ISRU on Mars: Challenges, Current Status, and Prospects

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Principal Investigator, MOXIE
What is In Situ Resource Utilization (ISRU)?

* Utilization vs. Transformation
  * We “utilize” space resources frequently, from parachutes on Mars to manufacturing in space vacuum
  * We’re really talking about transformation of resources; oxygen from carbon dioxide, hydrogen from ice, growing plants, etc.

* Gather the Low Hanging Fruit
  * Martian air is 1% as dense as on Earth, but 95% CO$_2$. Act like a tree and convert it to O$_2$.
  * Ice or hydrated soil are higher fruit. You need to find it, excavate it, transport it.

* Finally, think like a Martian
  * Warm in the sun, cold in the shade – beware the cold sky
  * Not much in the way of a cool breeze, but you sweat really well
  * Ice is nice, at high latitudes as permafrost or on polar caps. Vacation spots at the North Pole!
  * No fire, but lots of sparks
  * Generally clear skies
Basic DRA 5.0 scheme for Mars

- **Red** = transit to Mars
- **Green** = return from Mars
- **Blue** = on Mars orbit
- **Orange** = on Mars surface

**Legend:**
- ISRU?

**Diagram:**
- ERV-1
- MAV-1
- HAB
- Crew-1
- ERV-2
- MAV-2
- Crew-2
- ERV-3
- MAV-3
- Crew-3
Robotic ISRU: Make vs “buy”

★ Assumptions:
★ >25 kW power source will be emplaced on Mars
★ We have 12-14 months to produce propellant before crew launches

★ Low hanging fruit: \( \text{CO}_2 \rightarrow \text{O}_2 \)
★ Mass: ~1 mT for ISRU system saves ~25 mT transported \( \text{O}_2 \)
★ Constraints imposed on mission: None

★ Higher fruit: \( \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{CH}_4 \)
★ Mass: Additional ~0.7 mT for ISRU system saves ~7 mT transported \( \text{CH}_4 \)
★ Constraints imposed on mission:
★ Landing where water is available
★ Robotic prospecting, excavation, testing

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Source: M-WIP study
What are we doing about it?

* In the Laboratory
  * Discussed in Jerry Sanders talk

* Going to Mars: Priorities for human exploration
  * Radiation
    * MARIE (on orbit with Odyssey, landed module 2001 cancelled)
    * RAD (MSL Curiosity)
  * Entry, Descent, Landing
    * MEDLI (MSL Curiosity), MEDLI2 (M2020)
  * Astronaut health & safety, focus on dust
    * MECA (2001, cancelled, reflown for science value on Phoenix)
  * Environments and weather
    * MEDA(M2020)
  * Demonstrating ISRU:
    * MIP (2001, cancelled),
    * MOXIE (M2020)
Mars Oxygen ISRU Experiment

M. Hecht, MIT/HO (PI)
J. Hoffman, MIT (DPI)
G. Sanders, JSC
D. Rapp, Consultant
B. Yildiz, MIT
G. Voecks, JPL
K. Lackner, ASU
J. Hartvigsen, Ceramatec
P. Smith, Space Expl. Instr.
W. T. Pike, Imperial Coll.
M. Madsen, U. Copen.
C. Graves, DTU (Coll.)
M. de la Torre Juarez, JPL (Coll.)

Jet Propulsion Laboratory
California Institute of Technology
J. Mellstrom, Project Manager

MOXIE
The Mars Oxygen ISRU Experiment
On NASA’s Mars 2020 Rover

A joint project of NASA’s:
- HEOMD
- STMD
- SMD

Mars 2020 Rover

Jet Propulsion Laboratory
California Institute of Technology
J. Mellstrom, Project Manager
MOXIE Functional Block Diagram

Rover Chassis
RAMP
Thermal & Mechanical Interface

MOXIE Chassis
Oxygen Plant

- CO₂ Acquisition & Compression
- O₂ Production
  - Solid Oxide Electrolysis (SOXE)
- Composition Measurement
- Exhaust
  - O₂, CO+CO₂

