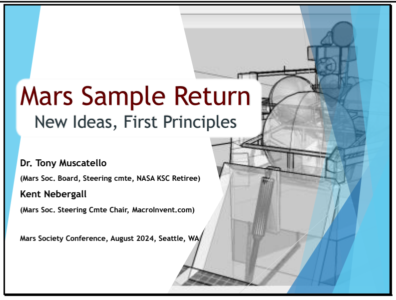
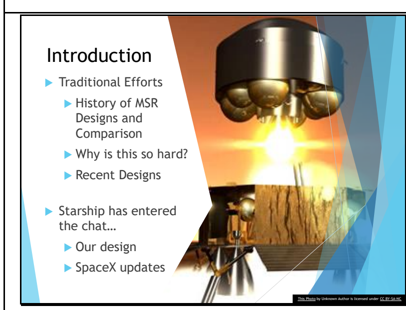
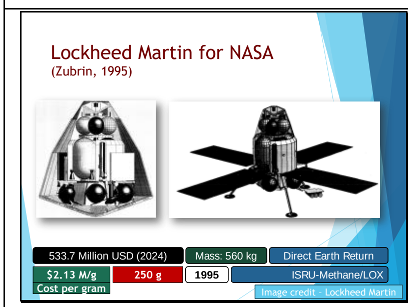
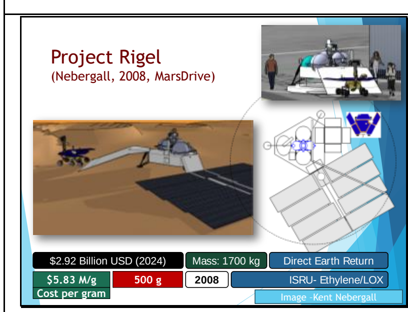


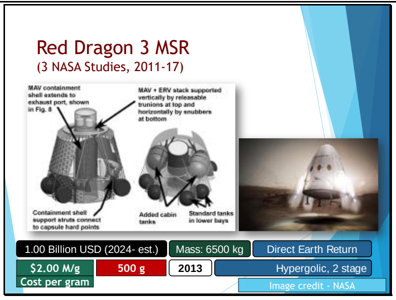
Hi everyone.

Hidden slide- reference only.

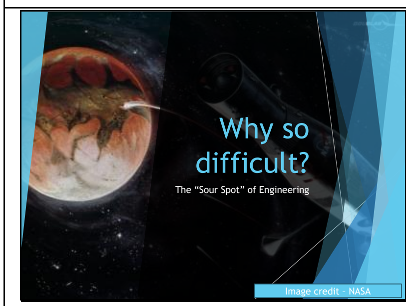


Let's begin with Mars Sample return design history, why it's been so hard so far, and our current concepts. Finally, I'll show Tony and I's concept for a Starship-based MSR mission.

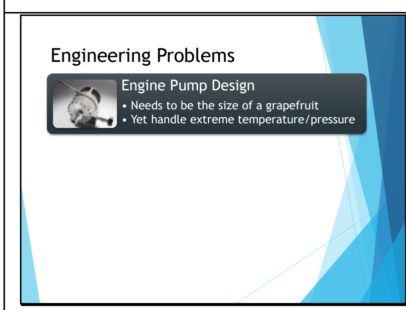
<table>
<tr>
<td>
</td>
<td>NASA started working on Mars Sample Return concepts in 1969. This was part of a human Venus-Mars Flyby mission design by Warner Von Braun. That's the medium-sized capsule with the yellow arrow in this image. After that, NASA discussed minimalist concepts with a tiny solid rocket and a very basic sample retrieval arm.</td>
</tr>
<tr>
<td>
</td>
<td>Here is one of Robert Zubrin's first Mars Sample Return designs with Lockheed Martin from 1995. This is from a 100-page analysis he did back then. This design is so old that the entry capsule on the left is Russian, and the rover is a Sojourner clone. Note that I'm putting a data comparison dashboard on the bottom of these slides with inflation-adjusted amounts, but many of those are estimated toward the end based on budgets for previous missions.</td>
</tr>
<tr>
<td>
</td>
<td>In 2008, I won a competition to design a Sample Return mission that needed to use In situ propellant production. I took a lot of inspiration from Zubrin's designs and current NASA projects to save engineering overhead.
I used a Curiosity type aeroshell around a Viking-like lander with a Spirit type sample rover.</td>
</tr>
</table>



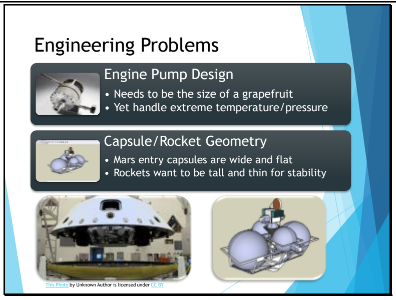
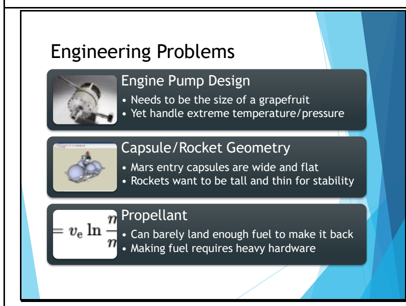
In the 2010's, three different NASA studies examined if a SpaceX Dragon capsule could land on Mars. The last of these efforts was a sample return concept. Tony was one of the NASA authors at the time.
Note the launch tube in the core of the capsule. I'm going to borrow this later.

