REACTION MECHANISMS IN COMBUSTIBLE REGOLITH/MAGNESIUM MIXTURES. A. Delgado and E. Shafirovich, Department of Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, eshafirovich2@utep.edu.

Introduction: Sustained space exploration will involve construction of landing/launching pads, radiation shielding, and other structures on the Moon and Mars. The production of construction materials from in-situ resources is of major importance as it will eliminate/reduce the costs of transporting them from Earth. Among various alternatives considered for fabricating construction materials in space, combustion-based methods offer low energy input and high utilization of local resources, simultaneously providing a heat generation source.

Recently, it has been demonstrated that lunar and Martian regolith simulants form combustible mixtures with magnesium (Mg) [1-5]. Figure 1 shows the adiabatic flame temperatures calculated for the mixtures of Mg with JSC-1A (lunar), JSC-Mars-1A, and Mojave Mars regolith simulants. Since reliable data on the mineral composition are available only for JSC-1A, it was assumed that the three regolith simulants are mixtures of simple oxides as shown in Table 1. It is seen that the curves for Mojave Mars and JSC-1A are close to each other, while JSC-Mars-1A exhibits higher temperatures. Combustion experiments at 20 wt% Mg and 30 wt% Mg have shown a more vigorous combustion for JSC-Mars-1A than for Mojave Mars [5].

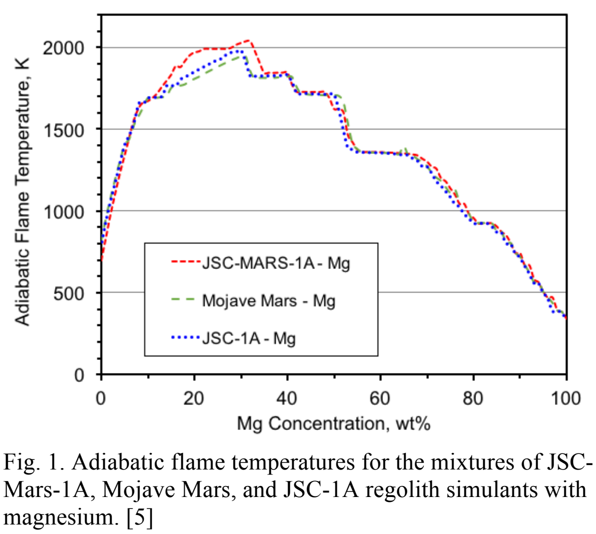

Fig. 1. Adiabatic flame temperatures for the mixtures of JSC-Mars-1A, Mojave Mars, and JSC-1A regolith simulants with magnesium. [5]

Table 1. Compositions of the regolith simulants [6, 7].

Compound	Concentration, wt%		
	JSC-1A	**JSC-Mars-1A**	**Mojave Mars**
SiO_2	45.7	43.48	49.4
Al_2O_3	16.2	22.09	17.10
Fe_2O_3	12.4	16.08	10.87
CaO	10.0	6.05	10.45
MgO	8.7	4.22	6.08
Na_2O	3.2	2.34	3.28
TiO_2	1.9	3.62	1.09

Analysis of the regolith simulant compositions implies that magnesium may interact with SiO_2 and Fe_2O_3 via thermite reactions:

$$SiO_2 + 2\ Mg \rightarrow Si + 2\ MgO, \quad \Delta H^\circ_{rxn} = -146 \text{ kJ per mol Mg} \tag{1}$$

$$Fe_2O_3 + 3\ Mg \rightarrow 2\ Fe + 3\ MgO, \quad \Delta H^\circ_{rxn} = -328 \text{ kJ per mol Mg} \tag{2}$$

The high adiabatic flame temperatures and more vigorous combustion for JSC-Mars-1A are apparently associated with the higher Fe_2O_3 concentration in this simulant. As seen in Table 1, Mojave Mars and JSC-1A contain 10.9 and 12.4 wt% Fe_2O_3, respectively, while JSC-Mars-1A contains 16.1 wt% Fe_2O_3. Since the reaction of Mg with iron oxide (Eq. 2) is more energetic than that with silica (Eq. 1), an increase in Fe_2O_3 content may lead to the higher combustion temperature.

The present paper focuses on verifying this hypothesis and clarifying the reaction mechanisms of the regolith/magnesium mixtures during combustion. Differential scanning calorimetry is used for this purpose.

Experimental: Each of JSC-1A, JSC-Mars-1A, and Mojave Mars regolith simulants was milled to a powder with a median diameter of 2–3 µm in a planetary ball mill (Fritsch Pulverisette 7 Premium Line) at a rotation speed of 1100 rpm using zirconia-coated bowls and zirconia grinding balls. The process included four 10-min milling periods separated by a 60-min pause for cooling. The milled regolith simulants were mixed with magnesium powder (−325 mesh, i.e., less than 44 µm, 99.8% pure, Sigma-Aldrich) for one hour in a three-dimensional inversion kinematics mixer (Bioengineering Inversing 2L).

The mixtures were analyzed using a differential scanning calorimeter (Netzsch DSC 404 F1 Pegasus). The mixture samples were placed in alumina crucibles and heated in an argon flow at a heating rate of 10 °C/min.

Results: JSC-1A, JSC-Mars-1A, and Mojave Mars simulants with 26 wt% Mg were heated to 650°C at a heating rate of 10 °C/min. Figure 2 shows the obtained DSC curves. The JSC-Mars-1A mixture showed the highest temperature while Mojave Mars the lowest.

