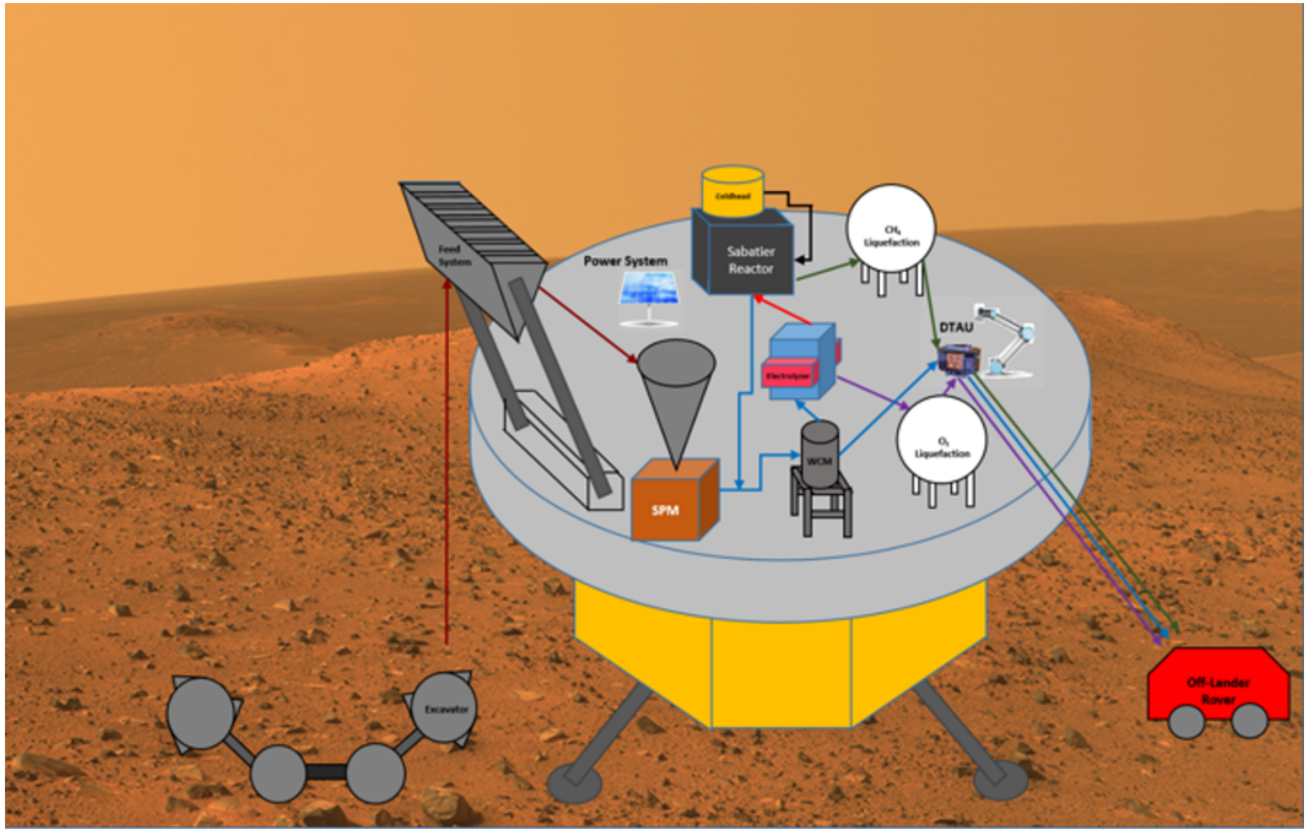

Mars Pathfinder ISRU Modeling and Simulation

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Mars Pathfinder Project

- The Mars Pathfinder project seeks to provide a testing platform for integrated Mars ISRU technologies being developed at NASA centers and work out operational problems of an end-to-end propellant production system.
- A system-level simulation model of the Mars Pathfinder system, in its hardware-in-the-loop (HWIL) integrated test configuration, was created at Kennedy Space Center (KSC) using Excel VBA in order to integrate multiple test data sets as well as legacy models.

