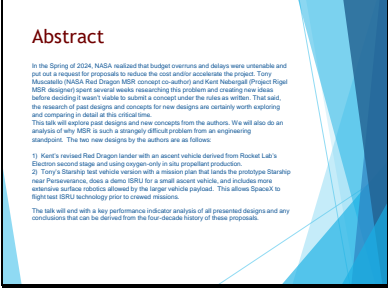
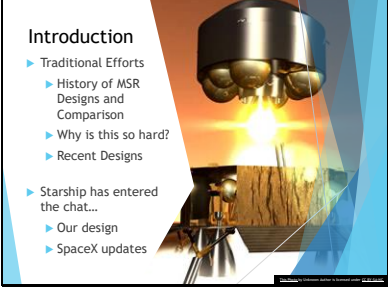
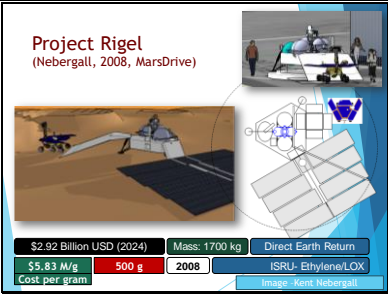
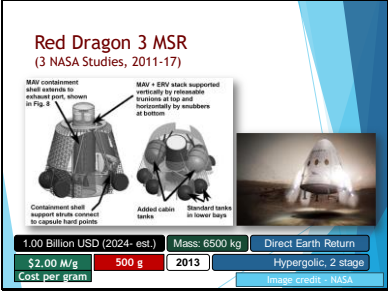
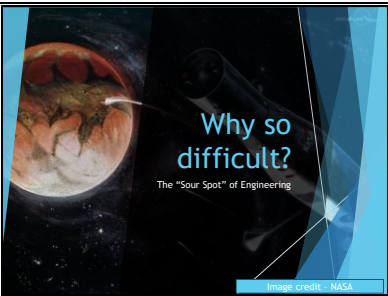
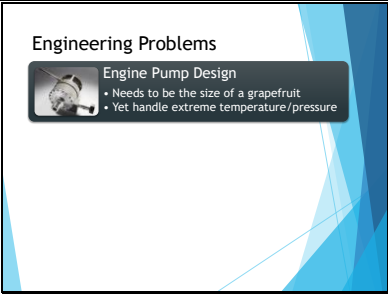
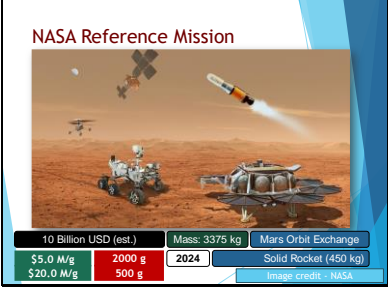
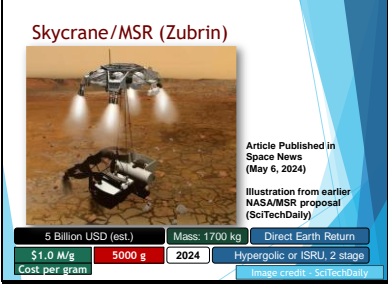
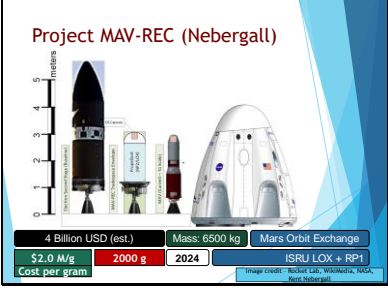