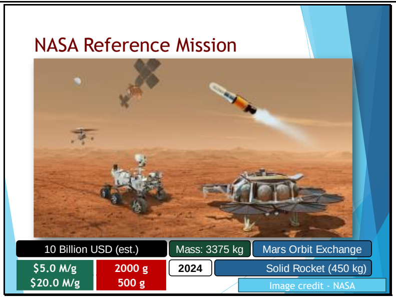
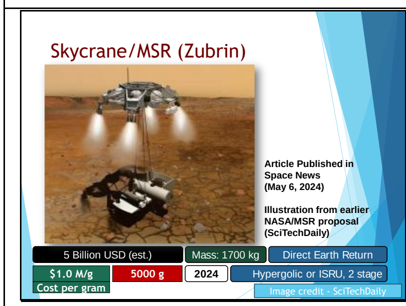
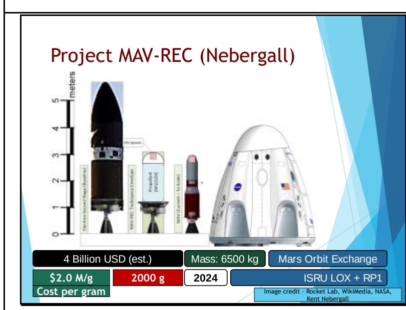


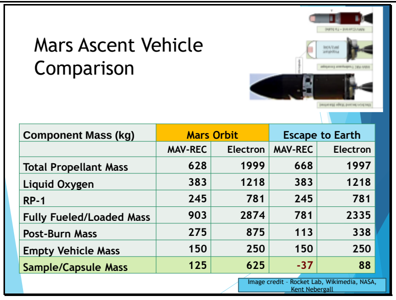
Which brings us to the current day. Over fifty years from the start… So why hasn't NASA done it yet? Regarding sample return, I used to say if we can't return a kilogram, we can't return a crew. But as it turns out, it's extremely difficult to return just a kilogram. When it comes to scaling, it's a sour spot of engineering. It's like cooking one French fry.



First, small rockets need small parts. If you make propellant on Mars, it's almost impossible to build a traditional cryogenic rocket pump the size of a grapefruit. The pressures, temperature differences, and tolerances would make it unreliable even if you could build one. Like running a watch on jet fuel, with half the watch cryogenically frozen. The metal needs to be thick enough to handle the pressures involved.

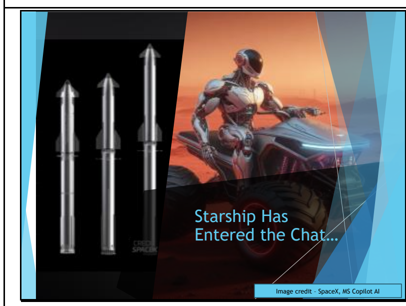
	Second, Mars probes have very flat landing capsules like flying saucers due to the thin atmosphere. This allows the lander to slow down enough to open the parachutes prior to hitting the ground. Ascent rockets for the samples, on the other hand, want to be long and skinny for stability reasons. Too short, and the rocket wants to tumble. So, you land a stable rocket horizontally, but raise it vertically. This adds complexity to the launcher. Or you launch a chonky rocket with a very agile guidance system to keep it from tumbling.
	Third, the ascent vehicle needs so MUCH propellant that sending all the fuel from earth dramatically limits your sample payload. But it also needs so LITTLE propellant that setting up a solar array and In Situ Propellant Production plant weighs almost as much as the fuel. If you build redundancy into the prototype fuel production plant, you get into engineering complexity which adds to cost and mass.
	Ironically, the fact that it SEEMS like it should be easy just makes it worse. Designers who start with systems that barely work on paper hit a wall late in the design process. They either make a breakthrough or cancel the project.

<table>
<tr>
<td>
</td>
<td>This is NASA's current design. It costs $10 billion and wouldn't return samples until 2045 – a situation that even NASA's administrator couldn't accept. I guess nineteen more years is a bit much. Seventy-six years is a long time for NASA to plan "the next step". This is less xenobiology and more Zeno's paradox.
So, NASA asked for proposals this past Summer to simplify it. They recently chose seven contractors and three NASA centers to make suggestions. We'll know by the end of the year which concepts from the ten proposals will be cherry picked so they can go on to the next stage.</td>
</tr>
<tr>
<td>
</td>
<td>Recently, Robert Zubrin wrote an editorial that suggested using a sky crane to land a sample return vehicle. He proposed both storable and in situ propellant production versions. I'm estimating $5 billion based on the missions this is based on, but it's a fifth the cost per gram as the NASA baseline. This picture is actually an older NASA concept that also used Sky crane.</td>
</tr>
<tr>
<td>
</td>
<td>I also wondered if NASA couldn't kit-bash a vehicle from off the shelf parts and came up with this. I revived Red Dragon a fourth time but build an ascent rocket based on Electron's second stage. Its fuel pumps are electric, so we avoid the miniaturization problem. We can just barely make an ascent vehicle with enough propellant to match the NASA design, if you make your oxygen using solar power on the surface. Or you can use NASA's solid rocket but without the split-second air launch. It would fit the core tube just fine.</td>
</tr>
</table>



Component Mass (kg)	Mars Orbit		Escape to Earth	
	MAV-REC	Electron	MAV-REC	Electron
Total Propellant Mass	628	1999	668	1997
Liquid Oxygen	383	1218	383	1218
RP-1	245	781	245	781
Fully Fueled/Loaded Mass	903	2874	781	2335
Post-Burn Mass	275	875	113	338
Empty Vehicle Mass	150	250	150	250
Sample/Capsule Mass	125	625	-37	88

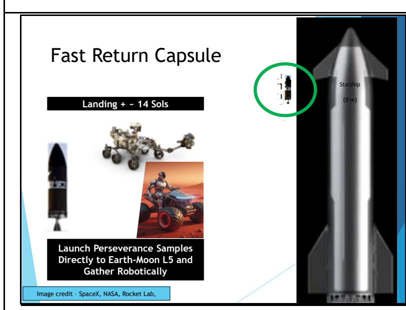
The Electron uses RP-1 for fuel, so you only have to make the oxygen. Here is a table comparing the designs, propellant needs, and sample return masses to both Mars orbit and direct flight to Earth. My baby Electron version can get 125 kg capsule to orbit but can't get back to Earth. If you could get a full-sized Electron second stage to Mars, it would be able to launch 625 kg to orbit or 88 kg to Earth proximity, assuming a 250-kg vehicle carrying it.



