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TEST-DEMONSTRATED ADVANTAGES OF SOLID-OXIDE WATER ELECTROLYSIS FOR SCALED-UP HYDROGEN PRODUCTION ON THE MOON

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INTRODUCTION

- In situ resource utilization (ISRU) of materials in space can enhance the affordability and sustainability of long-term space missions.
- Opportunity for ISRU: Converting electrical and/or solar energy and H_2O into propellants.
- Ice has been mapped in permanently shadowed regions of the lunar surface providing prospect of **advanced electrolysis to produce H_2 and O_2 on the Moon**..
- Lunar H_2/O_2 propellant production would support a **cislunar fueling architecture** for space transport (Sowers 2021a) that would greatly reduce energy and cost of deep space missions.

Source: Sowers (2021b), pg. 64

BACKGROUND

- Solid oxide electrolysis (SOEC) can achieve lower specific energy w_{sp} (kWh_{elec}/kg_{H2}) than PEM or alkaline electrolyzers (Schmidt et al. 2017, Lomax et al 2022).
  - $T \geq 700°C$ lowers thermal neutral voltage V_{tn} (due to no internal phase change).
  - Lower V_{OCV} at high T enables higher current density i (A/cm^2) and thus lower $w_{sp} < 46$ kWh_e/kg of H_2.
  - SOEC cell architecture can reduce ASR for high current i_{tn} at V_{tn}.
- High T SOEC feeds with H_2O vaporization requires optimal balance-of-plant (BOP) design to achieve $w_{sp} < 50$ kWh_{elec}/kg_{H2}.

$$V_{tn} = \frac{\Delta \bar{h}_{f,H2O}}{2F}, \quad V_{OCV} = \frac{\Delta \bar{h}_{f,H2O}}{2F} - \frac{T\Delta \bar{s}_{f,H2O}}{2F}$$

$$\Rightarrow \quad V_{tn} - V_{OCV} = \frac{T\Delta \bar{s}_{f,H2O}}{2F} = ASR * i_{tn}$$

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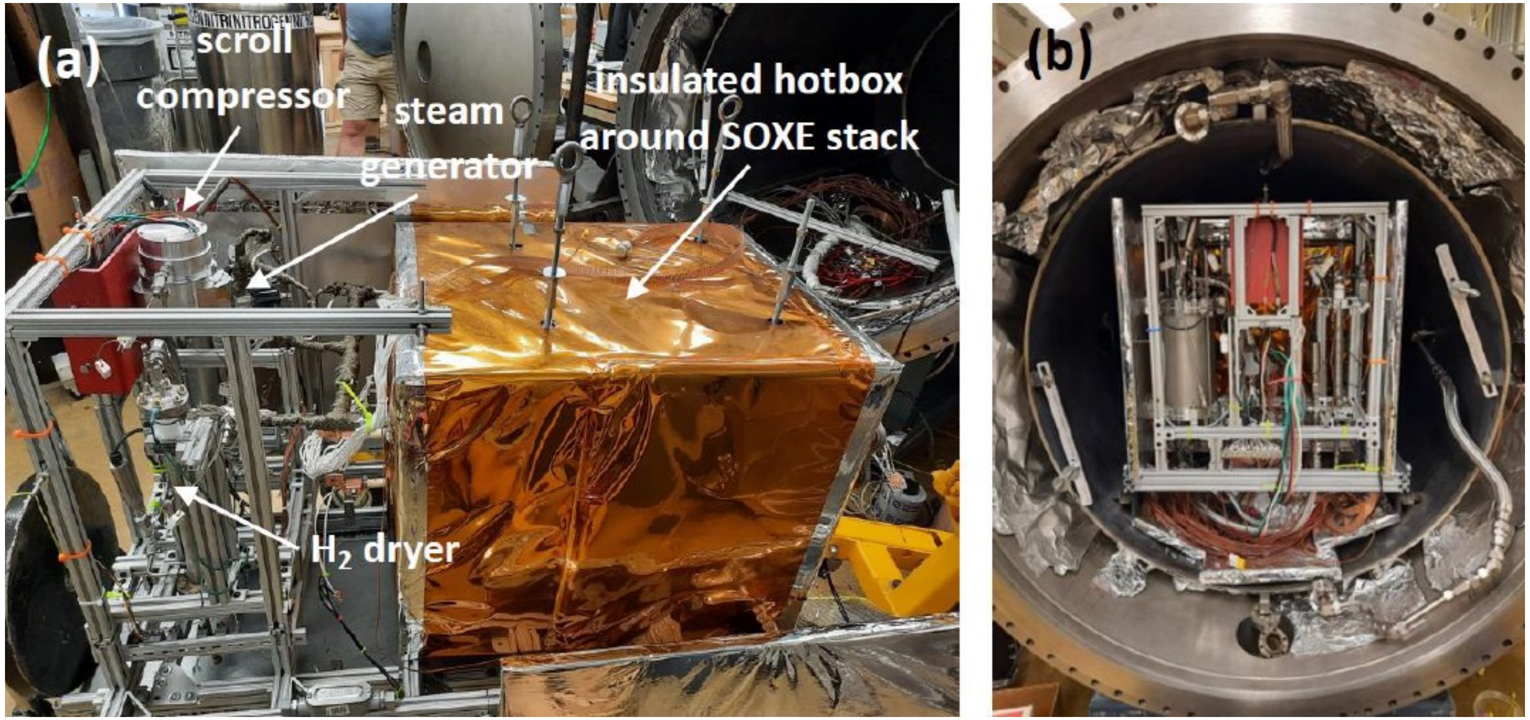
EXPERIMENTAL SYSTEM DESIGN AND TESTING



- NASA-sponsored collaboration between OxEon Energy and Colorado School of Mines designed, fabricated, and tested a lab-scale, lunar-oriented SOEC system with integrated BOP.
- Advanced TRL 4 → 5.
- *Performance objectives:*
  - H_2 production: 1.8 kg/day
  - System specific power: 50 kWh_{elec}/kg_{H2} produced
  - O_2 electrochemical compression: 1.5 bar
- Concurrent with testing, simulation, model benchmarking, scaled-up analysis, and scaled-up cost analysis were performed.