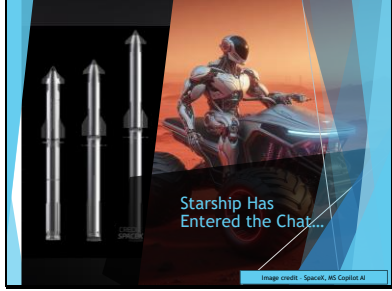
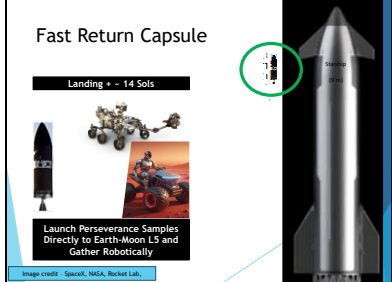
 <p>Mars Sample Return New Ideas, First Principles</p> <p>Dr. Tony Muscatello (Mars Soc. Board, Steering Cmte, NASA KSC Retiree) Kent Nebergall (Mars Soc. Steering Cmte Chair, MacroVent.com)</p> <p>Mars Society Conference, August 2024, Seattle, WA</p>	<p>Hi everyone.</p>
 <p>Abstract</p> <p>In the Spring of 2024, NASA realized that budget overruns and delays were untenable and put out a request for proposals to reduce the cost and/or accelerate the project. Tony Muscatello (NASA Red Dragon MSR concept co-author) and Kent Nebergall (Project Rigel MSR designer) spent several weeks researching the problem and creating new ideas. Before deciding to submit a concept under the name as written. That said, the research of past designs and concepts for new designs are certainly worth exploring and comparing in detail at this critical time.</p> <p>This talk will explore past designs and new concepts from the authors. We will also do an analysis of why MSR is such a strategically difficult problem from an engineering standpoint. The two new designs by the authors are as follows:</p> <ol style="list-style-type: none">1) Kent's revised Red Dragon lander with an ascent vehicle derived from Rocket Lab's Electron second stage and using oxygen-ethanol in situ propellant production.2) Tony's Starship land vehicle version with a reusable plane that lands the prototype Starship near Perseverance, uses a demo ISRU for a small ascent vehicle, and includes more extensive surface robotics allowed by the larger vehicle payload. This allows SpaceX to flight test ISRU technology prior to crewed missions. <p>The talk will end with a key performance indicator analysis of all presented designs and any conclusions that can be derived from the four-decade history of these proposals.</p>	<p>Hidden slide- reference only.</p>
 <p>Introduction</p> <ul style="list-style-type: none">▶ Traditional Efforts<ul style="list-style-type: none">▶ History of MSR Designs and Comparison▶ Why is this so hard?▶ Recent Designs▶ Starship has entered the chat...<ul style="list-style-type: none">▶ Our design▶ SpaceX updates	<p>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.</p>