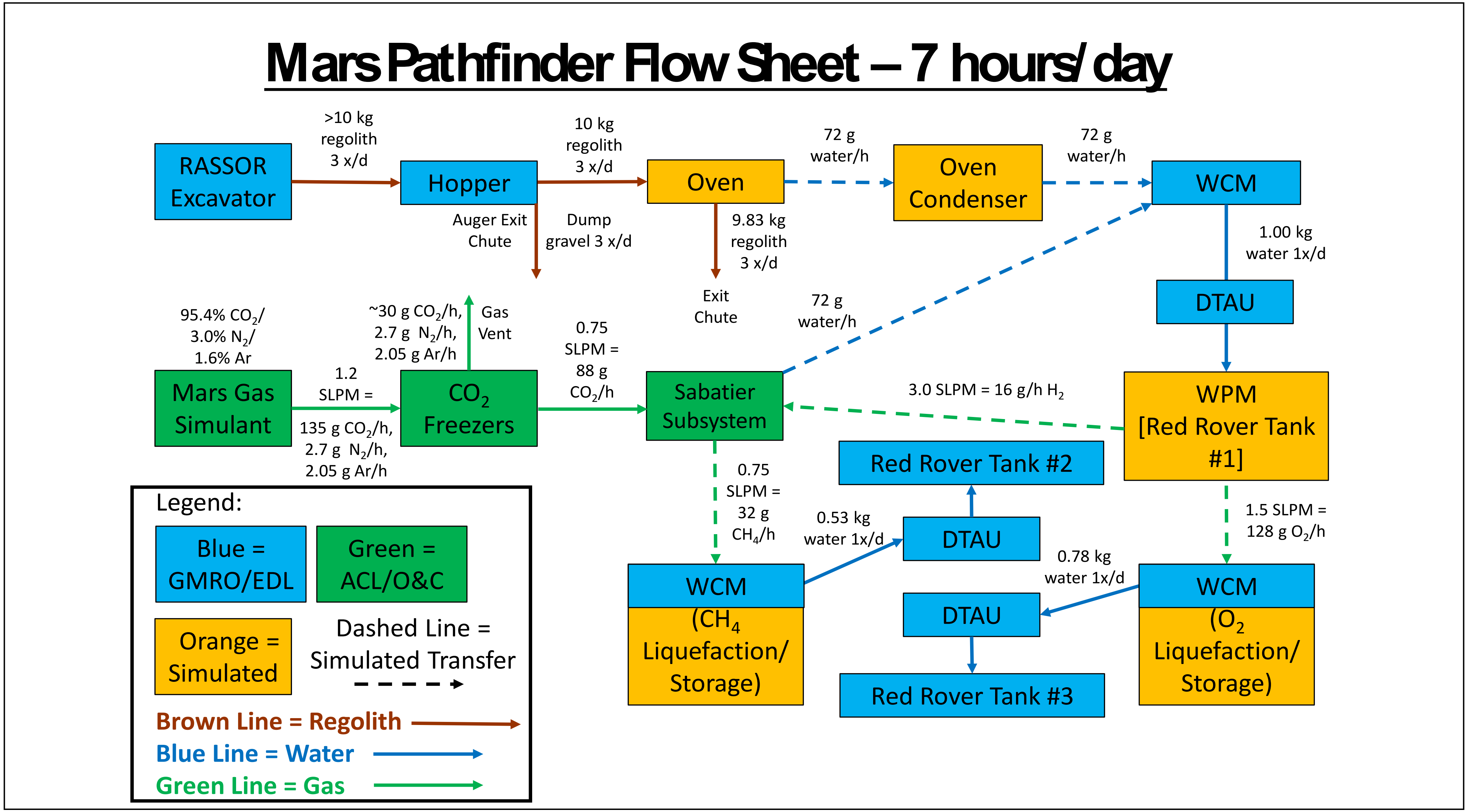
Simulation model of the Mars Pathfinder test used data from tests to tie inputs to outputs in each simulated subsystem.