When NASA awarded the seven Mars Sample Return study contracts, one is for SpaceX and Starship. So we can get past all these scaling issues that have dogged us for over half a century.

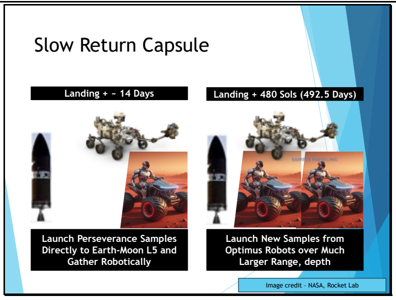
The difference between everything we've seen so far and Starship is literally the difference between a Maxi Van and a Boeing 747.

The cargo volume of Starship is 1000 cubic meters, which is the same as a 747 or the entire International Space Station.

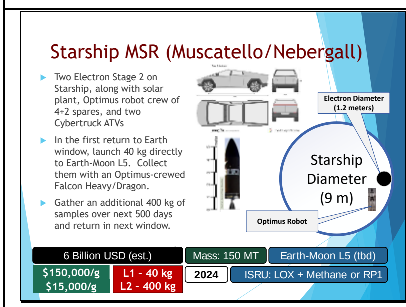


We can send two full-sized, fully fueled Electrons on a single Starship. That green circle is the Electron second stage to scale with Starship V2.

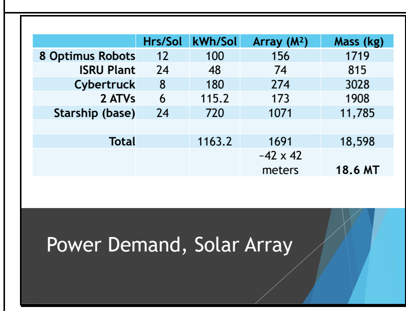
By the time this is sent to Mars, the Tesla Optimus humanoid robot will be in production. So send a couple robots to gather all the sample tubes and replenish the rover with new sample tubes before sending it on its way. That ascent rocket can be sent to orbit to meet the European orbiter from the ESA/NASA design if that's politically required. Or, it can bring the samples all the way back to a near-earth trailing orbit to allow either the ESA or SpaceX to collect them there for planetary protection. In that case, we get the samples to Earth in the very next launch window.



Meanwhile on Mars, the Starship is just getting started. It can send ATVs with Optimus robots to do additional research or a full CyberTruck if appropriate. If the truck bed carried a deployable solar array, this expedition crew of humanoid robots would gather samples across hundreds of kilometers for the next 480 days. As noted, each Electron can deliver 88 kg to Earth or 625 kg to Mars orbit. For comparison, all the Apollo missions combined gathered 382 kilograms of lunar samples across six landings. So, we can do roughly three Apollo missions worth of sample return direct to Earth or Earth proximity.

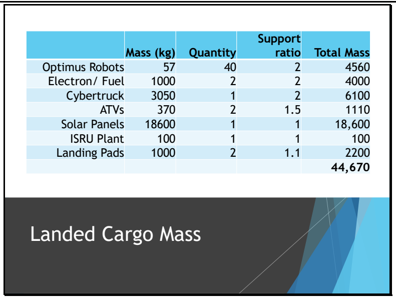


The full Electron second stage fits in a corner of one deck of the Starship payload bay. That box next to it is a picture of the Tesla Optimus humanoid robot. So the “crew” could be forty Optimus robots, with an average of twelve active on a given day. A CyberTruck and two ATVs could handle long range transport. We would set up a solar plant to charge the bots and equipment. We can use leftover oxygen from the landing tanks and make more on site to handle losses en route for the Electrons. We also want to make simple landing pads for the next Starship test flights.



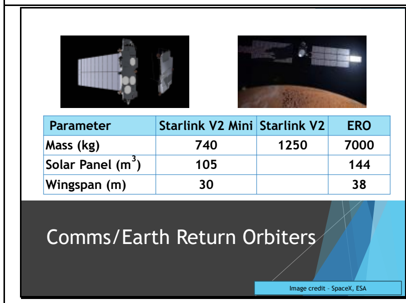
	Hrs/Sol	kWh/Sol	Array (M^2)	Mass (kg)
8 Optimus Robots	12	100	156	1719
ISRU Plant	24	48	74	815
Cybertruck	8	180	274	3028
2 ATVs	6	115.2	173	1908
Starship (base)	24	720	1071	11,785
Total		1163.2	1691	18,598
			~42 x 42 meters	18.6 MT

The power demands are sliced by hours per day when each system is active. For that, we get a solar array of under 19 tonnes, or almost half our payload. This array covers an area of 42 by 42 meters, because of course it does. Power demand for the Starship is assumed to be 30 percent that of the ISS, separate from the robots and vehicles.
The solar array big enough to road trip CyberTruck with four androids would fit mass-wise in the truck bed. Assuming two days of charging and exploring per one day of driving, you have unlimited range.



