Thermite reactions with oxides of iron and silicon during combustion of magnesium with lunar and Martian regolith simulants

Armando Delgado, Sergio Cordova, and Evgeny Shafirovich*

Department of Mechanical Engineering, The University of Texas at El Paso, El Paso, TX 79968,
USA

*Corresponding Author. Tel.: +1 915 747 6465; fax: +1 915 747 5019.

E-mail: eshafirovich2@utep.edu (E. Shafirovich).

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Abstract

It has been shown recently that mixtures of JSC-1A lunar regolith simulant with magnesium are combustible. Thermite-type reactions in these mixtures could be used for *in situ* production of construction materials on the Moon. Because of complex composition of lunar regolith, however, the mechanisms of these reactions are not well understood. Also, for Mars mission applications, it is important to explore the possibility of using Martian regolith in such mixtures. In the present paper, combustion of two Martian regolith simulants (JSC-Mars-1A and Mojave Mars) with magnesium is studied using thermodynamic calculations and combustion experiments. To understand the reaction mechanisms in these mixtures as well as in the mixtures of JSC-1A lunar regolith simulant with magnesium, thermoanalytical experiments are also conducted. It has been shown that the Martian regolith simulants form combustible mixtures with magnesium. The measured combustion temperatures and identified product compositions are in reasonable agreement with thermodynamic predictions. The mixtures of JSC-Mars-1A with magnesium at 20-30 wt% Mg exhibit higher temperatures and burn more vigorously than mixtures based on Mojave Mars, which is explained by the higher content of iron oxide in JSC-Mars-1A. For Mojave Mars, combustion is accompanied by oscillations in the front motion and by the formation of a layered structure of the product. This effect is more significant at lower concentrations of Mg. Thermoanalytical studies have shown that iron oxide plays a dominant role in the combustion of JSC-Mars-1A simulant with magnesium. However, Mg/SiO₂ mixture ignites at a temperature lower by approximately 100°C than for Mg/Fe₂O₃. For Mojave Mars material and JSC-1A lunar regolith simulant, which include more silica and less iron oxide, silica exhibits a significant effect on the combustion, promoting reactions at lower temperatures.

Keywords: heterogeneous combustion, thermites, combustion synthesis, magnesium, iron oxide, silica

1. Introduction

Recently, it has been proposed to use combustion of lunar regolith with aluminum [1-3] and magnesium [4-7] for the production of construction materials on the Moon. Thermite-type reactions between regolith and the added metal lead to the formation of products that are sufficiently strong for construction applications. An important advantage of this approach is small energy consumption because the combustion process is self-sustained and only small amount of energy is required for ignition. The required metal could be brought from Earth or obtained *in situ* by recycling the lander parts and by processing regolith [8]. Trade-off studies could be conducted to compare combustion synthesis of construction materials from regolith and transported/recycled/recovered metal, incorporation of regolith into thermoplastics [9-11], and high-temperature sintering of regolith using microwave [12, 13] or laser [14] radiation. Such studies, however, should involve a detailed mission analysis, which is beyond the scope of the present work.

Previous research has revealed significant advantages of Mg over Al in combustion with JSC-1A lunar regolith simulant. Combustion with Al requires significant preheating of the mixture [1], adding ilmenite as an oxidizer while keeping the regolith as an inert material [2, 3], or adding polytetrafluoroethylene as an additional reactant [15]. In contrast, the mixtures of JSC-1A with Mg ignite with no need for preheating or adding reactants, leading to a steady or spinning propagation of the combustion wave over the pellet at relatively low concentrations of Mg [4-7]. Further, use of SHS compaction (quasi-isostatic pressing immediately after combustion) for JSC-1A/Mg mixtures has enabled fabrication of products with a compressive strength exceeding 10 MPa, i.e., stronger than common bricks (5 MPa) [7].

Because of a complex composition of lunar regolith, however, the combustion mechanisms of its mixtures with metals are not well understood. For example, the mineral composition of JSC-1A lunar regolith simulant includes (in order of decreasing mass fraction) anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), albite ($\text{NaAlSi}_3\text{O}_8$), forsterite (Mg_2SiO_4), wollastonite (CaSiO_3), enstatite (MgSiO_3), ferrosilite (FeSiO_3), fayalite (Fe_2SiO_4), and other crystalline and amorphous phases [4]. For simplicity, it is possible, at the cost of a decreased accuracy, to represent the regolith composition as a mixture of simple oxides such as SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , Na_2O , etc. Among these, SiO_2 and Fe_2O_3 may exhibit thermite reactions with Mg:

It is unclear, however, which of these two oxides plays a greater role in the combustion process. Silica has a higher concentration in JSC-1A regolith simulant (45.7 wt% vs 12.4 wt% for Fe_2O_3 [16]), but iron oxide thermodynamically exhibits a higher heat release.

Another issue that was not studied previously is the fact that the tested JSC-1A simulant is just one material that is similar chemically to regolith in some specific areas of the Moon surface [16, 17]. Lunar dusts in other areas as well as Martian regolith are chemically different from JSC-1A [18, 19]. Thus, the hypothesis that Martian regolith forms combustible mixtures with magnesium should be verified experimentally.