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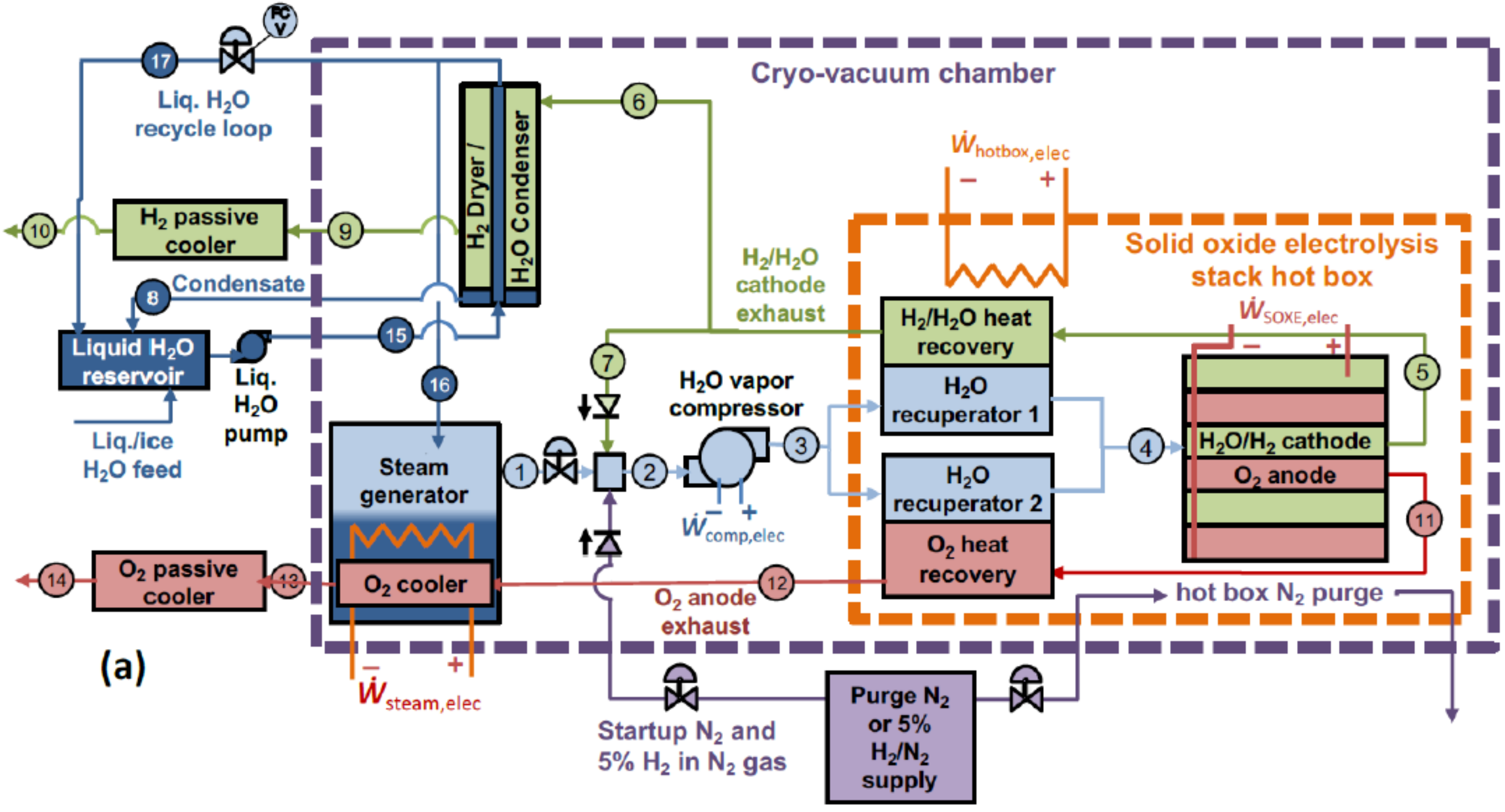
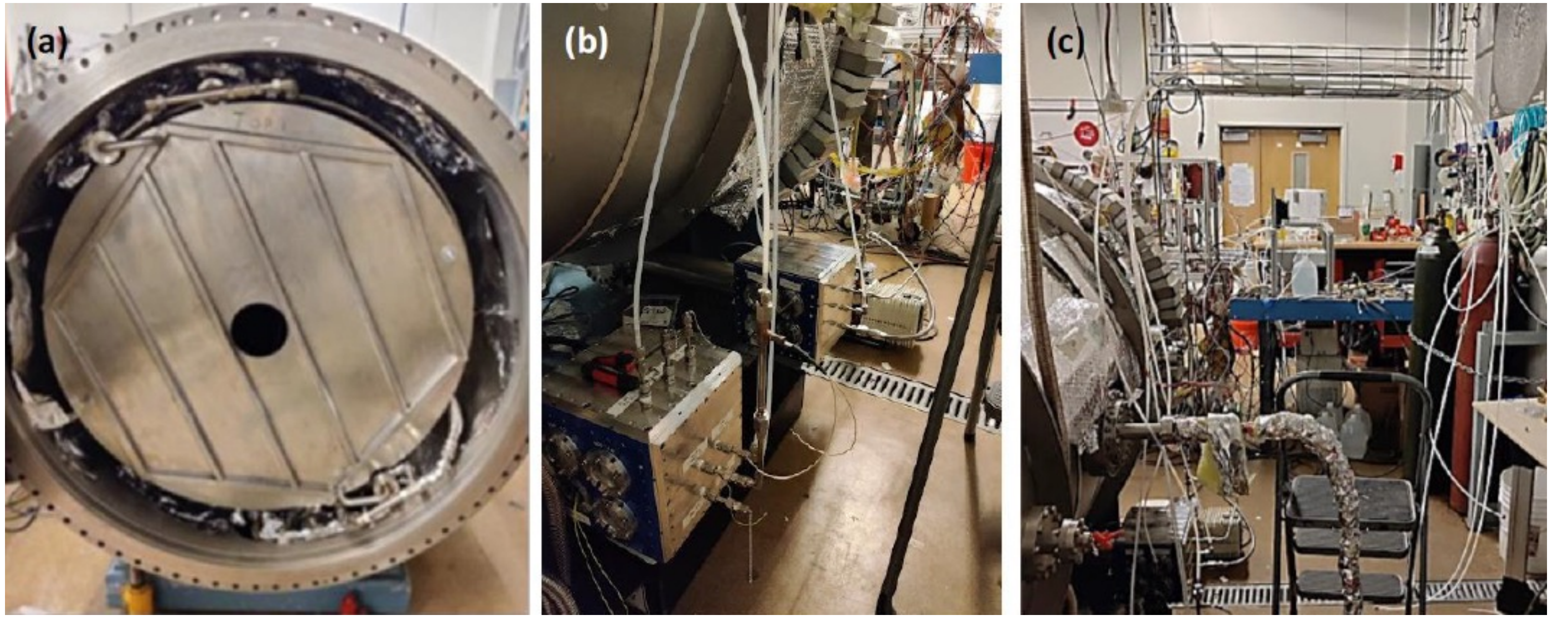
SOEC STACK AND BALANCE OF PLANT