	Mass (kg)	Quantity	Support ratio	Total Mass
Optimus Robots	57	40	2	4560
Electron/ Fuel	1000	2	2	4000
Cybertruck	3050	1	2	6100
ATVs	370	2	1.5	1110
Solar Panels	18600	1	1	18,600
ISRU Plant	100	1	1	100
Landing Pads	1000	2	1.1	2200
				44,670

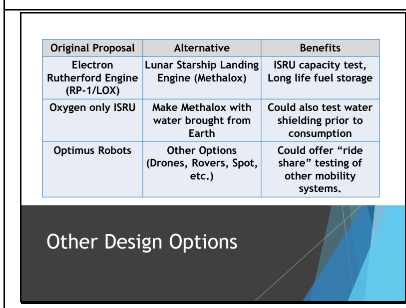
So with this wish-list of cargo we still have less than half the cargo weight capacity of Starship. And practically all if it will be commodity hardware by then, easily replicable.



Parameter	Starlink V2 Mini	Starlink V2	ERO
Mass (kg)	740	1250	7000
Solar Panel (m^3)	105		144
Wingspan (m)	30		38

While sending 400 kg to Mars orbit is tempting, the problem is getting it back from there. The current design uses a European vehicle that is a bit larger than Starlink V2 but MUCH heavier. There's a lot of room for trade studies here between sample size, transfer orbit types, and ease of return.

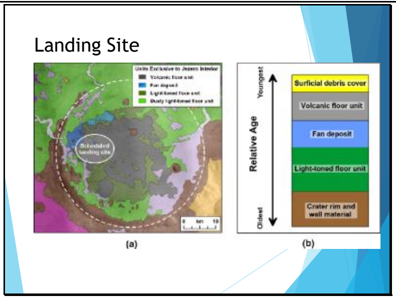
That said, we could send a LOT of Starlink satellites into Mars Orbit from a second Starship. Starlink satellites can not only provide global high-speed communications and laser links with Earth. They can also carry small telescopes to see car sized objects on Mars and remap the planet EVERY DAY at that resolution.



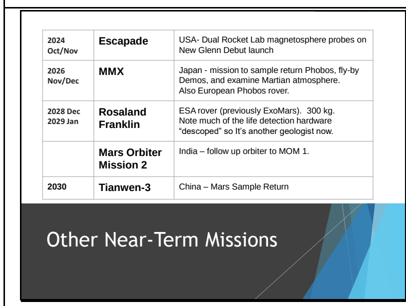
Original Proposal	Alternative	Benefits
Electron Rutherford Engine (RP-1/LOX)	Lunar Starship Landing Engine (Methalox)	ISRU capacity test, Long life fuel storage
Oxygen only ISRU	Make Methalox with water brought from Earth	Could also test water shielding prior to consumption
Optimus Robots	Other Options (Drones, Rovers, Spot, etc.)	Could offer "ride share" testing of other mobility systems.

So with unlimited possibilities, what other options are there? We could do an all SpaceX design by repurposing one of the Lunar Starship descent engines in place of the Rocket Lab Rutherford engine. I'm not sure of the capacity for this engine because it's not released yet, but I would be methane and oxygen, so a valid Mars Direct prototype for propellant production.

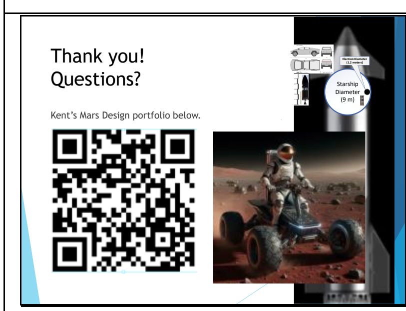
If finding water or ice is a problem, just bring it from earth as ballast and use it for radiation shielding experiments before converting it to rocket fuel. Use leftover landing propellant to send the two-week early return capsule back first. Conversely, if we want to rent space to other robot manufacturers, we could see a SPOT type robot, NASA drones, and so on also exploring the crater.



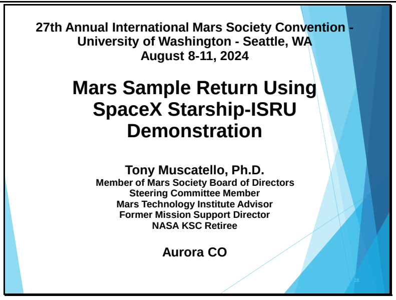
With something as big as Starship, we need to review the landing site. The Jezero crater was studied extensively prior to Perseverance as a landing site. Perseverance itself has studied it in greater detail than any other site on Mars. So the volcanic floor unit should have a good spot for Starship landing. I fact, it would be the most validated place on Mars for such a landing.

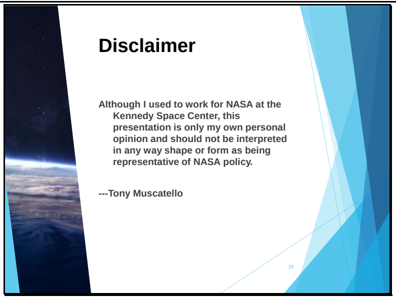


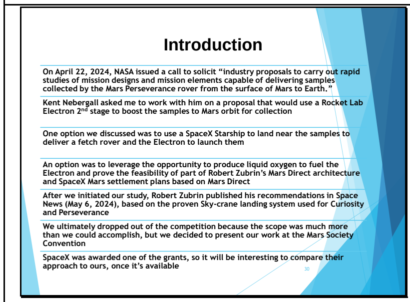
For context, these are all the Mars missions planned over the next six years. Without sample return, the US is barely doing anything. Most are coming out of Japan, China, Europe, and India. China also has a sample return mission planned for 2030, which involves a lander and an orbiter. It’s unclear how much they would bring back or from where, but it appears to be a simple one like the lunar sample returns.

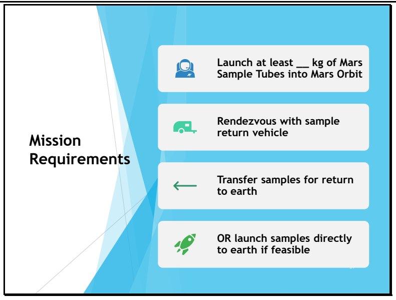


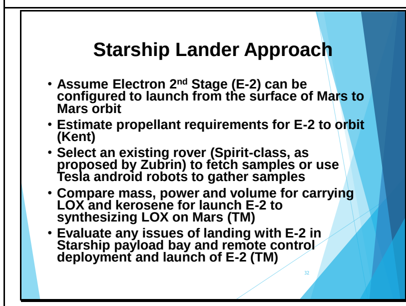
Thank you.