Mars Pathfinder Test Configuration

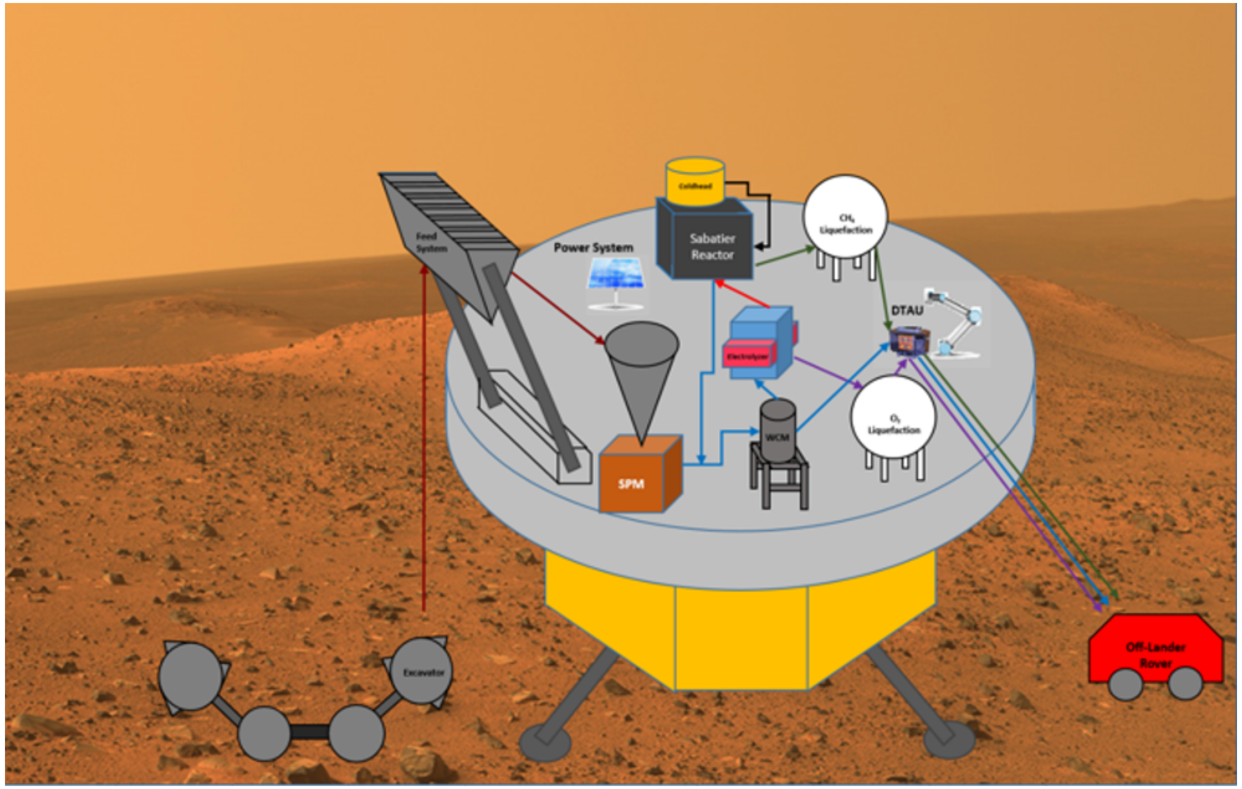
- The Mars Pathfinder system consists of seven subsystems that, together, constitute an integrated ISRU propellant-production system for Mars.
- A partially-integrated HWIL test of the system was performed at the KSC Granular Mechanics and Regolith Operations (GMRO) lab and Applied Chemistry Lab (ACL), using bottled gas mixture of Mars composition as the atmospheric input and construction sand as the "regolith" input.
- Purpose of this test was to run all available system hardware together in an integrated format over two daily cycles in October 2017
  - Control hardware and software used to communicate between test labs.
  - Methane produced as output and water used to simulated oxygen as the other output.
  - Water pumped out of lander to an off-lander rover in order to represent both propellants as "product".

Test carried out in GMRO lab and ACL lab; simulation model represents communication of oxygen, water, and regolith between lab subsystems.

Mars Pathfinder Flow Sheet



Mars Pathfinder Test Configuration



- **Left:** Mars Pathfinder test hardware configured for test. (Excavator, off-lander rover, auger feed system, water cleanup module, and lander mockup are pictured.)
- **Right:** Illustration depicting Mars Pathfinder system in the simulation.

