NOVEL IN SITU PERCHLORATE-BASED BLASTING AGENTS FROM MARTIAN REGOLITH RESOURCES.

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Introduction: The need for substantial resources forms a significant barrier to both short- and long-term settlement of Mars. The Martian landscape is rich in untapped metal and mineral ores, making *in situ* resource utilization (ISRU) valuable for circumventing the costly transport of Earth-based materials. However, the quantities of these materials necessary to meaningfully support future in-space activities would require large-scale excavation. Centuries of terrestrial mining history prove that explosive blasting is critical to economical mining. Rock crushing and grinding account for 30% of total mining energy, and blasting can drastically reduce the downstream work involved in these processes by decreasing the size of resulting debris and softening rock. [1,2] Blasting capabilities in a Martian setting would similarly be transformative towards expediting the acquisition of resources. In addition, explosive earthmoving on Mars would create several new opportunities for settlement, such as rapid construction of habitat foundations and emergency shelters or access to underground cave structures away from the extreme surface environment. [3,4]

ISRU explosive manufacture would bypass the expensive and hazardous transit of energetic materials to Mars. The global abundance of perchlorate salts within Martian regolith poses a strategic resource for explosive synthesis. The upper tens of centimeters of regolith and ground ice contain perchlorates at 0.5-1.0 wt.%, of which calcium perchlorate (CaP, $Ca(ClO_4)_2$) and magnesium perchlorate (MgP, $Mg(ClO_4)_2$) exist in a 60:40 wt.% ratio, respectively. [5,6] It is already desirable to remove these impurities since they would impede future agriculture and human metabolic function [7], so the repurposing of these waste oxidizers into solid energetics would be a strategic technological breakthrough.

The performance of CaP and MgP as energetic oxidizers has not been thoroughly investigated. A single study exists which explores their potential use for ISRU solid rocketry. [8] Alternatively, a simple, fully *in situ* explosive may be achievable by physical mixture of the Martian perchlorates with ISRU-derivable fuels, such as diesel, sulfur, and aluminum. [9,10,11] The objective of this work is to i) characterize the theoretical performance of CaP- and MgP-based explosives, ii) fabricate simple two- or three-component heterogeneous explosive mixtures, and iii) assess sensitivity and detonability of the charges to determine their potential as a safe yet effective explosive tool.

Methods: *Thermochemical Simulation.* Candidate formulations were screened using EXPLO5 V6.06 thermochemical code. [12] Detonation performance parameters were calculated based on the Chapman-Jouguet ideal detonation model paired with the Exp-6 product equation of state. For comparison to the most widely-used mining explosive, ANFO (94 wt.% ammonium nitrate (AN), 6 wt.% fuel oil), a similar theoretical maximum density (TMD) of 58.4% TMD is applied to all formulations. Fuel components were varied in 2.5 wt. % increments to explore two- and three-component mixtures and identify those which maximize detonation pressure and detonation velocity. The Langefors weight strength concept is utilized for comparison of the theoretical rock-breaking capacity of the candidate mixtures relative to ANFO. [13]

Energetic Manufacture. Three high-performing formulations identified from EXPLO5 were manufactured into explosive charges for experimental investigation. MgP and CaP are obtained from lab-grade chemical suppliers. The perchlorates were ground by hand using a mortar and pestle then dried in a vacuum oven at 60°C for 72 hours to remove moisture. The ground oxidizers had a mean particle diameter of ~200 µm with a D50 particle diameter of ~110 µm, as verified by microscopy survey. Diesel No.2 was the primary fuel while sulfur and spherical aluminum powder served as additives. Dried perchlorates were immediately wetted with diesel to block water-adhering sites on the particle surfaces. Acoustic mixing was applied at 60 g's for 3 minutes to homogenize the mixture. Additives were then incorporated, followed by a repeated stage of acoustic mixing.

Sensitivity and Detonation Testing. The sensitivity thresholds of the manufactured explosive subjects to various external stimuli were quantified. Drop weight impact testing, friction testing, and electrostatic discharge testing were performed to evaluate the hazards of accidental ignition during transport and handling.

