
| IDLE       | Turn on transducers, start logging data       | ∼ 1                | Turn on transducers, start logging data                                 |
| 1 Warm up SOXE | Turn on top and bottom SOXE heaters to bring SOXE up to | 90                | Temperature setpoint, typically 800 °C                                  |
| 2 Stabilize SOXE temperature |                                                     | 30                | The optimal duration for this step is under study                       |
| 3 Turn on compressor | Stabilize compressor speed and briefly establish gas flow | 0.1              | Begin oxygen production                                                 |
| 4 Apply SOXE voltage | Turn off power to SOXE stacks first | 0.01              | Turn off power to SOXE stacks first                                     |
| 5 Cool down SOXE | Transition to IDLE, turning off compressor and allowing SOXE to passively cool while continuing to acquire sensor data | 30                | Initiated by the rover at a set time, not under MOXIE control           |

Depending on experimental objectives, production of oxygen will involve additional steps for functions such as measuring ASR by quickly varying current, voltage, and/or flow, or comparison of operational modes by allowing the system to stabilize with different temperature or current setpoints. It is also possible to control the cooldown rate from the RCT at the conclusion of oxygen production, though more typically the instrument will return to IDLE and passively monitor the cooldown process.

Power Utilization  Since MOXIE has a large power demand and operational cycles are considered to be “consumables,” Mars 2020 intends to dedicate specific sols to MOXIE operation. The Mars 2020 Rover Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) continuously generates ∼ 110 W of electric power. Two lithium-ion batteries can store up to ∼ 1000 W-hrs, and the charge will typically be kept between 40–80% of maximum. Since the MMRTG continues to generate power during MOXIE operation, the expectation is that operation on a dedicated “MOXIE sol” can consume up to ∼ 1000 W-hr without impacting the energy availability for the following sol.

Table 10 summarizes MOXIE’s power consumption during a typical oxygen production run, corresponding to parameters summarized in Table 11. SOXE and compressor operation combined consume ∼ 220 W, divided roughly equally between the two. The SOXE portion includes ∼ 30 W for actual electrolysis, divided between voltage and heat, but the bulk of the power goes to makeup heat for thermal losses through the insulation and preheating of the gas. A goal for a future version of MOXIE is to dramatically increase the fraction of power that goes to electrolysis. Smaller contributions to the power budget include electronics, sensors, and voltage conversion losses, which amount to of order 25 W.
Table 10  Power requirements for steps in a typical MOXIE run corresponding to conditions specified in Table 11. Oxygen production is assumed to be at 6 g/hr, corresponding to 2 A current, with compressor speed of 3000 RPM, inlet pressure and temperature of 5 Torr and 250 K respectively, resulting in an inlet mass flow rate of 66 g/hr. The rover compute element (RCE) consumes an additional 110 W when the rover is “awake”.

| Mode                  | BOOT | IDLE | SOXE warmup | Stabilize SOXE T | Start compressor | O₂ production | IDLE/cooldown |
|-----------------------|------|------|-------------|-----------------|-----------------|---------------|---------------|
| Duration (minutes)    | 1    | 1    | 90          | 30              | 0.1             | 30            | 15            |

| Compressor Power (W)  | 106.0 |
| Top SOXE Heater (W)   | 88.0  | 45.6 | 45.6 | 50.4 |
| Bottom SOXE Heater (W)| 88.0  | 45.6 | 45.6 | 36.5 |
| SOXE (W)              |       | 29.2 |
| Electronics (W)       | 14.0  | 14.0 | 23.0 | 19.0 | 25.0 | 14.0 |
| Transducers (W)       | 0.3   | 0.3  | 0.3  | 0.3  | 0.3  | 0.3 |
| Composition Sensors (W)| 0.3 | 3.0  | 3.0  | 3.0  |
| Total Power (W)       | 14.0  | 14.3 | 199.3 | 113.5 | 119.5 | 250.4 | 17.3 |

Table 11  Typical conditions during O₂ production

| Property                              | Value               |
|---------------------------------------|---------------------|
| External pressure                     | 5.4 Torr            |
| Inlet pressure                        | 5.0 Torr            |
| External temperature                  | 240 K               |
| Compressor speed                      | 3000 RPM            |
| Mass flow through compressor (Fₛ)     | 66.7 g/hr           |
| O₂ flow rate in anode                 | 6.0 g/hr            |
| CO₂ flow rate in cathode exhaust      | 47.2 g/hr           |
| CO flow rate in cathode exhaust       | 10.5 g/hr           |
| Inert flow rate in cathode exhaust    | 3.0 g/hr            |
| Mole fraction CO (neglecting inerts)  | 0.26                |
| Fraction utilization                  | 0.26                |

For safety against possible short circuits in MOXIE that may affect the rover, parts of the rover electronics must remain activated while MOXIE is running. This will consume an additional 110 W, which is not included in the power requirements shown in Table 10.