- OxEon's SOEC stack achieve high reliability and relatively low ASR, with 65 cells/stack.
- Shell-and-tube H2 Dryer HX preheated liquid H_2O and cooled/dried H_2 exhaust.
- Steam generator boiled H_2O with ≤ 800 W_{elec} immersion heater.
- Scroll compressor (Air Squared) pulled vapor from steam generator and compressed at pressure ratios < 2 bar.
- Tube-in-tube recuperators heated steam on way to stack.

VACUUM CHAMBER TESTING



- BOP and component tests in ambient atmospheric conditions and in the vacuum chamber provided basis for integration and controls with the SOEC stack.
- Liquid N_2 was pumped through cryo-shroud to reduce chamber to -100℃ and single-torr pressures to approximate lunar environment (a).
- Long leads for instrumentation and power require vacuum feedthroughs with low noise (b & c)

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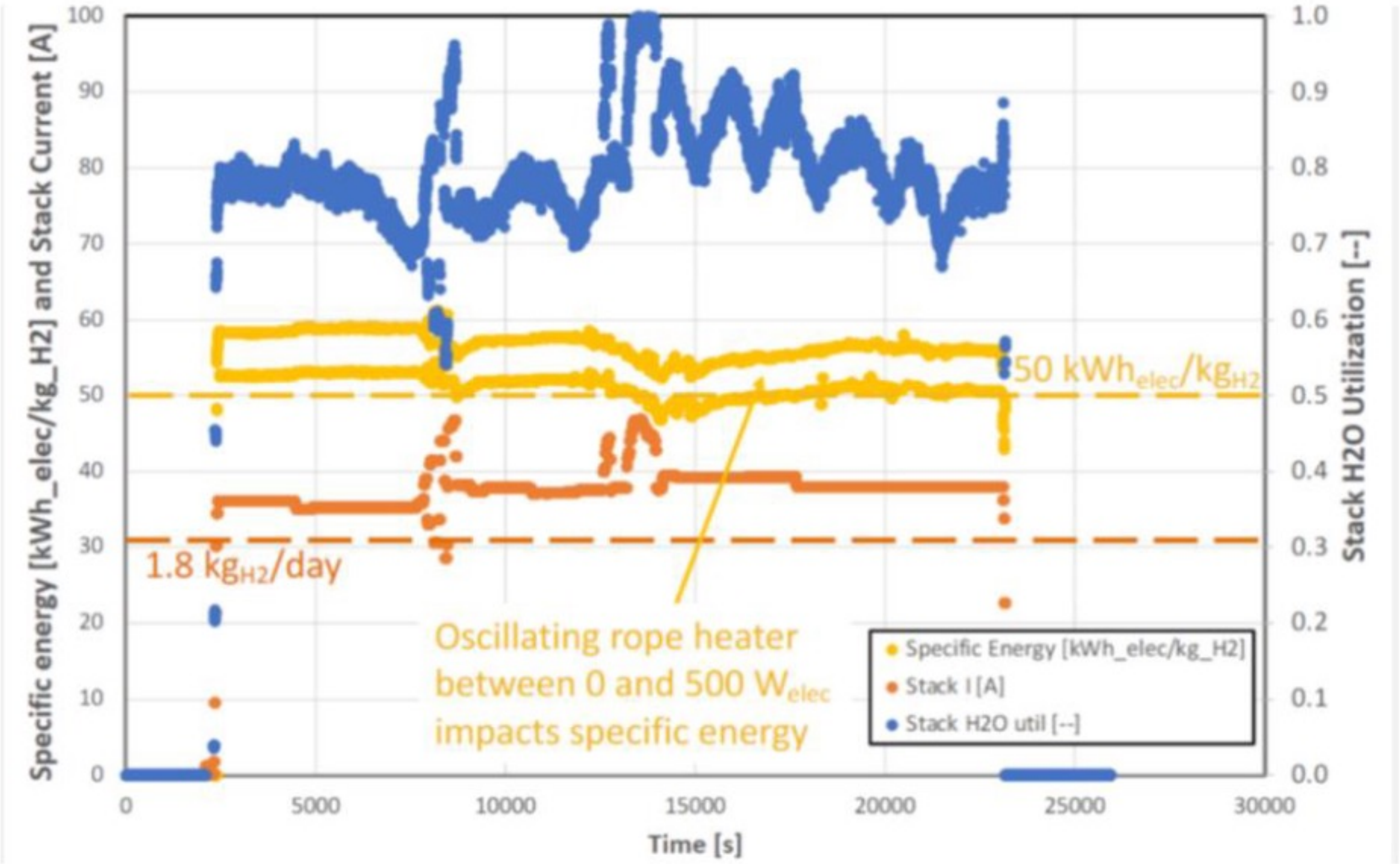
INITIAL EXPERIMENTAL RESULTS