 <p>History of MSR Concepts Proposals for Low-Cost Mars Sample Return Missions Image credit: NASA</p>	<p>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.</p>									
 <p>Lockheed Martin for NASA (Zubrin, 1995)</p> <table border="1" data-bbox="219 961 581 1014"> <tr> <td>533.7 Million USD (2024)</td> <td>Mass: 560 kg</td> <td>Direct Earth Return</td> </tr> <tr> <td>\$2.13 M/g</td> <td>250 g</td> <td>1995</td> </tr> <tr> <td>Cost per gram</td> <td></td> <td>ISRU-Methane/LOX</td> </tr> </table> <p>Image credit: Lockheed Martin</p>	533.7 Million USD (2024)	Mass: 560 kg	Direct Earth Return	\$2.13 M/g	250 g	1995	Cost per gram		ISRU-Methane/LOX	<p>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.</p>
533.7 Million USD (2024)	Mass: 560 kg	Direct Earth Return								
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 <p>Project Rigel (Nebergall, 2008, MarsDrive)</p> <table border="1" data-bbox="219 1497 581 1549"> <tr> <td>\$2.92 Billion USD (2024)</td> <td>Mass: 1700 kg</td> <td>Direct Earth Return</td> </tr> <tr> <td>\$5.83 M/g</td> <td>500 g</td> <td>2008</td> </tr> <tr> <td>Cost per gram</td> <td></td> <td>ISRU-Ethylene/LOX</td> </tr> </table> <p>Image: Kent Nebergall</p>	\$2.92 Billion USD (2024)	Mass: 1700 kg	Direct Earth Return	\$5.83 M/g	500 g	2008	Cost per gram		ISRU-Ethylene/LOX	<p>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.</p>
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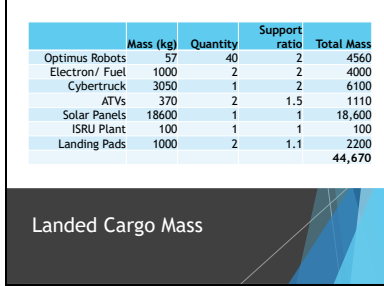
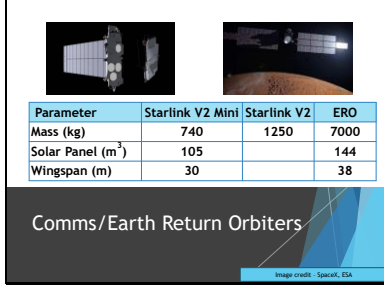
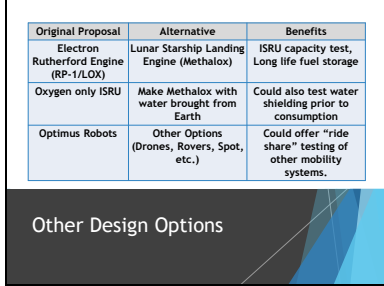
 <p>Red Dragon 3 MSR (3 NASA Studies, 2011-17)</p> <p>MAR containment shell extends to exhaust port, shown in Fig. 8</p> <p>MAR + EVV stack supported vertically by telescopic struts at top and horizontally by struts at bottom</p> <p>Containment shell support struts connect to capsule hand points</p> <p>Add cabin tanks</p> <p>Standard tanks in lower stage</p> <p>1.00 Billion USD (2024- est.) Mass: 6500 kg Direct Earth Return</p> <p>\$2.00 M/g 500 g 2013 Hypergolic, 2 stage</p> <p>Cost per gram</p> <p>Image credit: NASA</p>	<p>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.</p> <p>Note the launch tube in the core of the capsule. I'm going to borrow this later.</p>
 <p>Why so difficult?</p> <p>The "Sour Spot" of Engineering</p> <p>Image credit: NASA</p>	<p>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.</p>
 <p>Engineering Problems</p> <p>Engine Pump Design</p> <ul style="list-style-type: none"> Needs to be the size of a grapefruit Yet handle extreme temperature/pressure 	<p>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.</p>

 <p>Engineering Problems</p> <p>Engine Pump Design</p> <ul style="list-style-type: none"> Needs to be the size of a grapefruit Yet handle extreme temperature/pressure <p>Capsule/Rocket Geometry</p> <ul style="list-style-type: none"> Mars entry capsules are wide and flat Rockets want to be tall and thin for stability 	<p>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.</p>
 <p>Engineering Problems</p> <p>Engine Pump Design</p> <ul style="list-style-type: none"> Needs to be the size of a grapefruit Yet handle extreme temperature/pressure <p>Capsule/Rocket Geometry</p> <ul style="list-style-type: none"> Mars entry capsules are wide and flat Rockets want to be tall and thin for stability <p>Propellant</p> $= v_e \ln \frac{m}{n}$ <ul style="list-style-type: none"> Can barely land enough fuel to make it back Making fuel requires heavy hardware 	<p>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.</p> <p>If you build redundancy into the prototype fuel production plant, you get into engineering complexity which adds to cost and mass.</p>
 <p>Current Proposals</p> <p>Mars Sample Return in 2024</p>	<p>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.</p>