Simulation Model Architecture

- The simulation model consists of:
    1. An in-house physics-based simulation model of the rover/excavator Regolith Advanced Surface Systems Operations Robot (RASSOR).
    2. An empirically-based model of the Water Cleanup Module (WCM), Atmospheric Processing Module (APM), Soil Processing Module (SPM), and regolith feed auger subsystems, based on integrated and subsystem test data.
    3. Legacy, physics-based simulation models of the Electrolyzer, liquid oxygen (LOX) Liquefaction System, and liquid methane (LCH4) Liquefaction Systems.

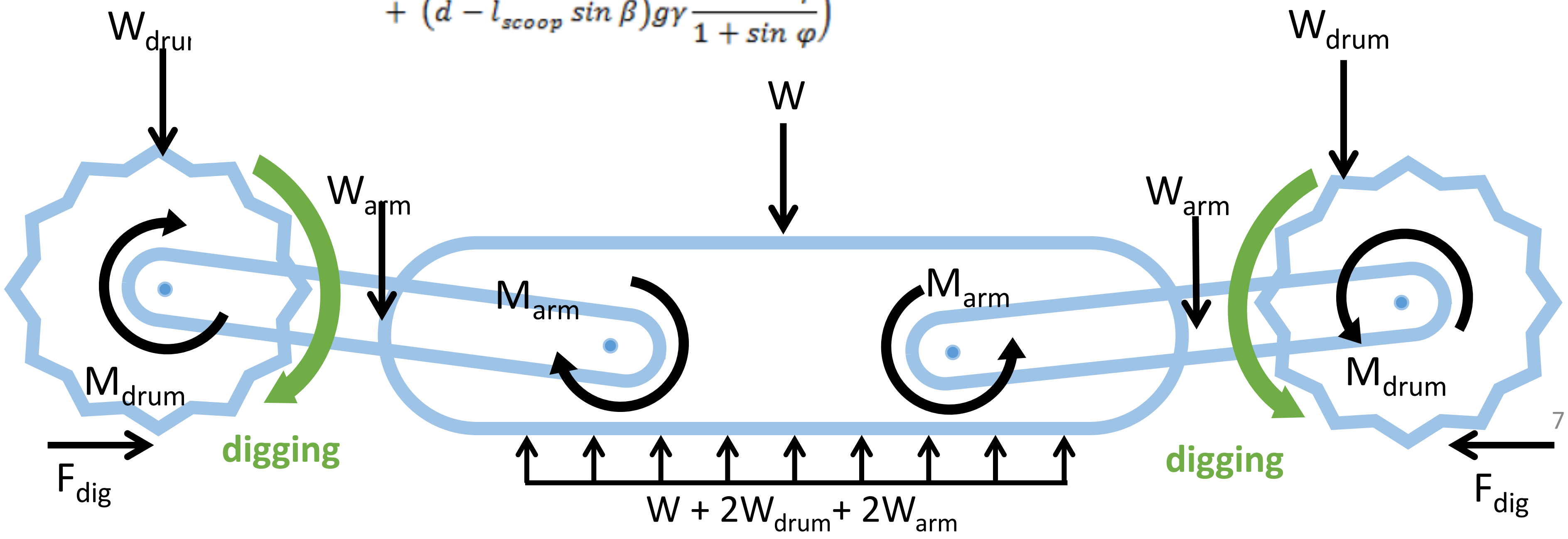
All the above subsystems are tied together to represent an ISRU propellant production system based on test data.

Subsystem Models

- *Excavator (RASSOR)*— This physics-based in-house model simulates the forces of excavation and traction exacted on the bucket drum excavator in operation, and, from these, calculates the energy needed to perform the regolith excavation. (See free-body diagram and bucket excavation equations to the right.)

