USE OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION'S (NASA'S) GLOBAL REFERENCE ATMOSPHERIC MODEL (MARS-GRAM) SOFTWARE FOR MODELING GAS CAPTURE AT THE MARTIAN SURFACE. J.V. Drew II, U.S. Army Command and General Staff College, Fort Leavenworth, KS 66027, jvdrew@mines.edu.

Introduction: Although incomplete, information about the Martian atmosphere and its constituent gases is sufficient to support a comprehensive atmospheric model. Since its inception in 1988, the National Aeronautics and Space Administration's (NASA's) Mars-Global Reference Atmospheric Model (GRAM) has modeled effects on spacecraft as they enter and pass through the Martian atmosphere. Mars-GRAM has been used in mission planning for the Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter, and the Mars Atmospheric Volatile Evolution missions and was validated by comparison with Mars Global Surveyor data [1].

With an expanded emphasis on in-situ resource utilization (ISRU), however, it is desirable to model the densities of atmospheric gases at a higher fidelity than is possible with simpler calculations based on atmospheric composition percentages. This paper suggests a novel application of NASA's Mars-GRAM to model the availability of an atmospheric gas by adjusting the parameters that have historically described a spacecraft's trajectory to instead describe sampling points across the volume of a notional gas collector. In this way, masses of constituent atmospheric gases can be modeled for ISRU gas-capture systems. The example presented models dinitrogen (N_2) gas, but the method could readily be applied to any atmospheric gas.

Background: The stated goal of NASA to establish a human presence on the Moon and Mars go hand-in-hand with maximizing, to the extent practicable, the use of in-situ resources. Although the most significant research efforts have thus far focused on developing water, oxygen (O_2) and, on Mars, carbon dioxide (CO_2) resources (e.g., [2], [3], [4]), investigations into the availability of other necessary elements, including argon (Ar) and N_2 are less mature.

Although N_2 is ubiquitous in Earth's atmosphere (constituting approximately 78%), Mars' atmosphere is only about one-sixtieth the density of Earth's and contains only about 2.59% N_2 on average [5], [6], [7]. At the Martian surface, dinitrogen densities have been measured at significantly lower percentages, however, demonstrating the potential inaccuracies of calculations that rely on component averages. For example, Curiosity's quadruple mass spectrometer (QMS) measured volume mixing ratios of the Martian atmosphere over a period of 105 sols in 2012 [8]. QMS provided data on N_2, assessing the volume mixing ratio as 1.93% (± 0.03%) [1], "30% lower than the Viking values" [8] and just over 25% lower than the adjusted average N_2 value of 2.59% [6]. These differences highlight the need to model constituent gases as accurately possible in order to properly scale ISRU systems (and by extension, mission cost) and to reasonably estimate system outputs (thereby reducing mission risk)

Method: Mars-GRAM employs two different models for atmospheric circulation, the Mars General Circulation Model (MGCM) and the Mars Thermospheric General Circulation Model (MTGCM) [1]. Of particular importance to this study is the MGCM, which models the atmosphere "from the surface to 80km altitude" [1]. Software is available from the NASA software catalog [9]. A supplemental Spacecraft Planet Instrument C-matrix Events (SPICE) library is necessary to properly execute ephemeris calculations; these are available from NASA's Navigation and Ancillary Information Facility (NAIF) at [10].

A test run was conducted via the executable file provided for Windows operating systems (MarsGRAM.exe) using the model's standard input parameters, which come with the software in a text file (Appendix B, [1]). Before any input parameters were changed, the outputs of the test run with default parameters were validated against the sample output parameters provided in Appendix C of [1].

Appropriately scaling the initial conditions for the changes in latitude and longitude required an intermediate step to accurately convert degree changes in latitude and longitude (the input parameters necessary to define the path) to linear distances across the surface of Mars. Planetary parameters from [6] were used to define a reference ellipsoid within the Matrix Laboratory's (MATLAB's) mapping toolbox. The definition of this ellipsoid allowed for calculations of the arclength and directional azimuth between the simulation's start and end points, accounting for the variation in linear distance over the ellipsoid.

Through trial and error, a realistic volume (7.82m^3) for a notional gas collector was approximated by allowing the sampling path to traverse 0.5m vertically and 5/100,000th of a degree in both latitude (~2.9m linear distance) and longitude (~2.7m linear distance). It was assumed that the values along the path would be representative of the N_2 values throughout the volume of the collector. The simulation was run under these conditions, changing the simulated date by one month on each iteration to provide a sense of the likely seasonal variability of dinitrogen on the surface. Each simulation stopped at the 500-second mark, when an altitude of 0.5m was reached. Thus, the model represents a cyclic intake and capture system more realistically than it does a continuous-flow system.