Fault Detection and Response  The MOXIE instrument is required to be capable of protecting against faults and to be capable of preventing faults from propagating across electrical, thermal, and mechanical interfaces with the rover. In almost all cases, a fault detection by MOXIE will have a simple response, return to IDLE, although a software hang-up (watchdog timer) will trigger a return to BOOT. As described elsewhere, many of the sensors on MOXIE have lower and/or upper safety and operational limits that are set in parameter tables or the RCT along with persistence values. If a reading from the sensor falls outside of its pre-defined limits, a fault will be declared, and MOXIE will be returned to IDLE mode in order to preserve instrument and rover safety.
Table 12  MOXIE data products following Planetary Data System processing level schema (PDS4)

| Raw data (EDR):                         |
|----------------------------------------|
| • Raw sensor readings                  |
| • Values calculated in situ            |
| • Event records                        |
| • Ancillary information to support thermal and performance models (External RAMP temperatures, Rover quaternion data, Bus Voltage profile., and external atmospheric temperature, pressure, and dust profiles as available from MEDA). |
| • Diagnostics                          |

| Partially Processed Data (RDR):        |
|---------------------------------------|
| • Data products in physical units based on nominal calibrations |

| Calibrated Data (RDR):                 |
|---------------------------------------|
| • Data products in physical units based on latest calibration, derived in part from the present data set. |

| Derived: Time series of calculated quantities |
|----------------------------------------------|
| • Inlet flow rate                            |
| • O₂ production rate                         |
| • O₂ purity                                  |
| • CO₂ utilization efficiency                 |
| • Open circuit voltage                       |
| • Area Specific Resistance                   |
| • Filter resistance                          |
| • Compressor efficiency                      |

| Derived: Higher order Products              |
|---------------------------------------------|
| • Electrochemical potentials                |
| • Dust accumulation rates                   |
| • Others TBD                                |

3.4 Data Processing, Distribution and Archiving

Data reduction will be accomplished with a mix of automated and manual processing. All formal data products, summarized in Table 12, will be posted on the Atmospheres node of the Planetary Data System (PDS). Since full sols are planned to be set aside for MOXIE operation, typically the data will be downlinked to the ground the same day.

The raw data will be processed in pipeline fashion by the Instrument Data System at JPL to produce Level 0 Engineering Data Records (EDRs) and Level 1 reduced data records (RDRs) representing the same data in physical units based on a nominal sensor calibration. In addition to channelized raw sensor data acquired at a 1 Hz cadence the EDRs contain Event Records (EVR), timing information, and supporting data from other instruments and sensors. These Level 1 RDRs should be considered “quick-look” products.

Level 2 RDRs, produced by the MOXIE Science Team, will look similar to Level 1 but with the most accurate possible sensor calibration, updated after each MOXIE run and taking into account initial ambient conditions and reconciliation of redundant sensor measurements. These three initial products reflect, respectively, the raw data acquired as digital numbers (DN), converted to standard engineering units (EU) and adjusted using most recent characterization data to calibrated units (CU). Typically, preparation of Level 2 data will be completed within one week of data receipt.
4 Ground Testing

MOXIE hardware development and procurement was done by NASA’s Jet Propulsion Laboratory (JPL), and JPL carried out extensive testing on engineering and flight hardware to demonstrate that MOXIE can produce the required amount of oxygen and operate for the required duration under expected Martian conditions. Ceramatec (now OxEon Energy) built and carried out testing of individual SOXE units, as described below. Further testing at MIT is devoted to deepening the understanding of how MOXIE works.

