MARS PATHFINDER ISRU MODELING AND SIMULATION.

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Introduction: The Mars Pathfinder project seeks to increase the technology readiness level of integrated Mars ISRU technologies being developed at NASA. As such, 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).

The Mars Pathfinder system consists of seven subsystems that, together, constitute an integrated ISRU propellant-production system for Mars, using the carbon dioxide found in Mars' atmosphere and water found in the regolith. 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 Mars gas as the atmospheric input and construction sand as the "regolith" input. The purpose of this test was to run all available hardware of the system together in an integrated format over two daily cycles in October 2017, using control hardware and software to communicate between test labs, in order to produce methane as an output and to simulate oxygen as the other output, pumping water out of the system to an off-lander rover in order to represent both propellants as the "product" of the system.

The purpose of the system-level simulation model was to represent this HWIL test using the Mars Pathfinder subsystems whose physical prototypes were available at KSC, while also making use of the data from the test as validation for these subsystem models, and then integrating these subsystem models together with legacy simulation models for the remaining subsystems, whose prototypes are located at other Centers and could not participate in the integrated test due to safety/transportation concerns.

The simulation model consists of a.) An in-house physics-based simulation model of the rover/excavator Regolith Advanced Surface Systems Operations Robot (RASSOR), b.) An empirically-based model of the WCM, Atmospheric Processing Module (APM), SPM, and regolith feed auger subsystems, based on integrated and subsystem test data and c.) Legacy, physics-based simulation models of the Electrolyzer, liquid oxygen (LOX) liquefaction system, and liquid methane (LCH_4) liquefaction systems, the latter of which, along with the SPM, comprise the subsystems that were not physically present at KSC and were simulated in the integrated HWIL test rather than used directly. These subsystem models were linked together into an overall system-level model, which was able to successfully simulate the production of "commodities" LCH_4 and LOX, the former in the quantities that were produced during the integrated test on each test day, and the latter in the quantities that would have been produced from the water that was cycled through the WCM if there had been a physical electrolyzer on Center at KSC.

This simulation model is unique in that it is validated using test data from subsystems partially integrated together for the first time, and also incorporates a relatively new physics-based model for bucket drum excavation. This will be useful in the future for overall system design, whether for parameter variation or for optimization. The model will be described below.

Overview of Subsystems: The subsystems modeled in this simulation are as follows:

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.

Auger—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.

Electrolyzer—This data-based legacy model, based on work performed in [1] and [2], 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: the *Cryocooler*, which simulates the system that extracts carbon dioxide from the air in solidified form, sublimates it, and stores it in a collection tank, and the *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 performed in [1] and [2], 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: This model is not a full simulation of Mars operations. It is aimed at simulating the ISRU system as it was configured in the integrated demo (both prototyped subsystems and subsystems that were simulated during the test), and is not a simulation of Mars operations. The power availability for the system was not limited by solar production, nor did it fluctuate based on the time of year or weather.

The subsystems simulated using physics-based models were the Excavator, Liquefaction System, and Electrolyzer. The Liquefaction System and Electrolyzer models used legacy models previously developed for ISRU modeling work performed under Constellation, whereas the Excavator model was completely new and programmed by the GMRO lab in parallel with their prototype work on RASSOR itself.

The 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. Cryocooler and Sabatier Reactor data (the two constitutive parts of the APM) 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. The models for the Cryocooler and Sabatier reactors, for the time being, were restricted to utilizing test data from October 2017, i.e. the days of the demo test.

Results: The 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, with 128 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. The outputs of the simulated system in grams per day of methane and oxygen are shown in Fig. 1 below, with a total output of 0.36 kg/day and 0.22 kg/day of LCH_4 and LOX, respectively. The former of the two results was well in line with expectations, given test results and performance expectations from the test conops. However, the latter of the two results was well below expectations, and can be traced to the performance of the Electrolyzer in simulation, whose physics-based model predicted separation of a relatively small mole fraction of oxygen from the water at the temperatures and pressures that the integrated HWIL test was run at. This indicates that 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, and that in turn may indicate the 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.

Additionally, power consumption was captured in system-level model simulation. These results were also expected, with the SPM, Electrolyzer, and Liquefaction systems—in short, the systems that were not physically present in the lab due to safety and logistical reasons, consuming the overwhelming majority of the powerused.

The results shown in this model represent an advancement in the ability to simulate system-level ISRU activity, and should be useful at other NASA Centers in the coming years for design, optimization, and trade studies for this technology.

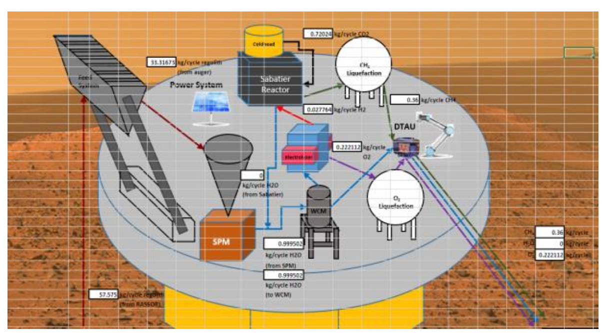

Figure 1. Simulation model propellant production results.

References: [1] E. Santiago-Maldonado and D.L. Linne (2007) *Proc. of 9th Ann. SRR*, [2] S. Schreiner, J. Hoffman, G. Sanders, K. Lee (2015) *Proc. of IEEE AC.*