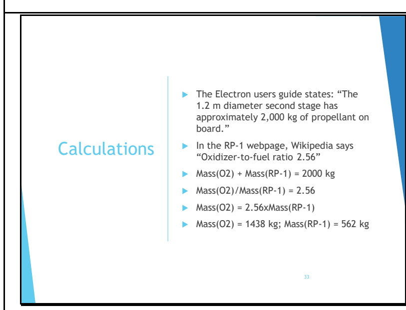

27th Annual International Mars Society Convention - University of Washington - Seattle, WA
August 8-11, 2024
Mars Sample Return Using SpaceX Starship-ISRU Demonstration
Tony Muscatello, Ph.D.
Member of Mars Society Board of Directors
Steering Committee Member
Mars Technology Institute Advisor
Former Mission Support Director
NASA KSC Retiree
Aurora CO

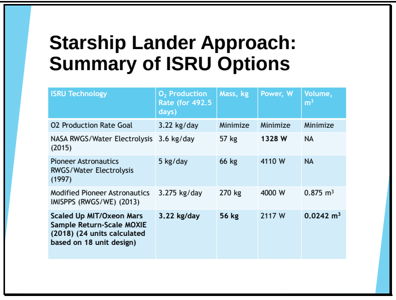

Disclaimer
Although I used to work for NASA at the Kennedy Space Center, this presentation is only my own personal opinion and should not be interpreted in any way shape or form as being representative of NASA policy.
---Tony Muscatello


Introduction
On April 22, 2024, NASA issued a call to solicit "industry proposals to carry out rapid studies of mission designs and mission elements capable of delivering samples collected by the Mars Perseverance rover from the surface of Mars to Earth."
Kent Nebergall asked me to work with him on a proposal that would use a Rocket Lab Electron 2nd stage to boost the samples to Mars orbit for collection
One option we discussed was to use a SpaceX Starship to land near the samples to deliver a fetch rover and the Electron to launch them
An option was to leverage the opportunity to produce liquid oxygen to fuel the Electron and prove the feasibility of part of Robert Zubrin's Mars Direct architecture and SpaceX Mars settlement plans based on Mars Direct
After we initiated our study, Robert Zubrin published his recommendations in Space News (May 6, 2024), based on the proven Sky-crane landing system used for Curiosity and Perseverance
We ultimately dropped out of the competition because the scope was much more than we could accomplish, but we decided to present our work at the Mars Society Convention
SpaceX was awarded one of the grants, so it will be interesting to compare their approach to ours, once it's available
30


Mission Requirements
Launch at least __ kg of Mars Sample Tubes into Mars Orbit
Rendezvous with sample return vehicle
Transfer samples for return to earth
OR launch samples directly to earth if feasible

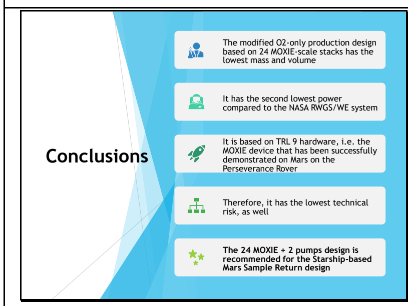

Starship Lander Approach
• Assume Electron 2nd Stage (E-2) can be configured to launch from the surface of Mars to Mars orbit
• Estimate propellant requirements for E-2 to orbit (Kent)
• Select an existing rover (Spirit-class, as proposed by Zubrin) to fetch samples or use Tesla android robots to gather samples
• Compare mass, power and volume for carrying LOX and kerosene for launch E-2 to synthesizing LOX on Mars (TM)
• Evaluate any issues of landing with E-2 in Starship payload bay and remote control deployment and launch of E-2 (TM)

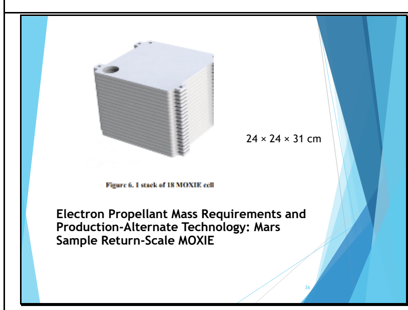

Calculations
The Electron users guide states: "The 1.2 m diameter second stage has approximately 2,000 kg of propellant on board."
In the RP-1 webpage, Wikipedia says "Oxidizer-to-fuel ratio 2.56"
Mass(O2) + Mass(RP-1) = 2000 kg
Mass(O2)/Mass(RP-1) = 2.56
Mass(O2) = 2.56xMass(RP-1)
Mass(O2) = 1438 kg; Mass(RP-1) = 562 kg



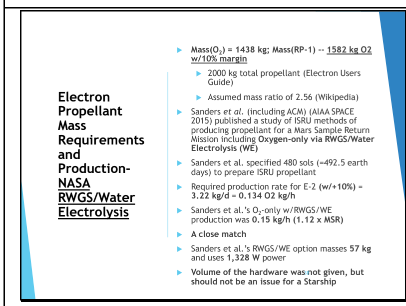
Starship Lander Approach: Summary of ISRU Options