Balovnev Bucket Equations.

$$
\begin{aligned}
\boldsymbol{F_{dig}} = {} & w(d+r-R)A_1(1 + \cot\beta \tan\delta) \\
& \cdot\left(\frac{dg\gamma}{2} + c\cot\varphi + gq + (d - l_{scoop}\sin\beta)g\gamma\frac{1-\sin\varphi}{1+\sin\varphi}\right) \\
& + we_bA_2(1+\tan\delta\cot\alpha_b)\left(\frac{e_bg\gamma}{2} + c\cot\varphi + gq + \frac{dg\gamma(1-\sin\varphi)}{1+\sin\varphi}\right) \\
& + A_3(d+r-R)(2s \\
& \quad + 4l_{scoop}\tan\delta)\left(\frac{dg\gamma}{2} + c\cot\varphi + gq \right. \\
& \quad \left. + (d - l_{scoop}\sin\beta)g\gamma\frac{1-\sin\varphi}{1+\sin\varphi}\right)
\end{aligned}
$$



Subsystem Models

- *Auger/Size-Sorter*—This data-based in-house model simulates the system that conveys the regolith into the Soil Processing Module (SPM) after receiving regolith from RASSOR.
- *Soil Processing Module (SPM)*— This data-based in-house model simulates the system that heats up the regolith to extract water after receiving regolith from the Auger.
- *Water Cleanup Module (WCM)*—This data-based in-house model simulates the system that the water (now extracted from the regolith) is pumped into, from the SPM and the Atmospheric Processing Module (APM), and is subsequently cleaned of impurities to a specified lower resistivity threshold.

Subsystem Models

- *Electrolyzer*—This physics-based legacy model, based on work reported by Santiago-Maldonado and Linne (2007) and Schreiner (2015), simulates the system that takes the WCM-cleaned water and converts it into hydrogen and oxygen—the former for supply to the APM, the latter for supply to the Liquefaction System.
- *Atmospheric Processing Module (APM)*—This is the system that extracts, collects, and processes the carbon dioxide from the Mars atmosphere into propellants. It consists of the following two data-based in-house models:
  - *Cryocooler,* which simulates the system that extracts carbon dioxide from the air in solidified form, sublimates it, and stores it in a collection tank.
  - *Sabatier Reactor,* which simulates the reactor in which carbon dioxide and hydrogen react to produce methane and water.
- *Liquefaction System*—This physics-based legacy model, based on work reported by Santiago-Maldonado and Linne (2007) and Schreiner (2015), simulates the system that takes the methane and/or oxygen gas and liquefies it for subsequent transport to the offloading umbilical and transfer off-lander.

Modeling Assumptions

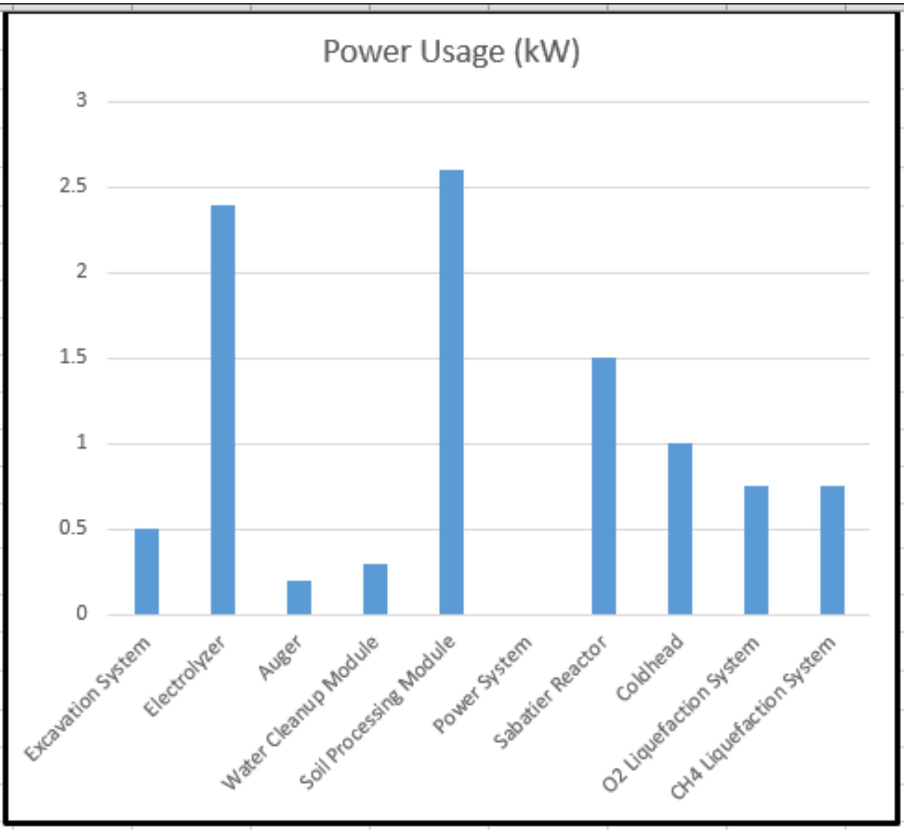
- Power availability for the system was not limited by solar production, nor did it fluctuate based on the time of year or weather.
- Liquefaction System and Electrolyzer models used legacy models previously developed for ISRU modeling work performed under Constellation.
- Excavator model was completely new and programmed by the GMRO lab in parallel with their prototype work on RASSOR itself.
- Remaining models were input-output models constituting lookup tables of test data. WCM and SPM test data was obtained from tests performed on each system at Johnson Space Center over June-December 2015, with the target conductivity and carbon filter varying in the case of the WCM, and the water content of the regolith varying in the case of the SPM.