 <p>NASA Reference Mission</p> <table border="1"> <tr> <td>10 Billion USD (est.)</td> <td>Mass: 3375 kg</td> <td>Mars Orbit Exchange</td> </tr> <tr> <td>\$5.0 M/g</td> <td>2000 g</td> <td>2024</td> </tr> <tr> <td>\$20.0 M/g</td> <td>500 g</td> <td>Solid Rocket (450 kg)</td> </tr> </table> <p>Image credit: NASA</p>	10 Billion USD (est.)	Mass: 3375 kg	Mars Orbit Exchange	\$5.0 M/g	2000 g	2024	\$20.0 M/g	500 g	Solid Rocket (450 kg)	<p>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.</p> <p>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.</p>
10 Billion USD (est.)	Mass: 3375 kg	Mars Orbit Exchange								
\$5.0 M/g	2000 g	2024								
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 <p>Skycrane/MSR (Zubrin)</p> <p>Article Published in Space News (May 6, 2024) Illustration from earlier NASA/MSR proposal (SciTechDaily)</p> <table border="1"> <tr> <td>5 Billion USD (est.)</td> <td>Mass: 1700 kg</td> <td>Direct Earth Return</td> </tr> <tr> <td>\$1.0 M/g</td> <td>5000 g</td> <td>2024</td> </tr> <tr> <td>Cost per gram</td> <td></td> <td>Hypergolic or ISRU, 2 stage</td> </tr> </table> <p>Image credit: SciTechDaily</p>	5 Billion USD (est.)	Mass: 1700 kg	Direct Earth Return	\$1.0 M/g	5000 g	2024	Cost per gram		Hypergolic or ISRU, 2 stage	<p>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.</p>
5 Billion USD (est.)	Mass: 1700 kg	Direct Earth Return								
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 <p>Project MAV-REC (Nebergall)</p> <table border="1"> <tr> <td>4 Billion USD (est.)</td> <td>Mass: 6500 kg</td> <td>Mars Orbit Exchange</td> </tr> <tr> <td>\$2.0 M/g</td> <td>2000 g</td> <td>2024</td> </tr> <tr> <td>Cost per gram</td> <td></td> <td>ISRU LOX + RP1</td> </tr> </table> <p>Image credit: Rocket Lab, Wikimedia, NASA, Kent Nebergall</p>	4 Billion USD (est.)	Mass: 6500 kg	Mars Orbit Exchange	\$2.0 M/g	2000 g	2024	Cost per gram		ISRU LOX + RP1	<p>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.</p>
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\$2.0 M/g	2000 g	2024								
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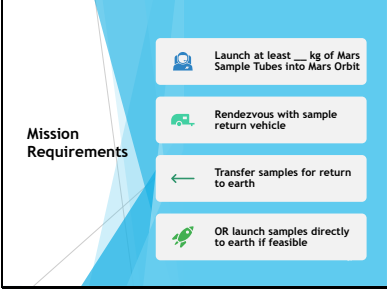
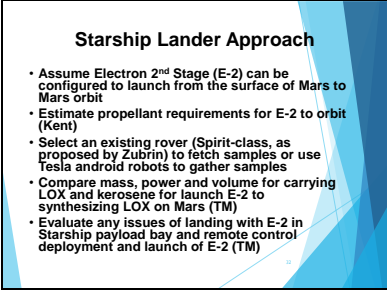
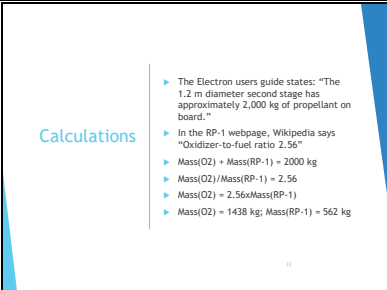
<p>Mars Ascent Vehicle Comparison</p>  <table border="1"> <thead> <tr> <th rowspan="2">Component Mass (kg)</th> <th colspan="2">Mars Orbit</th> <th colspan="2">Escape to Earth</th> </tr> <tr> <th>MAV-REC</th> <th>Electron</th> <th>MAV-REC</th> <th>Electron</th> </tr> </thead> <tbody> <tr> <td>Total Propellant Mass</td> <td>628</td> <td>1999</td> <td>668</td> <td>1997</td> </tr> <tr> <td>Liquid Oxygen</td> <td>383</td> <td>1218</td> <td>383</td> <td>1218</td> </tr> <tr> <td>RP-1</td> <td>245</td> <td>781</td> <td>245</td> <td>781</td> </tr> <tr> <td>Fully Fueled/Loaded Mass</td> <td>903</td> <td>2874</td> <td>781</td> <td>2335</td> </tr> <tr> <td>Post-Burn Mass</td> <td>275</td> <td>875</td> <td>113</td> <td>338</td> </tr> <tr> <td>Empty Vehicle Mass</td> <td>150</td> <td>250</td> <td>150</td> <td>250</td> </tr> <tr> <td>Sample/Capsule Mass</td> <td>125</td> <td>625</td> <td>-37</td> <td>88</td> </tr> </tbody> </table> <p><small>Image credit: Rocket Lab, Wikimédia, NASA, Rick Malvern</small></p>	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	<p>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.</p>
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 <p><small>Image credit: SpaceX, MG Capital AI</small></p>	<p>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.</p>																																												
<p>Fast Return Capsule</p> <p>Landing + ~ 14 Sols</p>  <p>Launch Perseverance Samples Directly to Earth-Moon L5 and Gather Robotically</p> <p><small>Image credit: SpaceX, NASA, Rocket Lab</small></p>	<p>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.</p>																																												