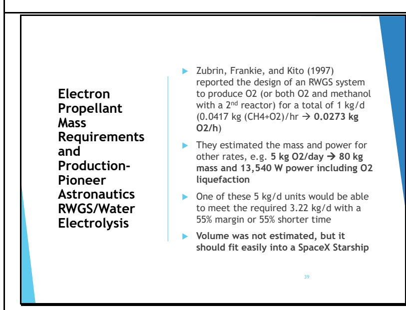
ISRU Technology	O_2 Production Rate (for 492.5 days)	Mass, kg	Power, W	Volume, m^3
O2 Production Rate Goal	3.22 kg/day	Minimize	Minimize	Minimize
NASA RWGS/Water Electrolysis (2015)	3.6 kg/day	57 kg	**1328 W**	NA
Pioneer Astronautics RWGS/Water Electrolysis (1997)	5 kg/day	66 kg	4110 W	NA
Modified Pioneer Astronautics IMISPPS (RWGS/WE) (2013)	3.275 kg/day	270 kg	4000 W	0.875 m^3
Scaled Up MIT/Oxeon Mars Sample Return-Scale MOXIE (2018) (24 units calculated based on 18 unit design)	**3.22 kg/day**	**56 kg**	2117 W	**0.0242 m^3**

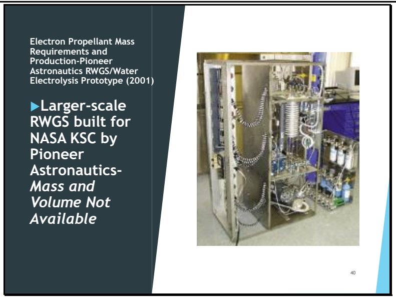


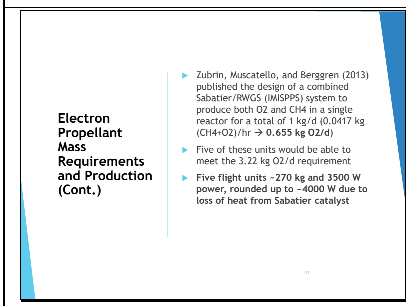


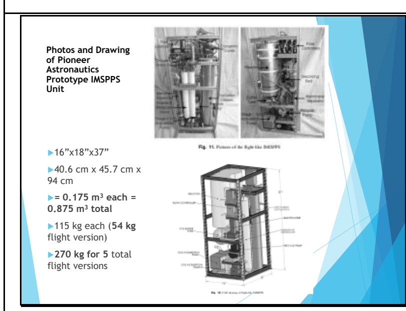

Supporting
Information Slides
37

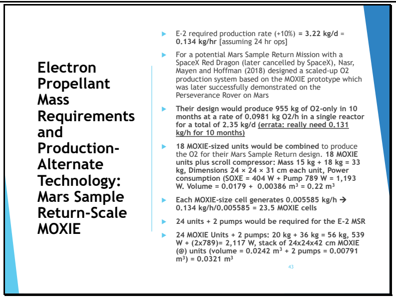

Electron Propellant Mass Requirements and Production- NASA RWGS/Water Electrolysis
Mass(O2) = 1438 kg; Mass(RP-1) -- 1582 kg O2 w/10% margin
2000 kg total propellant (Electron Users Guide)
Assumed mass ratio of 2.56 (Wikipedia)
Sanders et al. (including ACM) (AIAA SPACE 2015) published a study of ISRU methods of producing propellant for a Mars Sample Return Mission including Oxygen-only via RWGS/Water Electrolysis (WE)
Sanders et al. specified 480 sols (=492.5 earth days) to prepare ISRU propellant
Required production rate for E-2 (w/+10%) = 3.22 kg/d = 0.134 O2 kg/h
Sanders et al.'s O2-only w/RWGS/WE production was 0.15 kg/h (1.12 x MSR)
A close match
Sanders et al.'s RWGS/WE option masses 57 kg and uses 1,328 W power
Volume of the hardware was not given, but should not be an issue for a Starship

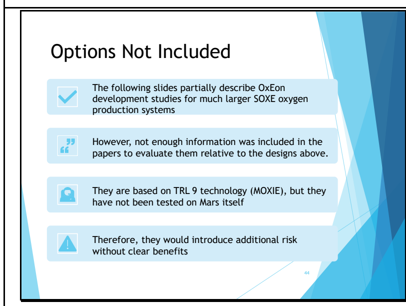

Electron Propellant Mass Requirements and Production- Pioneer Astronautics RWGS/Water Electrolysis
Zubrin, Frankie, and Kito (1997) reported the design of an RWGS system to produce O2 (or both O2 and methanol with a 2nd reactor) for a total of 1 kg/d (0.0417 kg (CH4+O2)/hr → 0.0273 kg O2/h)
They estimated the mass and power for other rates, e.g. 5 kg O2/day → 80 kg mass and 13,540 W power including O2 liquefaction
One of these 5 kg/d units would be able to meet the required 3.22 kg/d with a 55% margin or 55% shorter time
Volume was not estimated, but it should fit easily into a SpaceX Starship
39


Electron Propellant Mass Requirements and Production-Pioneer Astronautics RWGS/Water Electrolysis Prototype (2001)
Larger-scale RWGS built for NASA KSC by Pioneer Astronautics- Mass and Volume Not Available
40


Electron Propellant Mass Requirements and Production (Cont.)
Zubrin, Muscatello, and Berggren (2013) published the design of a combined Sabatier/RWGS (IMISPPS) system to produce both O2 and CH4 in a single reactor for a total of 1 kg/d (0.0417 kg (CH4+O2)/hr → 0.655 kg O2/d)
Five of these units would be able to meet the 3.22 kg O2/d requirement
Five flight units ~270 kg and 3500 W power, rounded up to ~4000 W due to loss of heat from Sabatier catalyst
41


Photos and Drawing of Pioneer Astronautics Prototype IMSPPS Unit
16"x18"x37"
40.6 cm x 45.7 cm x 94 cm
= 0.175 m³ each = 0.875 m³ total
115 kg each (54 kg flight version)
270 kg for 5 total flight versions