At the start, the greatest perceived risk was whether the SOXE could perform adequately. That included whether it would be leak-tight, survive multiple thermal cycles, survive launch and landing forces, generate adequate amounts of oxygen, and whether the oxygen would be adequately pure. Several generations of SOXE designs were built from 2016 through 2018 and were tested against these requirements. As problems developed in the early generations, changes were implemented in the SOXE design. The early incarnations of the SOXE were subjected to many rigorous tests, where voltage leads were attached to each of the ten cells, the stacks were thermally cycled, and oxygen production and purity were carefully monitored. Not only did the cells themselves require development, the method for surrounding them with built-in insulation while keeping the stack under compression also had to be perfected.

Seal Characterization  The requirement to produce oxygen at $> 99.6\%$ purity necessitated the use of a seal material that is capable of yielding a hermetic seal around anode and cathode internal manifold ports as well as between the pressurized stack and the much lower Mars atmospheric pressure. A glass seal material that partially devitrifies was selected. The electrical interconnects were made by Plansee in Reutte, Austria from 95Cr-5Fe-Y alloy, a material whose thermal expansion matches the electrolyte material, Sc-doped zirconia (ScSZ). First test of the new cell design using the first iteration of interconnects with the selected seal material showed low oxygen purity, indicating inadequate sealing both around gas ports and the edges that isolate electrode chambers from external atmosphere. Inspection of the stack after testing showed gaps in the external seal area, which were confirmed by MicroCT scans performed at JPL. A process for seal application was selected based on leak test results, and was then applied and refined in subsequent stack builds. All stacks built using the resulting seal application process showed a measured oxygen purity $> 99.6\%$ with the exception of a few stacks where the process cracked the electrolyte, creating an alternative leak path not involving the seal. The seal geometry was adjusted to eliminate the cell cracking, and with more experience in the process oxygen purity values $> 99.95\%$ were routinely achieved. Experimental results on the mass balance correlation of pressure decay leak rate and measured O$_2$ purity suggested that to meet the 99.6% oxygen purity requirement the leak rate value should be less than 0.28 g/hr CO$_2$. Most of the flight class stack builds measured a leak rate of less than 0.02 g/hr CO$_2$.

SOXE Stack Evaluation  Prior to packaging into SOXE assemblies, a lengthy and laborious process, SOXE stacks were characterized at the vendor, Ceramatec (now OxEon Energy), in a temperature-controlled oven with an external compression rig and voltage connections at each interconnect, providing near uniform temperatures throughout the SOXE and allowing individual cell voltages to be measured, which is not possible with the flight configuration of the SOXE. The SOXE stack development at Ceramatec required an intensive 2-year effort spanning two design iterations and hundreds of fabrication and testing process variations. The development effort encompassed more than fifty stack builds and
SOXE stacks used in the early phases of testing were all labeled with STX numbers. Major issues successfully addressed in the development phase included performance of the stack seals, power supply induced degradation, defining and mitigating cathode thermodynamic regimes for oxidation and carbon deposition, cell cracking during stack fabrication, braze joint integrity at the interface of the stack electrical and fluid connections to MOXIE system components, and quantifying the mechanical robustness of successfully fabricated stacks with respect to anticipated mission imposed loads such as axial constraining forces, shock, vibration, extreme thermal environments, and the repetitive heating and cooling from operational cycles.

At the conclusion of the development effort, JPL authorized the Ceramatec team to begin manufacturing a set of 12 flight qualified stacks from which to select the flight, EM, qual and other stacks. The stacks that were delivered to JPL from this effort bear JSA numbers. Ceramatec also produced numerous stacks for their own testing, which have CSA numbers. The final stack build steps of sealing and cathode reduction were completed in the test stands as part of the initial operating cycle, OC1. Assembled stacks were placed in a compression fixture with provisions for gas supply and preheat, pressure sense tubing, current supply leads and diagnostic voltage leads as shown in Fig. 38.

The flight series stack testing started with a prescribed initial operating cycle (OC1) protocol followed for each stack. The sequence consisted of a series of voltage steps from 9 V (nominal open circuit voltage is about 8 V) to 12 V in 0.3 V increments, known as an $I-V$ sweep. The stack was then run to produce oxygen for 120 minutes before sweeping back down to an actual open circuit condition. The down-sweep open circuit voltage (OCV) is recorded after flushing the anode with produced oxygen through the 120-minute full current operation. In most cases, any subsequent operating cycles (OC2, OC3, etc.) followed the OC1 sequence, with the omission of the flow sweep but with variation of the nominal flow rate each cycle to simulate MOXIE operation under different atmospheric conditions. Key performance parameters were the oxygen purity and the ASR. Most stacks reached the 4 Amp limit set by the flight power supply. Another important measure was the spread in individual cell voltages, which determines how closely the entire stack performance matches the limiting cell with regard to the CO reduction voltage constraint.