- Steam flow rates set at ≈ 17 g_{H2O}/min such that at V_{tn} steam utilization ε_{H2O} ≈ 80%.
- In-vacuum H_2 production target of > 0.075 kg_{H2}/h (1.8 kg_{H2}/day) was achieved for these conditions.
- Specific energy > 50 kWh_{elec}/kg_{H2} due to heat-tracing electric loads with non-optimized flow paths
- Tests paused and system reconfigured.

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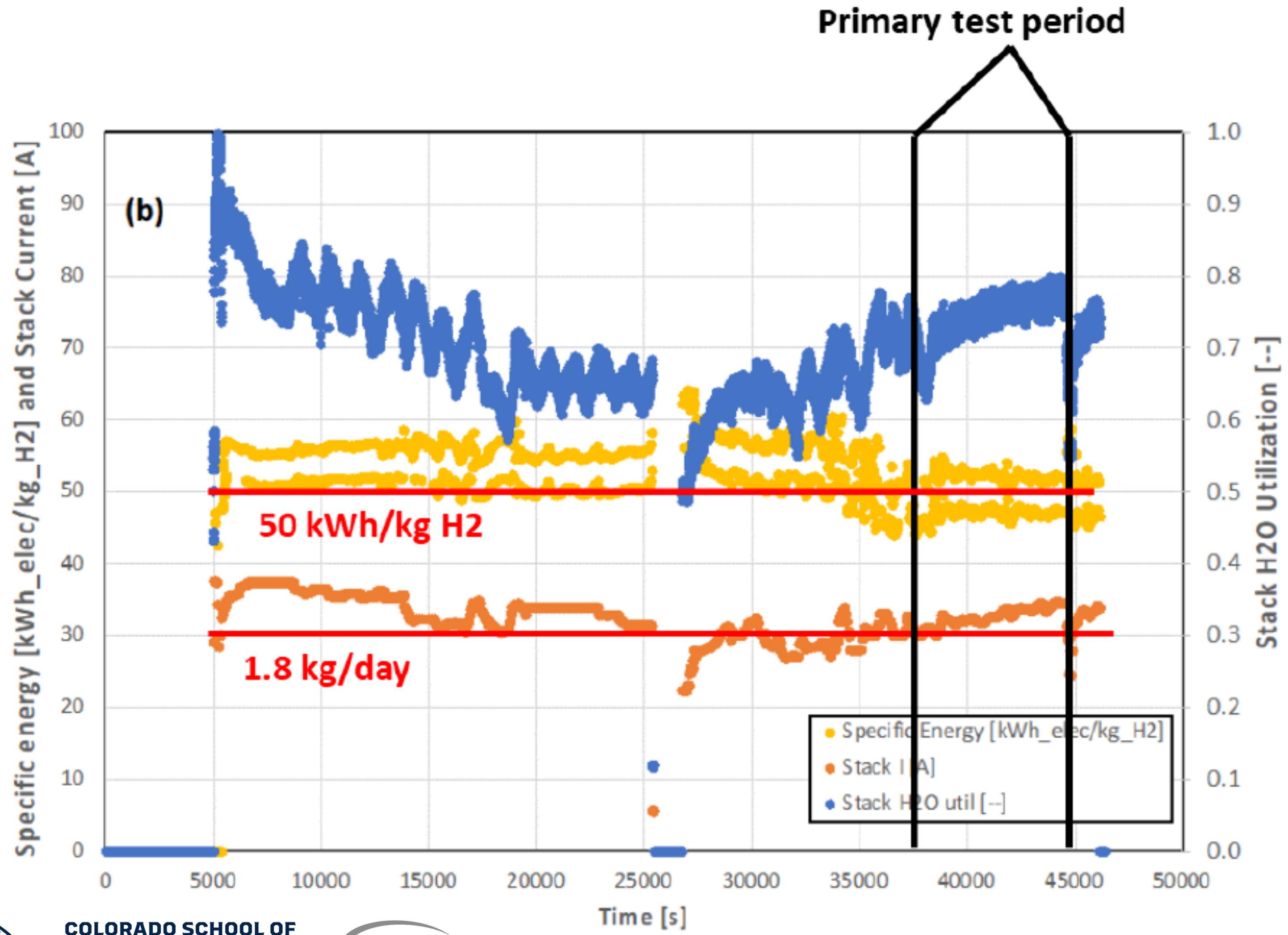
EXPERIMENTAL RESULTS (DAY 2)