One objective of the present research was to investigate combustion of Martian regolith simulants (JSC-Mars-1A and Mojave Mars) with magnesium and compare their combustion characteristics with those of JSC-1A/Mg mixtures. This part of research included thermodynamic calculations and combustion experiments.

As noted above, to fabricate stronger products, SHS compaction could be used [7]. To study combustion behavior and mechanisms, however, experiments in a gas environment are more convenient. The choice of the gas environment is an important issue. As discussed previously [7], combustion of regolith mixed with Mg or Al is hardly possible in ultrahigh vacuum (pressure less than 10^{-7} Pa) of the Moon because of vaporization of the metals during ignition so that a pressurized reactor is required. On Mars, mixtures of regolith with Mg could be burned in CO_2 , which constitutes 95% of the Martian atmosphere, but the low atmospheric pressure (0.6–1 kPa) would remain a problem. It has been reported that at pressure less than 25 Torr (3.3 kPa), ignition of JSC-1A mixed with FeTiO_3 and Mg led to the pellet disintegration [3]. On the other hand, no differences in the combustion behavior and front propagation velocity were observed for JSC-1A/Mg mixtures at pressures 10 kPa and 90 kPa [4]. Since the goal of the present work was to compare the Martian and lunar regolith simulants, all combustion experiments were conducted under identical conditions, i.e., in an argon environment at 1 atm. This was also

convenient for comparison with thermoanalytical experiments, conducted at atmospheric pressure.

It should be noted that on Mars it could be advantageous to use compressed Martian “air” (which is mainly CO₂) as an environment in the reactor. From this point of view, it would be important to conduct experiments on combustion of Martian regolith simulants with Mg in a CO₂ environment. The use of CO₂ instead of argon may influence the combustion process because Mg particles burn with CO₂ [20-24]. In the present research, however, the goal was to compare the Martian regolith simulants with the lunar one so that only argon was used as the environment.

The second objective of the research was to clarify the mechanisms of reactions that occur during combustion of the regolith simulants with magnesium. This was achieved using thermoanalytical experiments and X-ray diffraction analysis of quenched samples.

2. Experimental

JSC-Mars-1A and JSC-1A regolith simulants were obtained from ORBITEC, while Mojave Mars simulant was provided by NASA. In contrast with the actual lunar dust, JSC-1A is a quite coarse powder, which needs to be ground to the particle size of less than 100 µm for combustion with magnesium powder [4]. The two Martian simulants are also coarse [18, 19]. To compare the combustion characteristics of the three simulants, each of them was milled to a powder with a median diameter of 2–3 µm. This was achieved with a planetary ball mill (Fritsch Pulverisette 7 Premium Line) at a rotation speed of 1100 rpm using zirconia-coated bowls and zirconia grinding balls (diameter: 1.5 mm; the balls-mixture ratio: 4:1). Each of the four cycles included a 10-min milling period and a 60-min pause for cooling. The particle size distributions of the milled powders were measured using a laser diffraction particle size analyzer (Microtrac Bluewave), with isopropyl alcohol being used as a carrier fluid. For example, Figure 1 shows the particle size distribution for the milled JSC-Mars-1A simulant. The particle size distributions of two other milled powders are similar.

The milled regolith simulants were mixed with magnesium powder (–325 mesh, i.e., less than 44 µm, 99.8% pure, Sigma-Aldrich) in a three-dimensional inversion kinematics tumbler mixer (Bioengineering Inversina 2L) for one hour. The mixtures were then compacted into

cylindrical pellets (diameter: 13 mm, height: 21-24 mm) using a uniaxial hydraulic press (Carver).

To study the combustion process, the pellet was placed inside a windowed steel chamber (diameter 30 cm, height 40 cm), connected to a compressed argon cylinder and a vacuum pump. All experiments were conducted in an argon environment at 1 atm. The pellet was installed on a brass pedestal inside the chamber and ignited at the top by a tungsten wire heated with a DC power supply. The temperature in the middle of the pellet during combustion was measured by a thermocouple (K-type, 254- μ m diameter wire, Omega Engineering). The thermocouple, located in a two-channel ceramic insulator (outer diameter: 1.6 mm, Omegatite 200, Omega Engineering) was inserted into the pellet through a channel drilled perpendicularly to the pellet axis. Digital video recording (Sony XCD-SX90CR) was used for observation and for determination of the combustion front velocity. The combustion product compositions were characterized using X-ray diffraction analysis (Bruker D8 Discover XRD).

Thermal analysis of mixtures was conducted using a differential scanning calorimeter (Netzsch DSC 404 F1 Pegasus). The DSC was calibrated using standard materials (In, Sn, Bi, Zn, Al, and Au) obtained from the manufacturer. The temperature program was carried out for all these materials with three heating and two cooling segments so that the melting peak of each material was measured three times. All calibration runs were performed using alumina crucibles at a heating rate of 20 K/min and argon flow rate of 20 mL/min. The obtained melting points of the materials were introduced into a calibration file for the DSC software. An experimental error at 650 °C (the maximum temperature in the conducted DSC tests) was within 6 °C.