Stack test results were reported in a quad-chart format containing a summary of the test purpose, ASR, and $O_2$ purity in quadrant 1 (top right), an ASR time history graph in quadrant 2 (top left), a min/max/average stack current in quadrant 3 (lower left) and a cell voltage scatter graph in quadrant 4 (lower right). Quad-chart data for OC1 of stacks JSA-018, JSA-019 and JSA-020 are shown in Figs. 39, 40, and 41 respectively. (The JSA...
nomenclature refers to the final series of SOXE stacks produced by Ceramatec. JSA-19 was eventually selected as the flight model.) Note that stacks JSA-018 and JSA-020 both have higher oxygen purity than JSA-019 while also having higher ASR and greater cell voltage spread. The JSA-019 oxygen purity is still an order of magnitude better than the requirement.
Operational cycles were restricted for flight series stacks to preserve the higher performing early cycles for flight, EM (engineering model), and qual functions as selected. However, the quad chart reporting format was also applied to stacks used to test cycle lifetime and performance with flow changes as shown with stack CSA-007 for OC1–OC21 in Fig. 42.

The quadrant 2 ASR time histories can be seen to cluster by flow rate in the CSA-007 test data quad chart. Temperature variations also shift ASR. These variations of performance with flow rate, temperature, and operating cycle number need to be quantified in order to safely operate MOXIE in a variety of conditions on Mars. The development of an approach to account for the effect of flow variations using an intrinsic area specific resistance ($\text{ASR}_{\text{int}}$) based on the integral average Nernst potential from inlet to exit composition has been published previously (Hartvigsen et al. 2017a) and is discussed in detail elsewhere in this paper. Increase in $\text{ASR}_{\text{int}}$ from cycle to cycle was also measured and is discussed elsewhere in this paper.

A testbed analogous to the one at Ceramatec was established at JPL for testing the delivered stacks prior to packaging. There were significant differences between these early Ceramatec and JPL tests compared to the flight configuration. Most importantly, these tests were done with the SOXE units heated inside an oven, which provided a more uniform temperature distribution throughout the SOXE than the top and bottom end heaters used for flight. The tests used bottled gas and commercial flow controllers to supply the SOXE and control inlet and outlet pressure. Cell voltage measurement leads were spot welded to each interconnect. For much of the development cycle this testing was used as a guide to improving the fabrication process, mitigating failure and degradation pathways (such as by adding the CO recirculation line, described elsewhere), investigating the margins of safe operating space, and optimizing gas flow and stack current turn-on timing. Ultimately these facilities were used to establish a baseline calibration of the stacks and to rank order them for packaging in flight, engineering, and test assemblies.
Mechanical and Thermal Testing  SOXE stacks were subjected to relevant mechanical and thermal environments at Ceramatec and JPL with follow-up stack operational testing conducted at Ceramatec (Hartvigsen et al. 2017b).

Thermal Cycling  The MOXIE system must survive the extreme cold of deep space during the cruise phase, and also the temperature extremes the rover is exposed to on the Mars surface. Fortunately, the rover power system provides some moderation against the most extreme external conditions such that the hardware allowable flight temperature (AFT) range is $-40^\circ$C to $+50^\circ$C. Qualification and verification testing involved cycling SOXE stacks to the AFT low temperature of $-40^\circ$C for 60 cycles, three times the number of cycles planned for the primary mission. Three additional cycles to $-55^\circ$C were performed to show margin on temperature capability in addition to the required factor of three margin on cycle capability. One additional cycle reached $-65^\circ$C. No leakage was detected during thermal cycle testing at JPL or Ceramatec, where additional post-test operational cycles were conducted, showing no significant performance loss or change in oxygen purity.