- Better insulation and more efficient heat tracing lowered BOP parasitic loads associated with heating.
- Control gain changes on the BOP steam generator heater lowered steam generator heater power consumption.
- Steam utilization by the stack averaged ~73% for the duration of the primary test period.

FINAL EXPERIMENTAL RESULTS

Total	Stack	Stack Ins. Heater	Steam Gen Heater	Compressor	Heat Trace	m_{H2} production	H2O Utilization
[Wh_{elec}/kg_{H2}]	[Wh_{elec}/kg_{H2}]	[Wh_{elec}/kg_{H2}]	[Wh_{elec}/kg_{H2}]	[Wh_{elec}/kg_{H2}]	[Wh_{elec}/kg_{H2}]	[kg]	[--]
48.85	36.41	0.65	8.90	1.17	1.72	0.1595	0.725

- Average specific energy of 48.8 kWh/kg_{H2} (**>50 kWh/kg_{H2}**) was achieved at H_2 production rates > 0.075 kg_{H2}/h (> 1.8 kg_{H2}/day) for 2-h test.
- Total integrated system energy consumption of 7.8 kWh produced 0.1595 kg_{H2} at mean ε_{H2O} = 73%.
- Energy requirements were 75% to power SOEC stack, 18% to steam generator heater, 3.5% to heat tracing, and 2.4% to scroll compressor (operating at a pressure ratio of 1.8).
- Redesign (heat tracing, stack heaters, more compressed layout) can reduce specific energy further to < 46 kWh/kg_{H2}, even at lab-level 2.5 kW stack scale.

SIMULATION AND MODEL BENCHMARKING

- Experimental effort is complemented by simulation in MATLAB and Cantera (Dickson et al 2021). Stack concentration overpotential and applied stack voltages over thermoneutral (V_{tn}) are accounted for.
- Concentration overpotential and variation of i down length (x) of cathode represented indirectly in this model by:

$$V_{cell} \approx V_{OCV}(T, C_{\mathrm{H2O,el}}, x) + ASR(T)i(x) \quad [1]$$

$$I_{stack} = z_{cell} \int i(x)dx \quad [2]$$

$$\frac{i(x)}{2F} = -D_{\mathrm{H2O}} \frac{C_{\mathrm{H2O,ch}}(x) - C_{\mathrm{H2O,el}}(x)}{\Delta y_{\mathrm{cathode}}} \quad [3]$$

$$V_{OCV}(x) = \frac{RT}{4F} \ln \frac{P_{\mathrm{anode}}}{P_{\mathrm{cathode}} X_{\mathrm{O2,el}}(x)} \quad [4]$$

  - where $ASR(T)$ = area-specific resistance, I_{stack} = total stack current, z_{cell} = stack width, F = Faraday's constant, D_{H2O} = diffusion coefficient of H_2O, $C_{\mathrm{H2O}}(x)$ = H_2O concentration, R = universal gas constant, P = pressure, and $X_{\mathrm{O2,el}}(x)$ = equilibrium O_2 mole fraction.

- Solving Eq. 1-4 simultaneously for a discretized channel down the cathode, gives $i(x)$, V_{OCV}, and $C_{\mathrm{H2O,ch}}$. These provide stack current *I* and steam utilization $\varepsilon_{\mathrm{H2O,util}}$ for a given stack voltage V_{cell}.