Electronics
Data Acquisition & Control, Power Conversion & Distribution

- Process Control
- Process Monitor

Intake
Mars Atmosphere

Exhaust

RCE
- Data A
- Data B
RPAM
Power
- ~1:200 scale production
- ~1:400 scale operating time
- No product storage
- No fuel production
### Mars Oxygen ISRU Experiment

#### Mars 2020 Project

**Day in the Life**

**Version 8 (12/2/2015-jaj)**

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<th>&lt;5 min</th>
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<td>80-640 W-hr</td>
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<tr>
<td><strong>Rover</strong></td>
<td>Send SW- Select CMD</td>
<td>Send RUN CMD</td>
<td>Sleep</td>
<td>Wake</td>
<td>Retrieve Data</td>
<td>Ready to Uplink Data to Rover</td>
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<tr>
<td><strong>Moxie Modes</strong></td>
<td><strong>BOOT</strong></td>
<td><strong>IDLE</strong></td>
<td><strong>IDLE</strong></td>
<td><strong>RUN</strong></td>
<td><strong>IDLE</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Bold** = nominal design case

**Time:**
- 120-230 minutes

**Data:**
- 1.0-1.9 MB

**Power:**
- 320 W max
- Energy: 440 - 1000 W-hr

**Total:**
- 20 W
- 230 W
- 250 W
- 320 Watts
- 20 W

**Raw Data Rate:**
- 136 Bytes/s

**Power/Energy:**
- 30 min
- 120-230 minutes

**Energy:**
- 350 W-hr
- 80-640 W-hr
- 6 W-hr

**Data:**
- 1.0-1.9 MB
SOXE 11 cell stack fabricated by Ceramatec
SOXE Challenges

- Challenges & approaches
  - Dry CO₂ electrolysis
    - Custom materials
  - Heat/cool cycling
    - Controlled startup/shutdown; CTE matching
    - Cold-side compression to minimize pre-heat energy
  - Oxidation
    - CO recirculation
  - Coking
    - Limit on operating voltage
  - Low pressure environment
    - Hermetic (glass) sealing to formed interconnect
    - Compression fixture
  - Shock & vibration
    - Isolation mounting if needed

- Under development by Ceramatec, Inc. (a division of CoorsTek)
Things we know

- Area (22.7 cm²) and number of cells (10)
- Power supply limit: 4A, 35W.

Things we can estimate

- Starting ASR: ~2.5 Ω-cm² after a few test cycles
- OCV: ~0.8V
- Observed degradation: ~0.1 Ω-cm² per cycle.

Things we don’t know yet

- Safe operating voltage. Presumed somewhere between 1.2V (test condition) and 1.46V (thermal neutral).
- Safe CO₂ utilization fraction: We have run up to 60%. Currently running at 30%. General sense is that 50% is probably ok.
Scroll pump

Stationary Scroll Attaches Directly to Housing

Housing

Eccentric

Cam Followers Limit Moving Scroll Movement

Moving Scroll

• Alternatives: Cryogenic, sorption bed
Things we can estimate:
- Reference performance: 79 g/hr for inlet gas P=7.6 Torr, T= 20°C.
- Ambient pressure and temperature modulation: Varies predictably with season, time of day, and to a small extent, weather.
- Pressure drop from ambient to pump inlet: <10% (ignoring dust)

Things we don’t yet know
- Where we will land
- Safe CO₂ utilization factor (tested 30%, probably ok at 50%)
- Heating of gas from outside to pump inlet (so we’ll assume 20°C).

The MOXIE scroll compressor is under development by Air Squared, Inc., Broomfield, CO
Landing site characteristics

* Potential landing site elevations and pressure
  * Planet average: ~4.6 Torr, but not really relevant (see below)
  * Elevation: Varies over many kilometers, dominated by hemispheric dichotomy. Corresponding surface pressure varies by more than x2.