A small-scale shock sensitivity test was employed as an initial assessment of initiability and critical diameter. As a result of the small diameter, the chemiluminescent reaction travels into the sample explosive for some distance before failing (run-to-failure distance, RTF), and the RTF provides qualitative insight to the sample's ability to support chemical reaction. [14] Samples were packed to the prescribed 58.4% TMD in ten increments within polymethyl methacrylate (PMMA) tube. As shown in Fig. 1, an exploding bridgewire detonator prompted a strong shock into 25.4 mm of booster explosive which then propagated into the top of the sample explosive. The transparent confiner allowed high-speed recording at 10 Mfps. Three charges of each formulation were detonated within a enclosed, thick-walled detonation chamber with optical access.

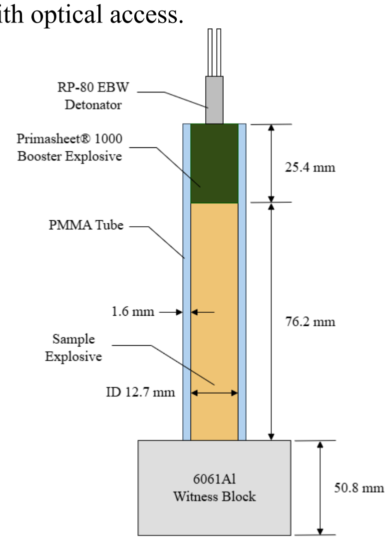

Fig. 1: *Illustration of experimental charge configuration for assessing shock sensitivity*

Results/Discussion: EXPLO5 simulations indicate that the selected Martian explosive formulations can achieve comparable or greater explosive performance than ANFO. A mixture of 80 wt.% of the Mars perchlorates (in the ratio they naturally occur) and 20 wt. % diesel produced the highest detonation pressure and velocity. When considering sulfur or aluminum additives, optimal compositions were 85 wt% Mars perchlorates with 12.5 wt% diesel and 2.5 wt. % of either additive. While the lower detonation pressure and velocity would intuit lower performance than ANFO, the Langefors weight strengths, calculated using the heat of detonation and product gas volume, yielded weight strengths relative to ANFO of 0.98-1.11. This implies that the rock-breaking capacity of the selected mixtures should be nearly equal if not greater than ANFO.

Sensitivity experiments generally showed similar ignition energy thresholds to ANFO, though additives show strong influences on resultant behavior. Initiation into the perchlorate-diesel mixture exhibited a mean RTF of 14 mm, lower than even granular AN without fuel oil (RTF of 25 mm). This suggests weaker transmission of energy and reduced sensitivity, thereby being safer to handle. Mixtures with addition of 2.5 wt% sulfur or aluminum yieelded mean RTFs of 28 mm and 36 mm between two shots, respectively. One sample of each sustained the reaction wave for the entire length of the 76.2 mm sample. It can be inferred that doping of sulfur or aluminum can significantly decrease the critical charge diameter, though the exact mechanism by which this occurs has yet to be explored.

The detonation performance of heterogeneous oxidizer-fuel mixtures is strongly influenced by parameters such as density, porosity, particle size, particle morphology, and more. These findings show that experimental variables must be tightly controlled so as to not affect test results. Nonetheless, repeated trials reveal exceptionally low sensitivity of the perchlorate blend with diesel, as well as a tunable sensitivity through small additions of sulfur or aluminum. For hypothetical Martian blasting, the explosive mixture without additive could be relatively safe for storage, handling, and transport. Additives could be introduced only at the site of employment to increase detonability so thorough charge detonation can be ensured.

Conclusion: Blasting technology on Mars could be pivotal to future mission architectures. Thermochemical software was used to validate the potential of simple ISRU explosive mixtures. Heterogeneous formulations of perchlorates found in Martian regolith with diesel, sulfur, and aluminum have calculated rock-breaking capacities which may match or outperform terrestrial mining explosives. Ideal mixtures were manufactured so that understanding of safety precautions and detonability of the formulations could be developed. This work lends credibility to the theoretical feasibility of CaP- and MgP-based blasting agents for the purpose of benefitting future excavation and construction on Mars.

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