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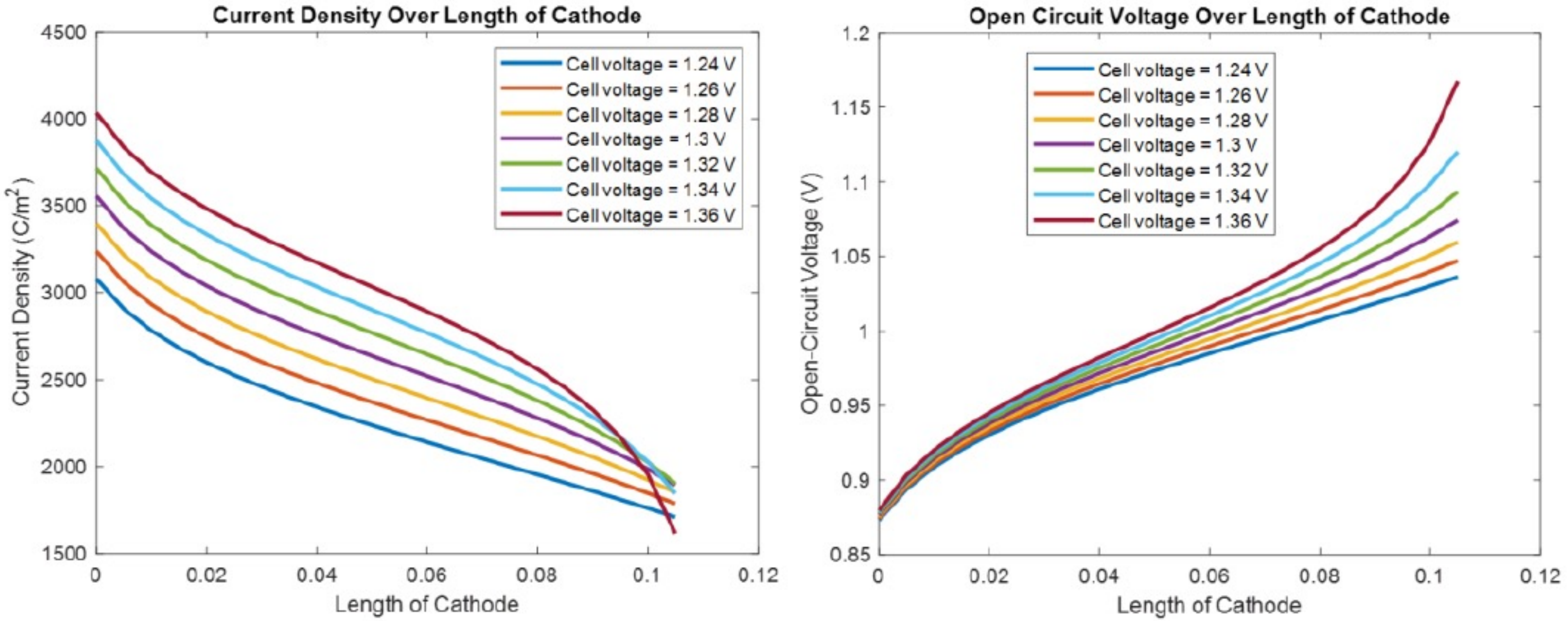
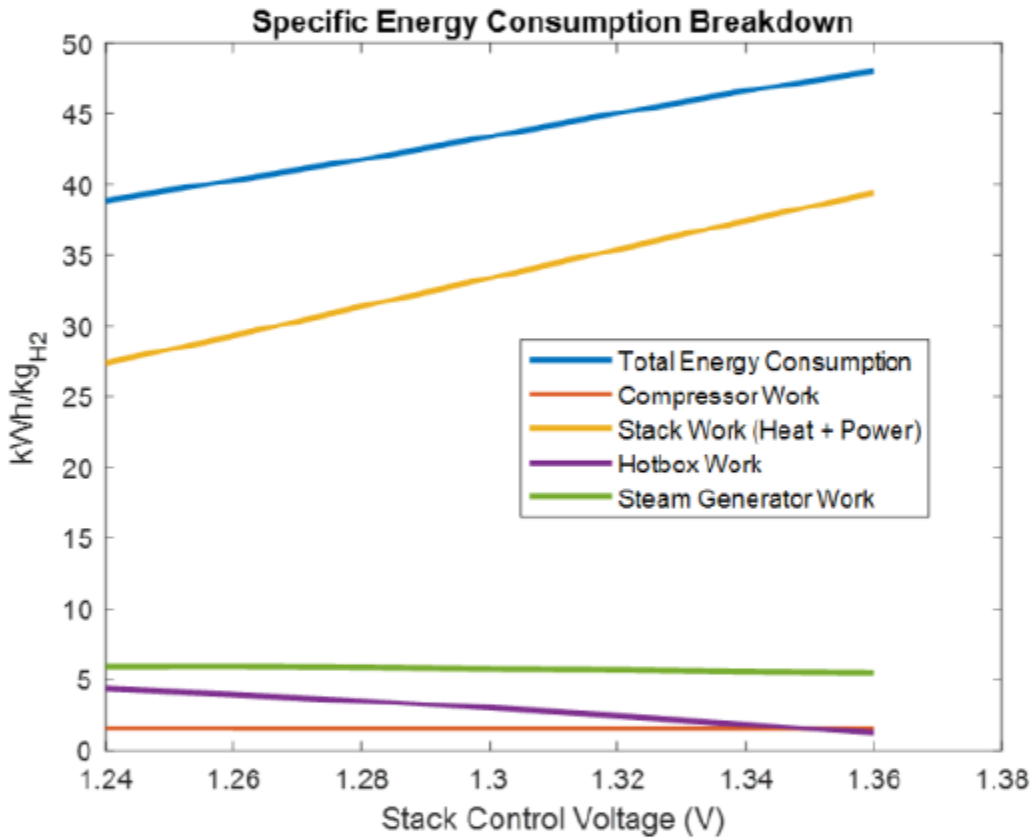
SIMULATION AND MODEL BENCHMARKING



- Curves reflect higher H_2O concentration gradients across the cathode at the beginning of the channel, followed by lesser gradients at the end.
- Sharp drop in *i*(*x*) at the end of the cathode at higher V_{cell} is due to $X_{H2O} \Rightarrow 0.0$ at high voltages.