* Likely landing sites
  * Prior to M2020: Lowlands favored for EDL. MSL, Viking < -3.6 km.
  * M2020: Sites considered between -2.6 and -0.6 km
  * Human landing: For EDL reasons, almost certain to be < -3.5 km.

* Types of pressure variation the rover will experience:
  * Seasonal: Up to 30% due to polar deposition of CO₂ (predictable)
  * Diurnal: 5-12% depending on topography (predictable)
  * Weather: A few % typically, up to 12% increase in global dust storms
  * Local topography: Several %, but below resolution of GCM
Example: Viking Pressure Data
What determines production rate?

- MOXIE production rate is a balance of:
  - SOXE capability (up to ~20g/hr O₂)
  - Power supply capability (limits production to 12 g/hr O₂)
  - Landing site (elevation determines inlet gas pressure)
  - Pump capability (for candidate landing sites, <10 g/hr O₂)
  - Safe operating margins (what fraction of the CO₂ can we use?)
  - Season and time of day (also determines inlet gas density)

- Demonstration is limited to M2020 capabilities
  - Limited volume, mass for experiment
  - Warm enclosure
  - Extremely limited power, shared with 6 other instruments and rover functions (driving, drilling, survival heating, etc.)
Landing site and season determine pump output

Pump capacity assuming 79 g/hr at 7.6 Torr, 20°C inlet

Max allowed O₂ production (g/hr) vs. Ambient pressure (Torr)

- 50% Utilization
- 30% Utilization

Predicted site *highs*
- (dust storm)

Predicted site *lows*
- (summer night)

Predicted site *highs*
- (fall day)

(Arrows are for VL-2 site)
ASR, available gas and power, determine SOXE Performance

O₂ production in 10-cell stack for 4A current limit, OCV=0.8V

- Current limit
- Fall day (nominal 50% utilization)
- Summer night (50% utilization)

O₂ production (g/hr) vs. ASR (ohm-cm²)

- 1V per cell
- 1.2V per cell
- 1.46V per cell

Current limits:
- 1.20V
- 1.00V
- 1.46V
Filter sensitivity to dust

- MOXIE will ingest ~50 mg dust through a 264 cm² pleated filter, or ~2 g/m².
- Incident velocity $v_0$ typically ~5 cm/s, comparable to Thomas study (right), but particles are typically larger.
- Begin to get in trouble between 1-10 g/m²
- Full-scale MOXIE will ingest ~5 kg dust over 1 year
- Dust storms result in up to x10 deposition.

\[ F = \rho v_0 A \frac{P_1 - P_2}{R} \]

\[ R = \frac{8 \eta L}{\pi r^4} \]

$v_0 = 5 \text{ cm/s}, \ d_p = 0.15 \ \mu \text{m. From D. Thomas et al. (1999) J. Aero. Sci., 30 (2), 235-246.}$
Dust conclusions

* Filters need to have huge surface area if they are not to obstruct flow, and are degraded by a few microns of dust

* The way forward?
  * Filter-less first-stage pumping?
  * Cyclone or electrostatic mitigation?
Considerations in eventual design

× Where do we land? Weigh *perceived* science value against:
  × Ready availability of water ice (i.e. high latitude)
  × Safety/ease of landing (low elevation, maybe low latitude)
  × Surface traverse capability

× Assuming low latitude (no ice)… what limits performance? What infrastructure is available?
  × Human base will likely need nuclear reactor \(\Rightarrow\) plentiful power during ISRU stage
  × Oxygen storage will likely need cryogenics \(\Rightarrow\) may as well use it for other systems, e.g.
    × Parallel, out-of-phase cryogenic CO\(_2\) acquisition instead of pump.
    × Separation of Ar, N\(_2\) for buffer gases in habitat.
    × Further purification of breathable O\(_2\).

× If we land at high latitude, ice would be readily available…
  × Would we want to do CO\(_2\) ISRU at all, or just get O\(_2\) from ice?
Special thanks to the amazing JPL Project Team!