	<p>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.</p>																																			
<ul style="list-style-type: none"> Two Electron Stage 2 on Starship, along with solar plant, Optimus robot crew of 4-2 spares, and two Cybertruck ATVs In the first return to Earth window, launch 40 kg directly to Earth-Moon L5. Collect them with an Optimus-crewed Falcon Heavy/Dragon. Gather an additional 400 kg of samples over next 500 days and return in next window. <p>6 Billion USD (est) Mass: 150 MT Earth-Moon L5 (tbd) \$150,000/g L1 - 40 kg 2024 ISRU: LOX + Methane or RP1 \$15,000/g L2 - 400 kg</p>	<p>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.</p>																																			
<table border="1"> <thead> <tr> <th></th> <th>Hrs/Sol</th> <th>kWh/Sol</th> <th>Array (M²)</th> <th>Mass (kg)</th> </tr> </thead> <tbody> <tr> <td>8 Optimus Robots</td> <td>12</td> <td>100</td> <td>156</td> <td>1719</td> </tr> <tr> <td>ISRU Plant</td> <td>24</td> <td>48</td> <td>74</td> <td>815</td> </tr> <tr> <td>Cybertruck</td> <td>8</td> <td>180</td> <td>274</td> <td>3028</td> </tr> <tr> <td>2 ATVs</td> <td>6</td> <td>115.2</td> <td>173</td> <td>1908</td> </tr> <tr> <td>Starship (base)</td> <td>24</td> <td>720</td> <td>1071</td> <td>11,785</td> </tr> <tr> <td>Total</td> <td></td> <td>1163.2</td> <td>1691 -42 x 42 meters</td> <td>18,598 18.6 MT</td> </tr> </tbody> </table> <p>Power Demand, Solar Array</p>		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 -42 x 42 meters	18,598 18.6 MT	<p>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.</p>
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<p>Landing Site</p>	<p>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. In fact, it would be the most validated place on Mars for such a landing.</p>															
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<p>Thank you! Questions?</p> <p>Kent's Mars Design portfolio below.</p>	<p>Thank you.</p>															

<p>27th Annual International Mars Society Convention - University of Washington - Seattle, WA August 8-11, 2024</p> <p>Mars Sample Return Using SpaceX Starship-ISRU Demonstration</p> <p>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</p> <p>Aurora CO</p>	
<p>Disclaimer</p> <p>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.</p> <p>—Tony Muscatello</p>	
<p>Introduction</p> <p>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."</p> <p>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</p> <p>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</p> <p>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</p> <p>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</p> <p>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</p> <p>SpaceX was awarded one of the grants, so it will be interesting to compare their approach to ours, once it's available</p>	