SIMULATION AND MODEL BENCHMARKING

- Stack work and heat produced increase with V_{cell} but are offset by reduced heat ≈ 38 kWh/kg_{H2}.
    - w_{sp} that would be expected of the stack at voltages 0.05-0.1 V above thermoneutral V_{tn}.
- Furnace heaters in hotbox now have less work to do and steadily decrease in specific energy consumed over the voltage range.
- BOP energy load such as steam generator heater and the scroll compressor, are hardly affected by change in V_{cell}.
- At scale w_{sp} ≈ 45 kWh/kg_{H2}, significantly below the 48.8 kWh/kg_{H2} during the test.
- **Lower w_{sp} can be found in future iterations and prototypes of this system, potentially pushing the specific energy consumption of the system below its stretch goal of 46 kWh/kg_{H2}.**



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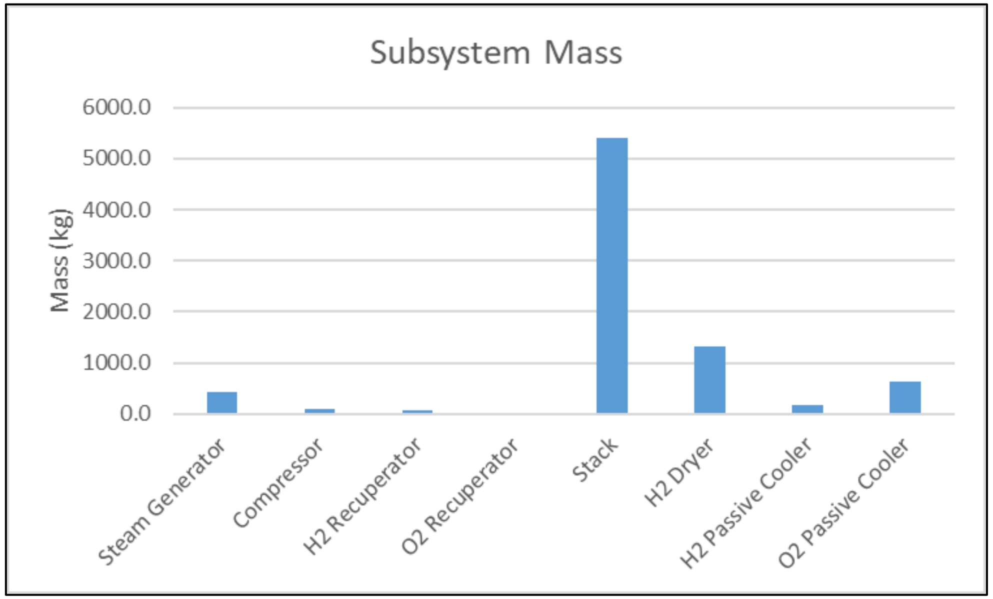
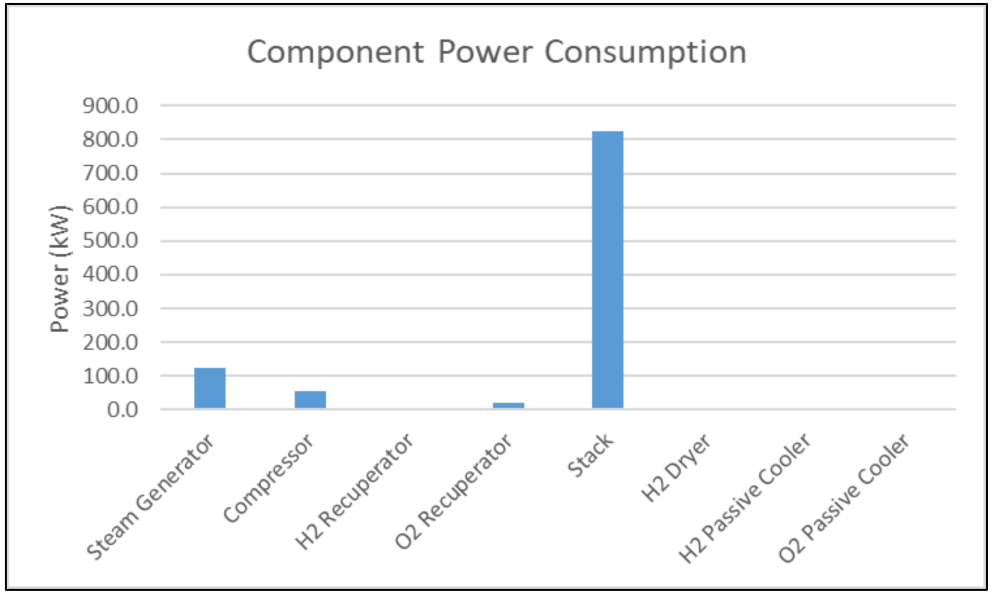
SCALED-UP PRODUCTION ANALYSIS

- To estimate scaled-up production, Excel model of each component was built based on an assumed scaling approach.
- Mass and power consumption was calculated as a function of overall hydrogen product rate.
  - Lab scale system was scaled to produce 657 kg/day of hydrogen.
  - Each mass included a 20% allowance for fittings, sensors, brackets, and other items not discretely estimated.
- Based on this approach, **total system mass was 8152 kg**.
  - Largest contributor was the solid oxide stack assembly at 5400 kg.
- The **average power consumption** of the full-scale system **was 1030 kW**.
  - Solid oxide stack assembly was the largest contributor at 826 kW.