Electron Propellant Mass Requirements and Production- Alternate Technology: Mars Sample Return-Scale MOXIE
E-2 required production rate (+10%) = 3.22 kg/d = 0.134 kg/hr [assuming 24 hr ops]
For a potential Mars Sample Return Mission with a SpaceX Red Dragon (later cancelled by SpaceX), Nasr, Mayen and Hoffman (2018) designed a scaled-up O2 production system based on the MOXIE prototype which was later successfully demonstrated on the Perseverance Rover on Mars
Their design would produce 955 kg of O2-only in 10 months at a rate of 0.0981 kg O2/h in a single reactor for a total of 2.35 kg/d (errata: really need 0.131 kg/h for 10 months)
18 MOXIE-sized units would be combined to produce the O2 for their Mars Sample Return design. 18 MOXIE units plus scroll compressor: Mass 15 kg + 18 kg = 33 kg, Dimensions 24 × 24 × 31 cm each unit, Power consumption (SOXE = 404 W + Pump 789 W = 1,193 W. Volume = 0.0179 + 0.00386 m³ = 0.22 m³
Each MOXIE-size cell generates 0.005585 kg/h → 0.134 kg/h/0.005585 = 23.5 MOXIE cells
24 units + 2 pumps would be required for the E-2 MSR
24 MOXIE Units + 2 pumps: 20 kg + 36 kg = 56 kg, 539 W + (2x789)= 2,117 W, stack of 24x24x42 cm MOXIE (@) units (volume = 0.0242 m³ + 2 pumps = 0.00791 m³) = 0.0321 m³
43


Options Not Included
The following slides partially describe OxEon development studies for much larger SOXE oxygen production systems
However, not enough information was included in the papers to evaluate them relative to the designs above.
They are based on TRL 9 technology (MOXIE), but they have not been tested on Mars itself
Therefore, they would introduce additional risk without clear benefits

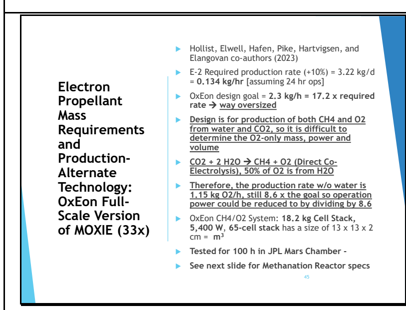
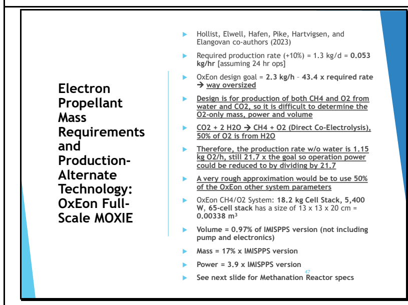
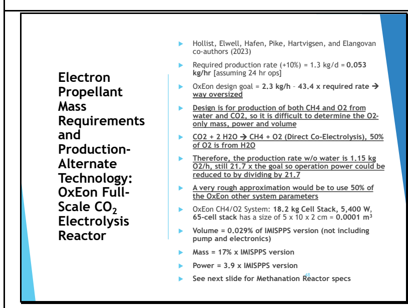
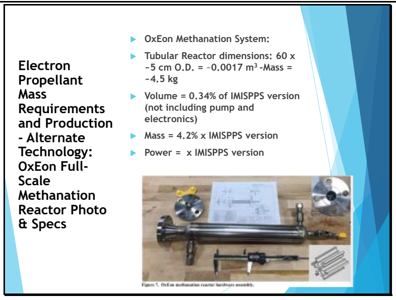
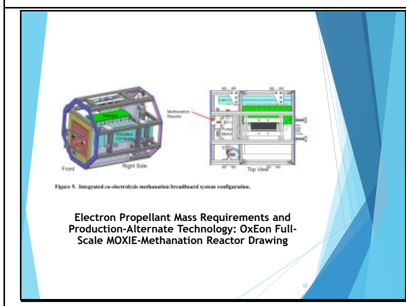

Electron Propellant Mass Requirements and Production- Alternate Technology: OxEon Full-Scale Version of MOXIE (33x)
Hollist, Elwell, Hafen, Pike, Hartvigsen, and Elangovan co-authors (2023)
E-2 Required production rate (+10%) = 3.22 kg/d = 0.134 kg/hr [assuming 24 hr ops]
OxEon design goal = 2.3 kg/h = 17.2 x required rate → way oversized
Design is for production of both CH4 and O2 from water and CO2, so it is difficult to determine the O2-only mass, power and volume
CO2 + 2 H2O → CH4 + O2 (Direct Co-Electrolysis), 50% of O2 is from H2O
Therefore, the production rate w/o water is 1.15 kg O2/h, still 8.6 x the goal so operation power could be reduced to by dividing by 8.6
OxEon CH4/O2 System: 18.2 kg Cell Stack, 5,400 W, 65-cell stack has a size of 13 x 13 x 2 cm = m³
Tested for 100 h in JPL Mars Chamber -
See next slide for Methanation Reactor specs
45

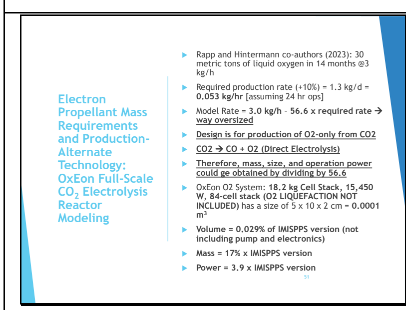

Figure 5. ISRU design variant 65-Cell SOXE, internally manifolded with sealed perimeter.
Figure 6. Size comparison of SOXE stacks from MOXIE and NextSTEP projects.
Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale MOXIE - Photos
46