The software, in effect, was programmed to model a "spacecraft" travelling a very short distance at a very slow velocity (about 4m in 500s with a change in altitude of 0.5 m). Although this motion makes no physical sense for modeling an interplanetary vehicle, the "spacecraft" functioned like an internal sampler measuring multiple data points within a pre-defined volume.

Results: Although not built as an ISRU modeling platform, Mars-GRAM was utilized for that purpose with adjustments to the input parameters, a novel application of the software. While additional input parameters could be adjusted for higher fidelity or for mission-specific scenarios, for the purposes of demonstrating the feasibility of the method, only the parameters governing height, latitude, longitude, and time were modified. Minimizing the number of changes to input variables reduced the potential for induced errors while still allowing for the estimation of N_2 across a predefined volume of space.

Execution of the simulation provided the results shown in Table 1. Mass percentages reflect estimates nearer to the values measured by QMS than the accepted atmospheric average (2.59%) or the older data of Viking. For this reason, the model is expected to provide more realistic constituent gas estimates. In this case, each cycle of the collector is modeled to take in about 1.5g to 2.6g N_2. Considering that humans need an estimated 14g of nitrogen (in bioavailable forms) per day [10], this notional collector provides a small but useful amount of N_2 for conversion into bioavailable forms.

Importantly, because Mars-GRAM was designed to model spacecraft trajectories, each step of the software's propagation depends upon the outputs of the previous step. It is therefore not possible to use the software to model a stationary object; in test runs, keeping the height, latitude, and longitude variables static led to a stream of constant outputs, including in the calculated values of the constituent gases, which defeated the purpose of the experiment to assess the potential for modeling atmospheric gas capture.

Conclusions: Simulation activities like this are useful in providing baseline values for ISRU projects that aim to harvest atmospheric resources. Concerns about in-situ availability, industrial conversion processes, and power requirements such as those expressed in [12], [13] remain valid for scoping such designs, but the design work now enjoys a firmer footing than would be provided through over-simplified calculations that use component averages. If employed, such component-based calculations could lead, as they did in this case, to an overestimation of resource availability, an under-design of system capacity, and a potentially dangerous scenario for any settlement dependent upon a minimum system output.

Simulated Date (yr. 2020)	N_2 Mass %	Yield for 1 m^3 (kg)	Yield of N_2 collector (kg)
Jan. 25	2.07	2.41E-04	1.88E-03
Feb. 25	2.06	3.01E-04	2.35E-03
Mar. 25	2.00	3.34E-04	2.61E-03
Apr. 25	1.88	3.00E-04	2.35E-03
May 25	1.71	1.98E-04	1.55E-03
Jun. 25	1.64	2.08E-04	1.63E-03
Jul. 25	1.60	2.90E-04	2.27E-03
Aug. 25	1.60	3.07E-04	2.41E-03
Sep. 25	1.64	3.25E-04	2.54E-03
Oct. 25	1.69	2.79E-04	2.18E-03
Nov. 25	1.71	1.99E-04	1.56E-03
Dec. 25	1.76	2.28E-04	1.79E-03

Table 1: Modeled N_2 mass % & yields

Significantly, this method could be used to estimate harvesting rates for any constituent gas from any planetary atmosphere. Although the focus for this paper was Martian N_2, NASA's family of GRAM software includes unique modeling routines for all of the planets in the solar system. Studies on CO_2 would be useful for O_2 separation, methane synthesis, or air diluent studies. Similarly, capturing Ar would be useful for diluting air or for use-cases that require an inert gas (e.g., in welding, lab experiments). Captured O_2, of course, has numerous potential applications. Until dedicated IRSU modeling software is developed for such efforts, however Mars-GRAM provides a useful alternative.

References: [1] Justh H.L. et al. (2021). Mars-GRAM: User guide. [2] Abbud-Madrid A. et al. (2016). Report of the Mars Water ISRU Planning Study. [3] Hoffman J. et al. (2022). *Sci. Adv.* 8(35). [4] Berggren M. et al. (2009). Ch. 21 in *Mars: prospective energy & material resources*. [5] Biferno A. (2023). "10 interesting things about air." NASA. [6] Williams D. (2023). Mars Fact Sheet. NASA. [7] Williams D. (2023). Earth Fact Sheet. NASA. [8] Mahaffy P. (2013). *Sci.* 341(6143), 263-266. [9] https://software.nasa.gov/. [10] ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels. [11] Smith S. et al. (2021). *Human adaptation to spaceflight*. NASA. [12] Yamashita M. et al. (2005). *J. of Sp. Tech. & Sci.* 21(2), 2-1 to 2-10. [13] Langenfeld N. et al. (2021). *Front. In Astron. & Sp. Sci.*, 8.