Mechanical Compressive Loading  The SOXE thermal packaging design may subject the stack to axial compressive loads as high as 4 kN in order to secure the stack against vibration induced displacement within the insulation package. Five SOXE stacks were loaded to 10 kN using Ceramatec’s load frame without detecting evidence of cell, interconnect or seal failure. Two operational cycles were run on stacks STX-016, STX-017, and STX-018 after the initial 10 kN compression loading to show the effect of the mechanical load on stack performance. No significant performance loss or change in oxygen purity was observed in the operational cycles following the 10 kN loading. Stacks STX-016 and STX-017 were then loaded in a higher capacity load frame to 25 kN without failure. Stack STX-018 was loaded to 62 kN before detecting a failure.
3-Axis Vibrational Testing  During launch, entry, descent, and landing the SOXE and its associated insulation and support structure (packaged SOXE) are exposed to random vibration as well as pyroshock loading. The vibration and shock exposure events are all experienced during non-operating conditions, so these tests do not need to be conducted with the stack under operating conditions. Testing was performed to verify that the packaged SOXE can survive these conditions. The random vibrational testing was performed at JPL using a dynamic shaker to apply the load spectrum to each of the 3 major axes. Testing included a baseline frequency sweep to characterize initial stack response followed by random vibration testing. Stack integrity was verified between each vibration level using a leak test apparatus similar to that used in mechanical load testing to detect structural failure of a cell, interconnect, or seal.

Shock Testing  Pyroshock testing was performed using a tunable beam shock apparatus. The SOXE assembly was mounted to a plate on the beam. A high-rate projectile driven by gas pressure impacted the beam to provide its excitation. Extensive calibration of the beam was performed using a mass dummy to achieve the desired shock response spectrum (SRS) before the actual hardware was tested. By varying the beam span, the desired knee frequency (1600 Hz) was obtained. Further tuning was performed by varying the system pressure, shape and size of projectile, and damping materials. Several test iterations were required to achieve the required SRS. The test article was then mounted to the tuned beam for the actual test. Each axis was tested independently, with two shocks applied along each axis orientation. Leak tests were performed after each axis was shocked to ensure that the stack was not damaged during the test.

Thermal/Operational Cycles  The primary mission requirements call for the capability to operate for a total of 20 cycles, with at least 10 cycles on Mars and at most 10 cycles pre-launch. The flight qualification plan required operating three stacks for 21 cycles with flight-like feed rates, while maintaining an oxygen purity > 98% and an oxygen production rate > 6 g/h through the final cycle 21. The baseline operating condition was 800 °C, at local ambient pressure (86 kPa typical at Salt Lake City), a nominal 100 g/hr CO₂ feed rate, and 2% stack inlet CO concentration to simulate exhaust gas recycling. Cycles 1–5 were operated with the nominal 100 g/hr CO₂ flow rate (i.e. not including the added CO), followed by 3 cycles at each of the following flow rates: 30 g/hr, 60 g/hr, 50 g/hr and 80 g/hr, with a 100 g/hr cycle following each set of reduced flow rate cycles. The 100 g/hr cycles are necessary for a direct comparison to baseline without having to compensate for the conversion-corrected average Nernst potential effect on performance.

SOXE Assembly Development  The SOXE assembly refers to the packaged unit inclusive of insulation, heaters and heater carriers, a spring compression system, heat exchangers for gas pre-heating and cooling, and a structural enclosure including electrical feedthroughs. A prototype assembly also accommodated nichrome wires spot-welded to each interconnect as well as thermocouples bonded to selected interconnects with high-temperature cement (Omegabond OB-600 or Omega CC-High Temp) to characterize thermal gradients. This assembly was designed to allow components to be changed as needed. Like the stack-level testing, this testing was performed in a vacuum chamber at Mars-like pressure using bottled gas, commercial gas flow controllers, and commercial power supplies.

The prototype SOXE assembly testing verified that thermal gradients in the stack did not unacceptably impact performance and that the compact spring provided sufficient compression for proper operation of the stack. In addition, one flight-like SOXE assembly was built as a qualification and life test unit. It underwent vibration testing, pyro shock testing, and a 40-cycle life test. At the end of 40 cycles, the stack was still capable of producing 6 g/hr of oxygen with an inlet stream of 80 g/hr CO₂.
FlatSat Testing  The so-called “FlatSat” testbed added a flight-like scroll compressor and flight-like composition sensors to the SOXE assembly. In addition, this testbed was the first to incorporate VFCDs, the first to draw gas using the compressor from a pressure-regulated Mars-like low-pressure environment, and the first to include exhaust gas recirculation. The electronics were flight-like but set up on a bench outside the test chamber, running flight-like firmware but with software conducive to real-time interaction. This setup was used to demonstrate the first end-to-end O₂ production and to tune the SOXE current and heater control loops. A FlatSat configuration of MOXIE is currently being installed in a laboratory at MIT for ongoing characterization during flight, an essential complement to validation on Mars.