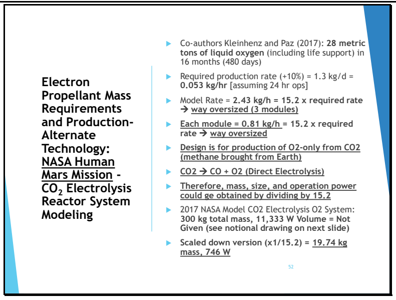

Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale MOXIE
Hollist, Elwell, Hafen, Pike, Hartvigsen, and Elangovan co-authors (2023)
Required production rate (+10%) = 1.3 kg/d = 0.053 kg/hr [assuming 24 hr ops]
OxEon design goal = 2.3 kg/h - 43.4 x required rate → way oversized
Design is for production of both CH4 and O2 from water and CO2, so it is difficult to determine the O2-only mass, power and volume
CO2 + 2 H2O → CH4 + O2 (Direct Co-Electrolysis), 50% of O2 is from H2O
Therefore, the production rate w/o water is 1.15 kg O2/h, still 21.7 x the goal so operation power could be reduced to by dividing by 21.7
A very rough approximation would be to use 50% of the OxEon other system parameters
OxEon CH4/O2 System: 18.2 kg Cell Stack, 5,400 W, 65-cell stack has a size of 13 x 13 x 20 cm = 0.00338 m3
Volume = 0.97% of IMISPPS version (not including pump and electronics)
Mass = 17% x IMISPPS version
Power = 3.9 x IMISPPS version
See next slide for Methanation Reactor specs
47


Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale CO2 Electrolysis Reactor
Hollist, Elwell, Hafen, Pike, Hartvigsen, and Elangovan co-authors (2023)
Required production rate (+10%) = 1.3 kg/d = 0.053 kg/hr [assuming 24 hr ops]
OxEon design goal = 2.3 kg/h - 43.4 x required rate → way oversized
Design is for production of both CH4 and O2 from water and CO2, so it is difficult to determine the O2-only mass, power and volume
CO2 + 2 H2O → CH4 + O2 (Direct Co-Electrolysis), 50% of O2 is from H2O
Therefore, the production rate w/o water is 1.15 kg O2/h, still 21.7 x the goal so operation power could be reduced to by dividing by 21.7
A very rough approximation would be to use 50% of the OxEon other system parameters
OxEon CH4/O2 System: 18.2 kg Cell Stack, 5,400 W, 65-cell stack has a size of 5 x 10 x 2 cm = 0.0001 m3
Volume = 0.029% of IMISPPS version (not including pump and electronics)
Mass = 17% x IMISPPS version
Power = 3.9 x IMISPPS version
See next slide for Methanation Reactor specs
48


Electron Propellant Mass Requirements and Production - Alternate Technology: OxEon Full-Scale Methanation Reactor Photo & Specs
OxEon Methanation System:
Tubular Reactor dimensions: 60 x ~5 cm O.D. = ~0.0017 m³ -Mass = ~4.5 kg
Volume = 0.34% of IMISPPS version (not including pump and electronics)
Mass = 4.2% x IMISPPS version
Power = x IMISPPS version


Front
Right Side
Top View
Figure 9. Integrated co-electrolysis methanation breadboard system configuration.
Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale MOXIE-Methanation Reactor Drawing
50


Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale CO2 Electrolysis Reactor Modeling
Rapp and Hintermann co-authors (2023): 30 metric tons of liquid oxygen in 14 months @3 kg/h
Required production rate (+10%) = 1.3 kg/d = 0.053 kg/hr [assuming 24 hr ops]
Model Rate = 3.0 kg/h - 56.6 x required rate → way oversized
Design is for production of O2-only from CO2
CO2 → CO + O2 (Direct Electrolysis)
Therefore, mass, size, and operation power could ge obtained by dividing by 56.6
OxEon O2 System: 18.2 kg Cell Stack, 15,450 W, 84-cell stack (O2 LIQUEFACTION NOT INCLUDED) has a size of 5 x 10 x 2 cm = 0.0001 m³
Volume = 0.029% of IMISPPS version (not including pump and electronics)
Mass = 17% x IMISPPS version
Power = 3.9 x IMISPPS version
51


Electron Propellant Mass Requirements and Production-Alternate Technology: NASA Human Mars Mission - CO_2 Electrolysis Reactor System Modeling
Co-authors Kleinhenz and Paz (2017): 28 metric tons of liquid oxygen (including life support) in 16 months (480 days)
Required production rate (+10%) = 1.3 kg/d = 0.053 kg/hr [assuming 24 hr ops]
Model Rate = 2.43 kg/h = 15.2 x required rate → way oversized (3 modules)
Each module = 0.81 kg/h = 15.2 x required rate → way oversized
Design is for production of O2-only from CO2 (methane brought from Earth)
CO2 → CO + O2 (Direct Electrolysis)
Therefore, mass, size, and operation power could ge obtained by dividing by 15.2
2017 NASA Model CO2 Electrolysis O2 System: 300 kg total mass, 11,333 W Volume = Not Given (see notional drawing on next slide)
Scaled down version (x1/15.2) = 19.74 kg mass, 746 W
52

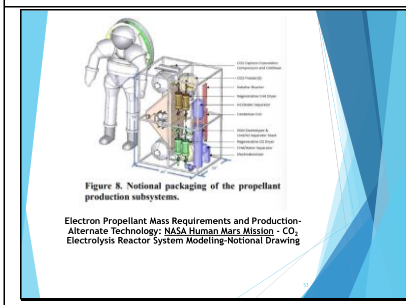


Figure 8. Notional packaging of the propellant production subsystems.
Electron Propellant Mass Requirements and Production-Alternate Technology: NASA Human Mars Mission - CO_2 Electrolysis Reactor System Modeling-Notional Drawing
53