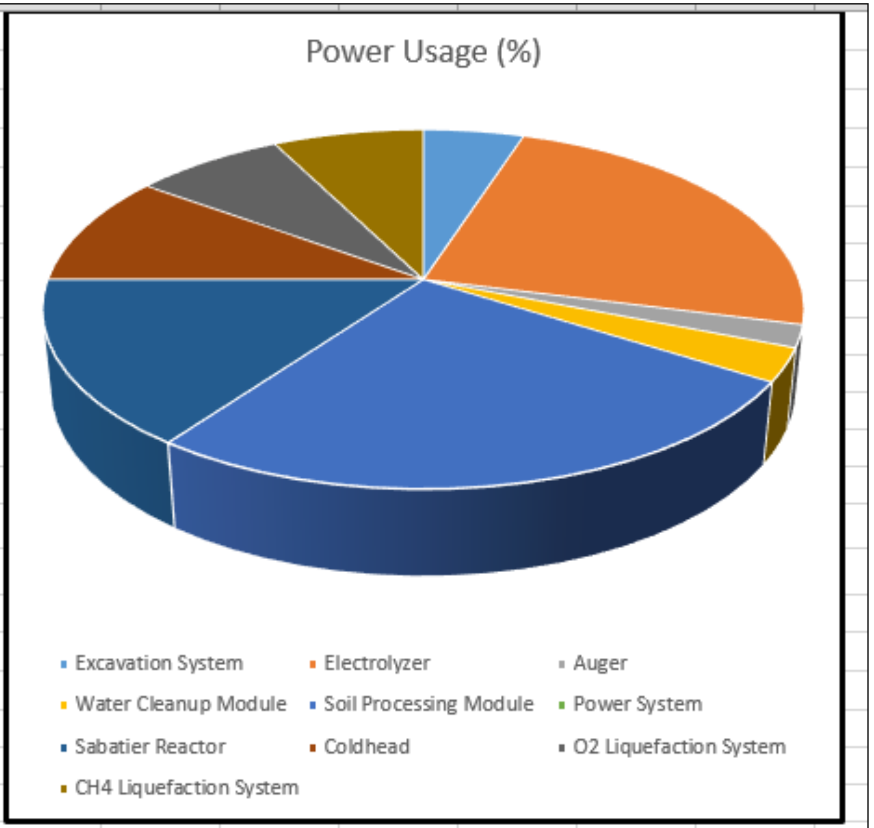
Modeling Assumptions

- Cryocooler and Sabatier Reactor data were obtained from repeated tests on both the latter systems performed at Kennedy over May-October 2017, with the design of the cryocooler and size of the reactor varying.
- Test data for the remaining subsystem, the Auger model, was obtained from repeated tests of the auger subsystem in the GMRO lab, running the auger at its default “fast” speed for 5 minutes, each test varying the mass amount of regolith in the auger hopper.