MOXIE Testbed
More MOXIE

Backup slides
Anatomy of MOXIE

Mars atm. → Funnel → Scroll Pump → Compressed CO₂ → SOXE → Vent

Control Electronics

Mars 2020 Project

Jet Propulsion Laboratory
California Institute of Technology

MEDA

Filter
Sensor
VFCD
Cooling

T P RH Wind
**Where does MOXIE power go?**

<table>
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<th>Component</th>
<th>Power (W)</th>
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<td>SOXE current</td>
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<tr>
<td>Pump</td>
<td>110</td>
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<td>Stack heaters (mostly make-up heat)</td>
<td>72</td>
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<tr>
<td>Sensors, incl. panel heating</td>
<td>9</td>
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<tr>
<td>Electronics, mostly DC/DC conversion</td>
<td>67</td>
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</table>

**Total** 320W
What limits $O_2$ production?

1. **Inlet flow**
   - Together with $CO_2$ utilization fraction, determines $O_2$ production
   - Limited by overall pump capability
   - Limited by inlet gas density, which is determined by:
     - Ambient pressure & temperature
     - Pressure drop across filter, including dust

2. **Available power**
   - Safe current limit of 4A
   - Power limit of 35W per supply (not normally a constraint)
   - Circuit limit of 10A (not normally a constraint)
   - Thermal constraints at high power (depends on many factors)

3. **SOXE capability**
   - All the electrochemistry is captured in one empirical number, ASR, and a more-or-less constant number, OCV
   - Scale by area ($22.7 \, cm^2$ and number of cells ($5 \times 2 = 10$)
   - Limited by safe operating voltage and % $CO_2$ utilization, largely TBD

*How do these factors rank in importance?*
Global Climate Model predicts

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<td>5.86</td>
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Notes

* "Dust Storm Max Solar" mode.
** Now at -4292
[a] Added at 2nd workshop
[b] Eliminated after 2nd workshop
[c] Under consideration for science assessment only.

[3] From Mike Mischna
SOXE Development Summary

- Results & Findings:
  - Low ASRs (2-2.5)
  - Stable to heat/cool cycling
  - Oxidation is a bigger challenge than coking
  - SOXE capability exceeds MOXIE resources on Mars

- Still to be studied:
  - Limits on CO₂ utilization, voltage, temperature
  - Long-term performance (>1000 hrs)
SOXE extensibility

★ MOXIE is intended to be ~1% scale model of eventual human-scale system
★ SOXE is readily scalable by increasing # of stacks.
★ Indications are that lifetime is acceptable but more tests needed.
★ May want to cascade stacks to utilize “waste” CO₂
Pump Trades and extensibility

• Trade for MOXIE
  • Scroll pump was found to be the only feasible approach on a small scale that can do real time compression without intermediate storage.

• Trade for full-scale mission
  • Scroll pump can be scaled at least 10-fold, is energy-efficient, and lifetime should be adequate.
  • Cryogenic options may be more favorable if cryogenic subsystem is used for O₂ storage. Energy may not be a factor.
## Benefits of ISRU propellant

<table>
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<tr>
<th>ELEMENT</th>
<th>DRM-1 (mT)</th>
<th>DRM-3 (mT)</th>
<th>COMMENT</th>
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<td>Ascent capsule</td>
<td>4</td>
<td>6</td>
<td>Includes crew of 6</td>
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<tr>
<td>Ascent propulsion stage</td>
<td>3</td>
<td>5</td>
<td>Typically 15% of propellant requirement</td>
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<tr>
<td>Propellant (CH4 + O2)</td>
<td>26</td>
<td>39</td>
<td></td>
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<tr>
<td>Mass saved in LEO if ISRU produces CH4 + O2</td>
<td>300 -500</td>
<td>440-800</td>
<td>Depends on assumptions re: aerocapture/propulsion</td>
</tr>
<tr>
<td>Mass saved in LEO if ISRU produces only O2</td>
<td>230-380</td>
<td>330-620</td>
<td>Depends on assumptions re: aerocapture/propulsion</td>
</tr>
</tbody>
</table>