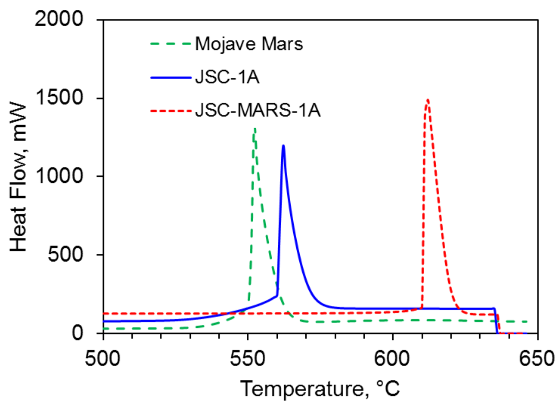

Fig. 2. DSC curves for mixtures of JSC-1A, JSC-Mars-1A, and Mojave Mars simulants with Mg.

The observed order of peaks correlates with the ratio of silica and iron oxide in the simulants. Indeed, based on the data in Table 1, the SiO_2-Fe_2O_3 ratios by mass in Mojave Mars, JSC-1A, and JSC-Mars-1A simulants are 4.54, 3.69, and 2.70, respectively. This implies that the peak temperature increases with decreasing the SiO_2-Fe_2O_3 ratio.

To verify the correlation of the peak temperature with the SiO_2-Fe_2O_3 ratio in regolith, ternary $SiO_2/Fe_2O_3/Mg$ mixtures were tested in the DSC. In these mixtures, SiO_2−Fe_2O_3 mass ratio was varied, while the magnesium content was controlled by stoichiometry. Three ternary mixtures were prepared:

- SiO_2−Fe_2O_3 mass ratio: 2
  (71 wt.% Mg/SiO_2 and 29 wt% Mg/Fe_2O_3)
- SiO_2−Fe_2O_3 mass ratio: 1
  (55 wt% Mg/SiO_2 and 45 wt% Mg/Fe_2O_3)
- SiO_2−Fe_2O_3 mass ratio: 0.5
  (38 wt% Mg/SiO_2 and 62 wt% Mg/Fe_2O_3)

Figure 3 shows the DSC curves obtained for the three mixtures. Again, with decreasing the SiO_2−Fe_2O_3 mass ratio, the peak temperature increases. This confirms that the order of peaks for Mg/simulant mixtures in Fig. 2 is related to the SiO_2−Fe_2O_3 mass ratio.

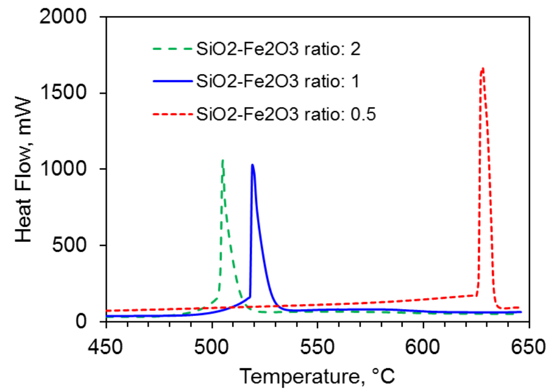

Fig. 3. DSC curves for $SiO_2/Fe_2O_3/Mg$ mixtures with SiO_2−Fe_2O_3 mass ratios of 2, 1, and 0.5.

Further, the order of the adiabatic flame temperatures for the three simulants at 20−30 wt% Mg (Fig. 1) also corresponds to the decrease in the SiO_2−Fe_2O_3 mass ratio. Iron-rich regolith/magnesium mixtures exhibit higher temperatures and more vigorous combustion owing to the higher exothermicity of Mg−Fe_2O_3 reaction (Eq. 2). However, the lower temperature required for Mg−SiO_2 reaction makes it easier to ignite mixtures with the iron-lean (i.e. silica-rich) regolith simulants.

Conclusion: The high content of iron oxide plays an important role in the combustion of JSC-Mars-1A simulant with magnesium. For Mojave Mars and JSC-1A regolith simulants, where the concentration of iron oxide is lower, silica also plays a significant role in the reactions with magnesium by enabling the ignition at lower temperatures.

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References: [1] C. White, F. Alvarez, E. Shafirovich, J. Thermophys. Heat Tr. 25 (2011) 620−625. [2] F. Álvarez, A. Delgado, J. Frias, M. Rubio, C. White, A.K. Narayana Swamy, E. Shafirovich, J. Thermophys. Heat Tr. 27 (2013) 576−583. [3] F. Álvarez, C. White, A.K. Narayana Swamy, E. Shafirovich, Proc. Combust. Inst. 34 (2013) 2245–2252. [4] A. Delgado, E. Shafirovich, Combust. Flame 160 (2013) 1876−1882. [5] A. Delgado, S. Cordova, E. Shafirovich, Combust. Flame 162 (2015) 3333−3340. [6] C.S. Ray, S.T. Reis, S. Sen, J.S. O'Dell, *J. Non−Crystalline Solids* 356 (2010) 2369−2374. [7] G.H. Peters, W. Abbey, G.H. Bearman, G.S. Mungas, J.A. Smith, R.C. Anderson, S. Douglas, L.W. Beegle, *Icarus* 197 (2008) 470–479.