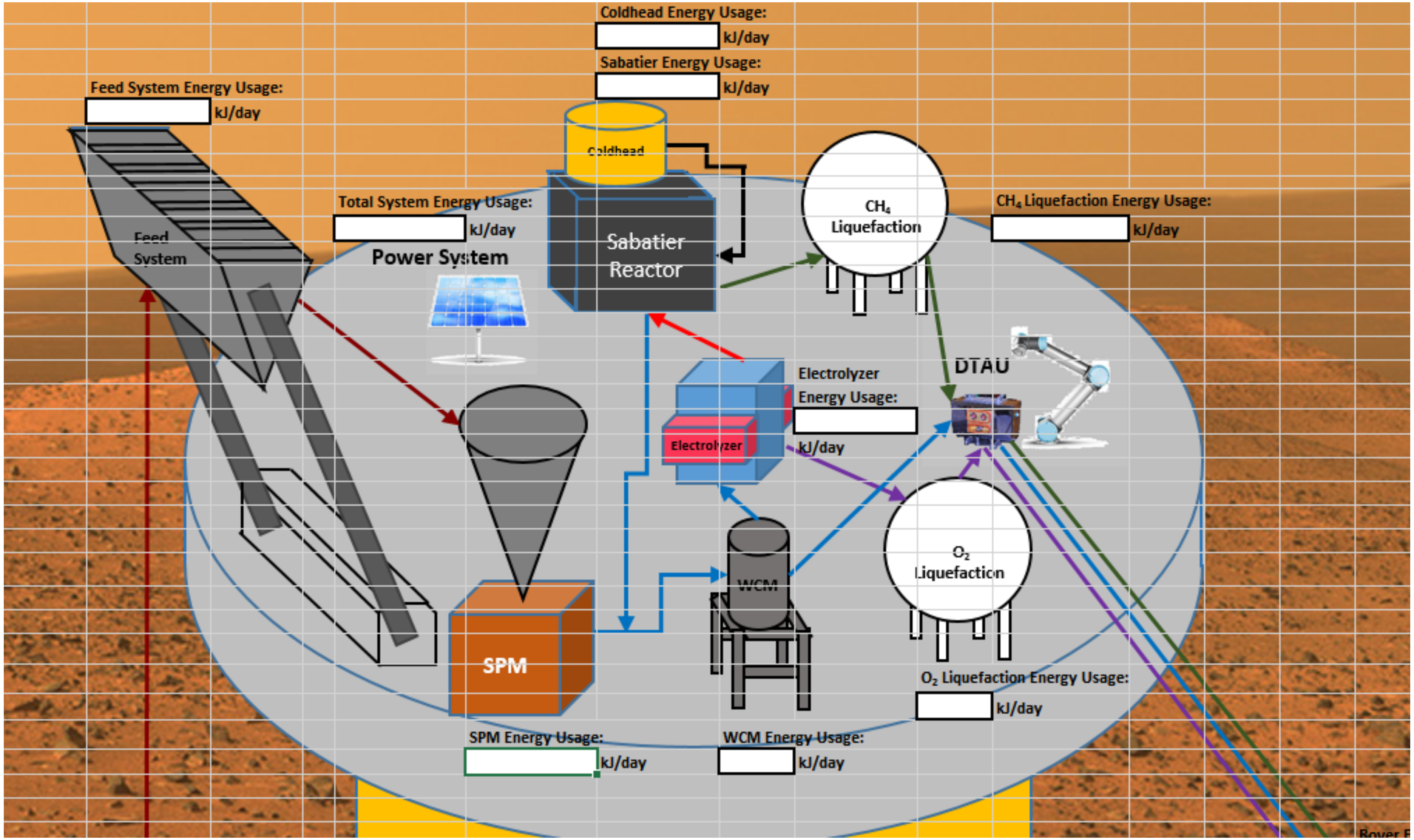
Model Output Graphics (example)

Energy Consumption	
Day (sol):	**240**
Location:	
Excavation System	0.5
Electrolyzer	2.4
Auger	0.2
Water Cleanup Module	0.3
Soil Processing Module	2.6
Power System	0
Sabatier Reactor	1.5
Coldhead	1
O_2 Liquefaction System	0.75
CH_4 Liquefaction System	0.75
Total Power Used:	10