Engineering Model (EM) Testing  The MOXIE EM was a pathfinder for the assembly and testing of the FM during development. During the EM test campaign, the software was upgraded to a flight-like version capable of running Run Control Tables (RCTs). Both the EM and FM were primarily operated in a bell jar test system that allowed for pressure regulation and ambient-temperature environmental thermal control. Testing with the EM validated the flow control system and SOXE packaging, performed the first autonomous O₂ production run using RCTs, and provided a platform to debug flight software. The EM also was used for pyro shock testing, to verify the MOXIE design’s electromagnetic compatibility with the Mars 2020 systems, and to shake out thermal vacuum (TVAC) test procedures prior to FM TVAC testing.

The EM currently remains at JPL for support during the early phases of the Mars 2020 mission. It will eventually be transported to MIT for validation of RCTs and other data tables prior to commanding and in support of troubleshooting.

Flight Model (FM) testing  In order to preserve as much of its SOXE stack life as possible, the FM was subjected to the minimum number of thermal cycles consistent with required acceptance testing, including an initial commissioning run, pre- and post-vibration test runs, and a run during TVAC testing. Its SOXE assembly underwent an improved commissioning process, its compressor was the best-performing out of the lot of flight-qualified compressors, and its composition sensors underwent additional screening and electronics conformal coating prior to integration. After TVAC testing, the MOXIE-FM was installed into the Mars 2020 rover body. Rover-level testing is limited to basic system functionality checks until arrival on Mars.

5 Extensibility

From the perspective of the development of MOXIE, extensibility refers to scaling the technology to eventually support a human mission to Mars. MOXIE has demonstrated that solid oxide electrolysis of CO₂ is viable at a level of maturity appropriate for flight. It is now understood how such a system works, what its viable ranges of operation are, what its weaknesses are, and how to avoid them. But the most important product of the MOXIE experiment will be a roadmap to a full-scale system.

In the course of developing MOXIE, we have acquired a good understanding of the issues involved and the most promising technology approaches to be pursued. Overall, the severe Mars 2020 mass, volume, and power constraints have driven requirements for MOXIE that are more stringent than they will be for a scaled-up ISRU system. Scaled-up systems will not have to be cycled more than a few times and will benefit from features such as pressure
regulators and insulated ovens that will allow them to operate under a narrower range of conditions. The fraction of resources devoted to infrastructure such as insulation, electronics, and mechanical structure will shrink dramatically relative to the actual oxygen-producing components, and efficiencies in gas thermal control will be introduced that cannot be realized in short bursts of operation. Lessons learned from MOXIE development will result in more mass and volume-efficient dust filtering systems and more power-efficient gas collection systems. Modularity and redundancy will increase robustness, and improved sensor networks will significantly enhance ground-based diagnostic insight as well as real-time adaptive control of electrolysis potentials. Damage mitigation strategies such as advanced autonomy, self-cleaning dust filters, use of hydrogen for cell regeneration or a closed-cycle water system for co-electrolysis may become practical.

On the other hand, an eventual full-scale oxygen producing ISRU system for a human mission will be required to operate over a significantly longer total time than MOXIE, which may result in additional degradation of filters, compressors, and electrolysis components. MOXIE also falls short of addressing key components of such a system, including liquefaction, storage, and transfer of oxygen to a propellant tank.

Based on the NASA Design Reference Architectures (DRA) published since the 1990s, the major role of a full-scale extrapolation of MOXIE ISRU would be to produce sufficient oxygen propellant over a ∼ 14-month period to enable the Mars Ascent Vehicle (MAV) to deliver the crew to rendezvous with an Earth Return Vehicle waiting in Mars orbit. A 2015 study (Polsgrove et al. 2015) assuming a crew of four, consistent with the latest DRA, concluded that 6.0 metric tons (MT) of methane and 22.6 MT of oxygen would be needed to produce a total ascent propellant load of 28.6 MT. By comparison, Polsgrove et al. (2015) estimate that 9.0 mT of methane and 33.2 mT of oxygen would be needed to support a crew of 6.