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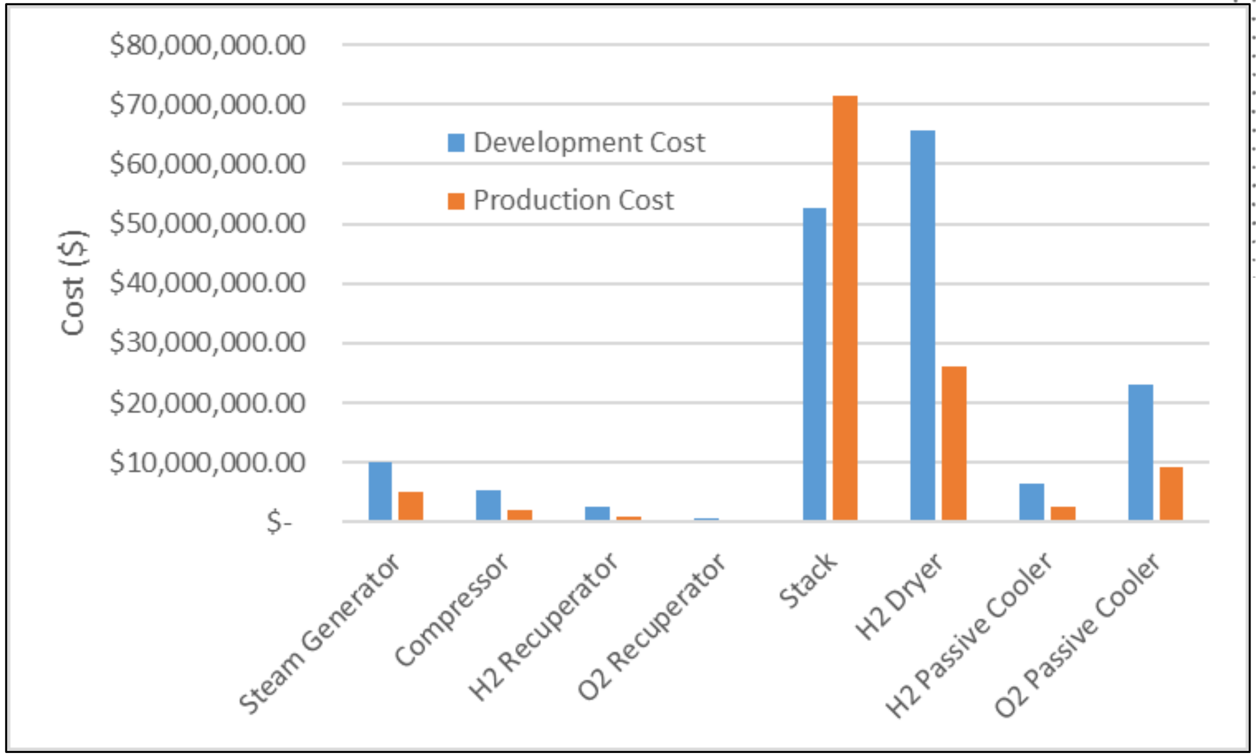
SCALED-UP COST ANALYSIS

- Cost model for the propellant production operation was based on mass estimates for each of the architecture elements shown in figure.
  - Non-recurring costs included the cost to develop the system, the cost to manufacture the system and the cost to transport the system to the Moon.
  - Recurring costs included the cost to operate, maintain and repair the system.
- Development cost and production cost for the subsystem were determined by multiplying the mass by a factor in dollars per kilogram ($/kg).
  - This factor was modified by a complexity factor from subsystem to subsystem.
- The value of the development and production cost factors represents a commercial, for profit, development approach.
  - In this approach, all the cost and cost risk are borne by the system developer, tending to keep costs low and timelines short.

COST ANALYSIS

- The nominal development cost factor used was $50,000/kg. This value corresponds to aerospace industry experience for hardware of average complexity.
- The production costs for the subsystems were estimated with a nominal cost factor of $20,000/kg.
  - Same complexity factor was used for both development and production cost.
  - When subsystems or components are produced in quantities larger than one, a learning curve is applied. The first unit cost (C_1) is assumed to be the cost factor times the complexity factor.



- n^{th} unit cost:

$$C_n = C_1 n^{\log_2 f}$$

where f = the learning curve exponent.

COST ANALYSIS RESULTS

Launch configuration	Mass delivered (kg)	Cost ($M)
Single	4,000	140
Dual	12,000	308

- The above scaling analysis was performed for a lab scale target production rate of 1.8kg/day. The actual laboratory verified production rate was somewhat greater at 2.2kg/day.
- **Total development cost is $160M**, **production cost is $108M,** and **total mass is 7383 kg** with achieved production rate of 2.2 kg/day as benchmark**.**
- Other component of non-recurring cost: Launch and landing cost.

Parameter	Current Estimate (target production rate)	Current Estimate (achieved production rate)	Previous Estimate (Sowers 2021)
Mass (kg)	8152	7383	4000
Average Power Consumption (kW)	1030	1030	1000
Development Cost ($M)	166	160	200
Production Cost ($M)	118	108	80
Launch Cost	No Change		

- Each launch could land either 4mT or 12mT depending on whether upper stage refueling was utilized.
- **Total launch and landing cost: $280M for single** configuration, **$308M for dual**.

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COST ANALYSIS RESULTS

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Production Cost ($M)	118	108	80
Launch Cost	No Change		

- Using dual configuration, this results in a total development, production, and launch cost of **$576M using achieved production rate** of 2.2 kg/day as benchmark.
- Additional modeling for operation and cost during scaled-up production will be performed to refine this analysis as part of Dickson PhD dissertation.

CONCLUSION AND FUTURE WORK

- Experimental testing, paired with supporting modeling and cost analysis, indicated the potential for SOEC systems to produce H_2 in a lunar environment at w_{sp} < 50 kWh_{elec}/kg_{H2}.
- SOEC technology is a good candidate to become the **standard in rocket fuel production from water on the Moon**.
- This project is a baseline for future scale-up, endurance testing, and move toward more ambitious operation in the field of space resources.
- NASA Program Manager – Dr. Koorosh Araghi (at far left).

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QUESTIONS?

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