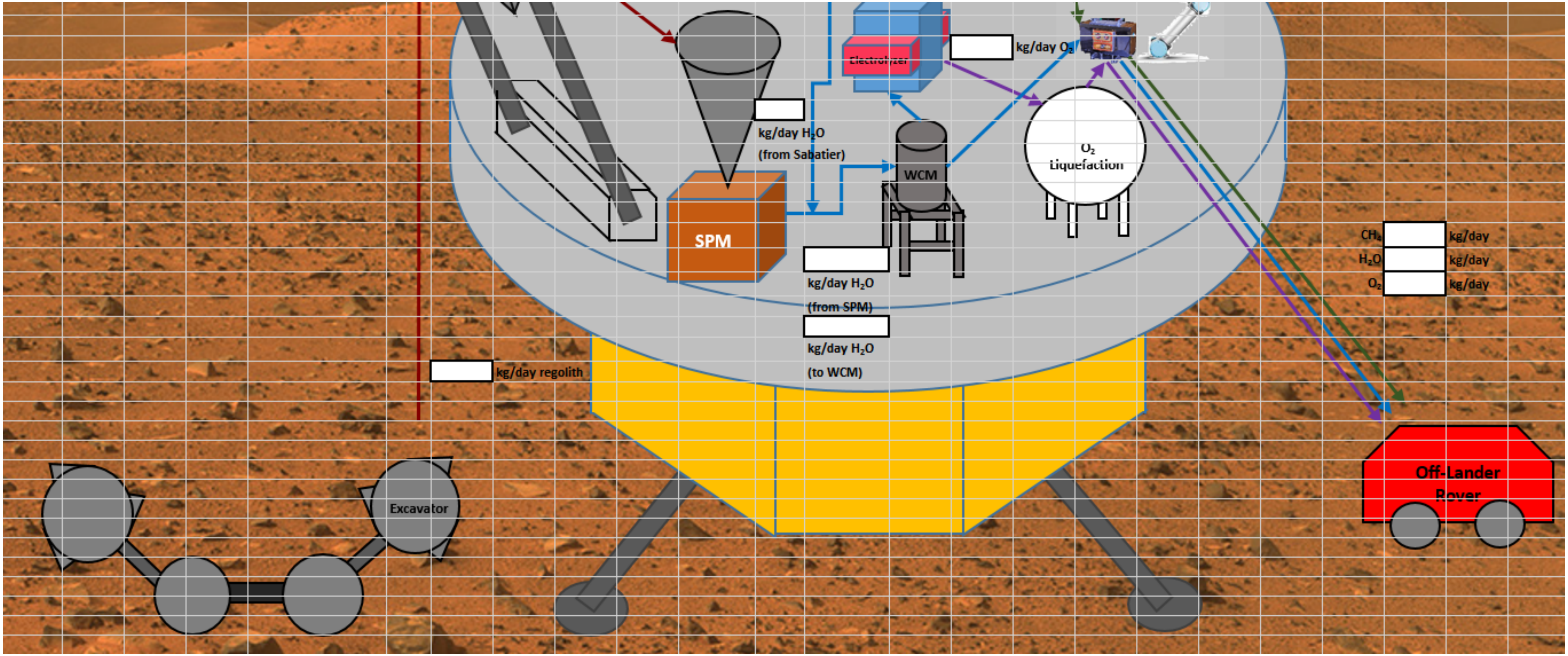




Model Output Graphics



Model Output Graphics



Results / Conclusions

- Model was used to simulate the propellant output of the Mars Pathfinder system during an end-to-end integrated HWIL test based on these data-based and physics-based models.
- 88 grams per hour of CO_2 and 16 grams per hour of H_2 used as inputs for 10 hours per day of system operation. Target production of methane in model was 32 g/hr, i.e. 0.320 kg/day
- The outputs of the simulated system in grams per day of methane were well in line with expectations, given test results and performance expectations from the test conops.
- The simulated production of oxygen was *not* validated by test data and was based on a physics-based legacy model. Future integrated tests will need to include comparisons tests of several electrolyzers.

Simulation discrepancies from HWIL test performance can be attributed to Electrolyzer model.

Conclusions

- More aspects of system operation, such as environmental conditions that were not captured in the lab HWIL test, will have considerable impact on ISRU system-level results.
- This may imply a need to more thoroughly represent temperature and pressure impacts on system performance in future partially-integrated tests, especially for subsystems that are not physically present.

Results shown in this model represent an advancement in the ability to simulate system-level ISRU activity. This should be useful in future ISRU projects in the coming years for design, optimization, and trade studies for these technologies.

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