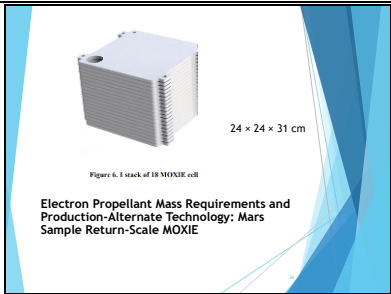
 <p>Mission Requirements</p> <ul style="list-style-type: none"> Launch at least <u> </u> kg of Mars Sample Tubes into Mars Orbit Rendezvous with sample return vehicle Transfer samples for return to earth OR launch samples directly to earth if feasible 	
 <p>Starship Lander Approach</p> <ul style="list-style-type: none"> 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) 	
 <p>Calculations</p> <ul style="list-style-type: none"> 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" $Mass(O_2) = Mass(RP-1) \times 2.56$ $Mass(O_2) = 2.56 \times Mass(RP-1)$ $Mass(O_2) = 1438 \text{ kg}; Mass(RP-1) = 562 \text{ kg}$ 	


Starship Lander Approach: Summary of ISRU Options



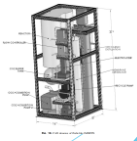
ISRU Technology	O ₂ Production Rate (for 492.5 cases)	Mass, kg	Power, W	Volume, m ³
O ₂ Production Rate Goal	3.22 kg/day	Minimize	Minimize	Minimize
NASA RWGS/Water Electrolysis (2015)	3.6 kg/day	57 kg	1328 W	NA
Pioneer Astronautics RWGS/Water Electrolysis (1997)	5 kg/day	66 kg	4110 W	NA
Modified Pioneer Astronautics WISPPS (RWGS/WE) (2013)	3.275 kg/day	270 kg	4000 W	0.875 m ³
Scaled Up MIT/Oxon 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

Conclusions



- The modified O₂-only production design based on 24 MOXIE-scale stacks has the lowest mass and volume
- It has the second lowest power compared to the NASA RWGS/WE system
- It is based on TRL 9 hardware, i.e. the MOXIE device that has been successfully demonstrated on Mars on the Perseverance Rover
- Therefore, it has the lowest technical risk, as well
- The 24 MOXIE + 2 pumps design is recommended for the Starship-based Mars Sample Return design


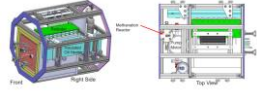


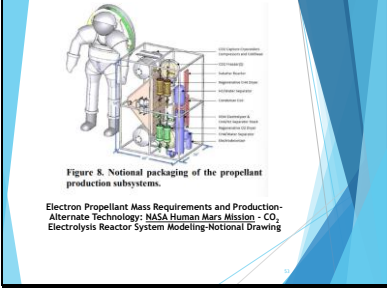
 <p style="text-align: center;">Supporting Information Slides</p>	
<p>Electron Propellant Mass Requirements and Production-NASA RWGS/Water Electrolysis</p> <ul style="list-style-type: none"> ▶ Mass(O₂) = 1438 kg; Mass(RP-1) = 1582 kg O₂ w/10% margin <ul style="list-style-type: none"> ▶ 2000 kg total propellant (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 (=+92.5 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 	
<p>Electron Propellant Mass Requirements and Production-Pioneer Astronautics RWGS/Water Electrolysis</p> <ul style="list-style-type: none"> ▶ 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 → 90 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 	

<p>Electron Propellant Mass Requirements and Production-Pioneer Astronautics RWGS/Water Electrolysis Prototype (2001)</p> <p>► Larger-scale RWGS built for NASA KSC by Pioneer Astronautics- Mass and Volume Not Available</p> 	
<p>Electron Propellant Mass Requirements and Production (Cont.)</p> <ul style="list-style-type: none"> ► Zubrin, Muscatello, and Berggren (2013) published the design of a combined Sabatier/ RWGS (MSPPS) 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 	
<p>Photos and Drawing of Pioneer Astronautics Prototype MSPPS Unit</p>  <p>► 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</p> 	