The time between placing the MAV on Mars and having to confirm readiness for a human mission during the next launch cycle is ∼ 14 months. Taking this as the period of ISRU production, the minimum required rate of oxygen production would be 2.2 kg/hr for a crew of four and 3.3 kg/hr for a crew of six.

5.1 SOXE Scale-Up

Scaling of Capacity Since oxygen production is ultimately proportional to total cell area, scale-up of the SOXE to support a human mission requires an increase of a factor of ∼ 400 in area, assuming the same conservative ∼ 0.1 A/cm² current utilized by MOXIE. To address this goal, OxEon Energy has demonstrated cells with active area of 100 cm² (∼ 5 times greater than MOXIE cells), has stacked them 60 cells high (compared to 10 for MOXIE), and has wired pairs of stacks in tandem for added robustness (Fig. 43). The stack pair thus offers a factor of ∼ 60 greater capacity than the MOXIE stack, and 6–8 such pairs would satisfy the full-scale ISRU requirement. With 60 cells per stack, the driving voltage will be 6× greater than required for MOXIE.

Scaling of Mass and Volume From the standpoint of extensibility, the makeshift MOXIE oven consumes an excessive amount of mass, volume, and power resources (in the form of heat leakage) considering the small size of the stack itself. A substantially larger stack could have been accommodated with modest impact on the size of the overall SOXE assembly but could not in any case have been supported under the MOXIE power budget.

Thermal insulation, in particular, need not get thicker as the stack capacity increases, so it might be argued that the size of the assembly will scale as the square of the stack dimension while the capability scales as the cube. The same scaling argument applies to the relative
fraction of heat loss from the stack through the insulation, which for MOXIE is of order 10–20% of the power consumption of the full system. That fraction should increase as the square of the dimension while the electrochemical power will scale as the cube. In practice, a larger system is also expected to place the stack in a fully enclosed oven.

An even larger disparity can be argued for the mechanical compression system, as the existing spring system could potentially support a much larger stack without modification. Performance is also expected to improve with size, as the mass penalty for a fully enclosed oven will diminish relative to the size of the overall system.

**Scaling of Power**  In a typical “MOXIE sol” it is expected that \( \sim 1000 \) W-hr will be allocated to the instrument. Detailed operational plans are described elsewhere in this manuscript, but it is relevant to note here that the electrochemical power required to operate MOXIE, \( P = nI V_{TN} \) where \( n = 10 \) cells, \( I = 2–4 \) A, and \( V_{TN} = 1.46 \) V, is in the range of 30–60 W, while operating the full system is in the range of \( \sim 300 \) W. At \( \sim 130 \) W, the compressor is the largest single contribution to the power budget. Of order 60 W is attributable to heat loss through the SOXE assembly insulation and the dumping of heat from the exhaust gases. Voltage conversion losses account for \( \sim 5\% \) of the total power, while the electronics themselves account for less than 10%. Of these items, only the compressor is expected to scale with production capacity. Since compression power use greatly exceeds the thermodynamic demands, it is recommended that significant research be directed to improving compression efficiency.

For MOXIE, preheating the SOXE to its operating temperature of 800 °C requires at least 2 hours and consumes approximately half the total energy budget, a cost that would be negligible for any future continuously operating system.

Finally, subsequent to delivery of MOXIE it was determined that the rover compute element (RCE) is required to monitor for possible damaging shorts in MOXIE heater and compressor controllers, incurring a penalty of an additional 110 W compared to when the RCE is in “sleep” mode. For a typical run this change will consume more than a third of the overall energy budget. As with other electronics, it is not expected that this sort of monitoring overhead will increase as electrochemical production is scaled up.

### 5.2 Compressor Scale-Up

With respect to scale-up, the power required to operate the MOXIE compressor poses a challenge. The choice of a scroll compressor for MOXIE was strongly influenced by the
severe constraints on mass and volume imposed by the Mars 2020 mission, with less priority on energy efficiency. Thermodynamic compression only accounts for about 21% of total power for the selected compressor, with the remainder due principally to scroll tip and bearing friction. MOXIE’s compressor thus requires as much as 120 W to pump 66 g/hr under conditions typical of the Mars 2020 landing site. If scaled linearly to 23 kg/hr, the power requirement would be an unacceptably high 42 kW.