<p>Electron Propellant Mass Requirements and Production-Alternate Technology: Mars Sample Return-Scale MOXIE</p> <ul style="list-style-type: none"> 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), Isaac Mayer 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 2.39 kg/d correct; really needs 0.331 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 x 24 x 31 cm each unit, Power consumption 60W, 404 W + Pump 389 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/d/0.005585 = 23.9 MOXIE cells. 24 units + 2 pumps would be required for the E-2 MSR 24 MOXIE Units + 2 pumps: 20 kg + 34 kg = 56 kg, 539 W + (2x789) = 1,117 W, stack of 2x4x24x24 cm MOXIE (8) units (volume = 0.6242 m³ + 2 pumps = 0.00791 m³) = 0.6321 m³ 	
<p>Options Not Included</p> <ul style="list-style-type: none"> The following slides partially describe OxExon 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. 	
<p>Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale Version of MOXIE (33x)</p> <ul style="list-style-type: none"> Hollist, Elwell, Hafem, Pihl, Hervigsen, and Dlangovan 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 	

  <p>Figure 5. MOXIE design, nominal 45.4 kg MOXIE, currently assembled with solar generator.</p> <p>Figure 6. Size comparison of MOXIE stack from MOXIE and JPL/ITP photos.</p> <p>Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale MOXIE - Photos</p>	
<p>Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale MOXIE</p> <ul style="list-style-type: none"> Hollist, Ewell, Hafon, Pike, Harrivigen, 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/hr - 43.4 x required rate → <i>way oversized</i> 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/hr (still 11.7 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, 60-cell stack has a size of 13 x 10 x 20 cm = 0.00338 m³ Volume = 0.97% of IMSPPS version (not including pump and electronics) Mass = 17% x IMSPPS version Power = 3.9 x IMSPPS version See next slide for Methanation Reactor specs 	
<p>Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale CO₂ Electrolysis Reactor</p> <ul style="list-style-type: none"> Hollist, Ewell, Hafon, Pike, Harrivigen, 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/hr - 43.4 x required rate → <i>way oversized</i> 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/hr (still 11.7 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, 60-cell stack has a size of 13 x 10 x 20 cm = 0.00338 m³ Volume = 0.029% of IMSPPS version (not including pump and electronics) Mass = 17% x IMSPPS version Power = 3.9 x IMSPPS version See next slide for Methanation Reactor specs 	

<p>Electron Propellant Mass Requirements and Production - Alternate Technology: OxEon Full-Scale Methanation Reactor Photo & Specs</p> <ul style="list-style-type: none"> ▶ OxEon Methanation System: ▶ Tubular Reactor dimensions: 60 x -3 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  <p><small>Figure 7. OxEon methanation reactor hardware assembly.</small></p>	
 <p><small>Figure 8. Integrated co-electrolysis methanation breadboard system configuration.</small></p> <p>Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale MOXIE-Methanation Reactor Drawing</p>	
<p>Electron Propellant Mass Requirements and Production-Alternate Technology: OxEon Full-Scale CO₂ Electrolysis Reactor Modeling</p> <ul style="list-style-type: none"> ▶ 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 = 0.093 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 be 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 = 0.02% of IMISPPS version (not including pump and electronics) ▶ Mass = 17% x IMISPPS version ▶ Power = 3.9 x IMISPPS version 	

<p>Electron Propellant Mass Requirements and Production-Alternate Technology: NASA Human Mars Mission - CO₂ Electrolysis Reactor System Modeling</p> <ul style="list-style-type: none"> ▶ Co-authors Kleinhenz and Paz (2017): 28 metric tons of liquid oxygen (including life support) in 16 months (400 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 → <i>way oversized</i> (3 modules) ▶ Each module = 0.81 kg/d, = 15.2 x required rate → <i>way oversized</i> ▶ 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 be 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 	
 <p>Figure 8. Notional packaging of the propellant production subsystems.</p> <p>Electron Propellant Mass Requirements and Production-Alternate Technology: NASA Human Mars Mission - CO₂ Electrolysis Reactor System Modeling-Notional Drawing</p>	