In practice, a full-scale electrolysis system is likely to run at lower pressure, reducing the load on the compressor, and a larger compressor is expected to be significantly more power efficient if for no other reason that the ratio of contacting surface area to chamber gas volume will scale favorably. In addition, the anticipated landing sites for the first human missions are likely to be at substantially lower elevations that the high site chosen for Mars 2020, potentially increasing the density of the ambient gas by 30% or more. Surveying compressor options, assessing the cumulative power benefits of the scale-up, and assessing the lifetime of next generation compressors is a high priority for future research.

The most straightforward way to reduce power investment in compression is to improve the utilization fraction of the collected CO₂. Future systems should be able to utilize CO₂ more efficiently by techniques such as lowering the cathode pressure, better controlling the operating voltage relative to the threshold for destructive carbon formation, and use of alternative cathode materials that effectively increase the carbon threshold to allow higher CO₂ utilization, and which are not damaged by carbon deposition if it does occur (Skafte et al. 2019).

If such improvements are not realized, another approach to reducing the compression burden would be to recover and recycle unused pressurized CO₂ from the cathode exhaust. The mass flow rate of Mars atmosphere required to generate 2.2 kg/hr of oxygen is estimated to be $6.34/U$ kg/hr, where $U$ is the effective fractional utilization of the CO₂, taking into account the possible separation and recycling of the cathode effluent. This is plotted in Fig. 44 for a crew of four. Recycling even a moderate fraction of unused CO₂ in the cathode exhaust produces major benefits when the fractional utilization is less than $\sim 0.4$. A recycling strategy might be implemented, for example, by using the recovered CO₂ as feedstock for a downstream set of SOXE stacks. The benefits of separation are strongly influenced by the overall system design. For example, if CO is to be captured for use as a fuel in surface mobility systems (e.g. Landis and Linne 2001) then separation becomes a requirement, and there would be little reason not to use the recovered CO₂.

5.3 Dust Rejection

The huge volume of dust that Mars gas would entrain in a full-scale Mars ISRU has always been a source of concern; the dust cannot be allowed to enter the electrolysis system. MOXIE has demonstrated that the combination of a baffle and a well-chosen HEPA filter can deflect and reject a large fraction of this dust, and the remainder can be captured on a reasonably sized filter without excessive pressure drop due to clogging. Like the scaling arguments for the SOXE and compressor, a full-scale filtering system must accommodate 200× the inlet flow rate of MOXIE. A full-scale system must also accommodate the cumulative accumulation of over 10000 hours of operation compared to an expected 100 hours or less for MOXIE; however, separate tests and analyses of the MOXIE filtering system indicate that it has sufficient capacity to accommodate 10000 hours of accumulation (Hecht et al. 2017).

The same analysis concluded that a full-scale system could require a pleated filter with up to 4 m² face area, which would dominate the structural design, under the assumption that the
density of entrained dust in the air drawn through the filter is the same as in the surrounding atmosphere. However, wind tunnel tests of the filters (McClean et al. 2017, 2018) suggested that only approximately 20% of the dust was captured by the filter. The working hypothesis is that the paucity of captured particulates was a result of the test geometry, which drew the air in an orthogonal direction from its flow vector while the particles tended to follow a ballistic trajectory. Fluid dynamical analysis is underway to confirm this suggestion but, if correct, it implies that substantially smaller filters would be sufficient in a full-scale system.

5.4 Future Studies

Once robust operation under a range of Martian conditions has been verified, MOXIE will have demonstrated that solid oxide electrolysis (SOXE) of CO₂ is a viable ISRU technology for Mars. With scale-up of the SOXE subsystem well underway, future work should focus on identifying a large-scale compressor technology and pressure regime that consumes substantially less power, validating that a mechanical baffle is sufficient to separate dust from the intake stream, and examining the robustness of an integrated full-scale system against 10000 hours of continuous operation. Beyond MOXIE, further progress will demand definition of an architecture to capture, store, and utilize the generated oxygen and potentially the CO fuel product.

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