The mixture samples placed in alumina crucibles were heated in an argon flow (20 mL/min) at heating rates of 5 °C/min or 10 °C/min, depending on the test. In some tests, the heating process was terminated at different temperatures and the condensed products were cooled in argon for subsequent XRD analysis.

3. Results and discussion

3.1. Thermodynamic analysis of combustion of Martian regolith simulants with magnesium and aluminum

Thermodynamic calculations of the adiabatic flame temperature and combustion products for the mixtures of two Martian regolith simulants with magnesium and aluminum were conducted using THERMO (version 4.3) software, which is based on the Gibbs free energy minimization and contains a database of approximately 3000 compounds [25]. Of specific importance is the capability of this code to handle multi-phase thermite reactions with many compounds. This software was used for thermodynamic analysis of combustion of JSC-1A lunar regolith simulant with Mg, Al, and Ti/B additives [4].

The concentration of metal (Mg or Al) was varied from 0 to 100%, while initial reactants were at 298 K and pressure was 1 atm in all calculations. A major problem in these calculations was the fact that quantitative mineral compositions of JSC-Mars-1A and Mojave Mars simulants remain unknown. The literature search revealed only qualitative mineral compositions. To enable calculations, these materials were represented as mixtures of simple oxides. The simple oxide compositions of all three simulants are known [16, 18] and they are presented in Table 1. Note that for JSC-1A, the quantitative mineral composition is also known [4]. Thus, thermodynamic calculations for the Martian regolith simulants were conducted for the compositions presented in Table 1.

Figure 2 shows the adiabatic flame temperatures obtained for the mixtures of Mg and Al with JSC-Mars-1A and Mojave Mars simulants (simple oxide compositions). For comparison, the results obtained for Mg with JSC-1A (both mineral [4] and simple oxide compositions) are also shown. It is seen that Mg exhibits higher temperatures than Al for all regolith simulants.

It is also seen that the curves for Mojave Mars and JSC-1A (simple oxides) are very close to each other, while JSC-Mars-1A exhibits higher temperatures. This is apparently associated with Fe_2O_3 concentrations in the simulants. 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% of this oxide. Since the reactions of Mg and Al with Fe_2O_3 are more energetic than those with SiO_2 , an increase in Fe_2O_3 content leads to the higher adiabatic flame temperature.

Note that the substitution of actual minerals with simple oxides inevitably created an error in the adiabatic flame temperature. The comparison of the curves obtained for JSC-1A, with simple oxide and mineral compositions, shows that the simple oxide composition exhibits higher temperatures. This may be explained by the higher negative formation enthalpies of mineral phases than those of simple oxides from which these mineral phases were formed. It is

reasonable to suggest that the same trend would remain for two other simulants. The fact that the use of simple oxide compositions predicts higher temperatures than the actual ones should be accounted for in the comparison with experimental results.

The thermodynamic calculations provided compositions of combustion products for all tested mixtures. For illustration, Table 2 shows the products of mixtures of the three simulants with 20 wt% Mg and 26 wt% Mg (the latter is the optimal concentration for combustion of JSC-1A/Mg mixture if the mineral composition of JSC-1A is assumed [4]). The results presented in Table 2 were obtained for simple oxide compositions of all simulants (including JSC-1A) shown in Table 1. Note that THERMO software shows the products using molecular formulas. For easier understanding, the second column in Table 2 shows the same products as mixtures of simple oxides. The third column indicates states of the compounds: S – solid, L – liquid, and G – gas.

Analysis of Table 2 shows that the major phases are MgO and mixtures of MgO, CaO, Al₂O₃, and SiO₂. Significant amounts of FeSi and Si as well as around 1 or 2 wt% Si₃Ti₅ are also present in the products of all six mixtures. It is important that there is no iron oxide in the products, while only part of silica is reduced. This indicates that both thermite reactions (Eqs. 1 and 2) occur, but there is not enough Mg for the reduction of all available silica. It can therefore be concluded that the reaction of Mg with Fe₂O₃ (Eq. 2) is thermodynamically preferential under these conditions.

Comparison of the product compositions for JSC-1A represented as a mixture of simple oxides with those for JSC-1A represented as a mixture of minerals [4] shows some differences. It is reasonable to expect that if the quantitative mineral compositions of the Martian regolith simulants become known, more accurate phase compositions of products can be calculated for combustion of them with Mg, but some features, such as the preferential reduction of iron oxide, will remain.

To better understand the results obtained for the mixtures of regolith simulants with Mg and Al, thermodynamic calculations were also conducted for binary mixtures Fe₂O₃-Mg, SiO₂-Mg, Fe₂O₃-Al, and SiO₂-Al. Figure 3 presents the obtained adiabatic flame temperatures. It is seen that the temperatures for iron oxide-based mixtures are much higher than those for silica-based mixtures, which is explained by the higher exothermicity of Mg and Al reactions with iron oxide. Comparison with Fig. 2 shows similar features of regolith-based and silica-based curves, which is apparently associated with the high concentrations of silica in the regolith simulants. Note that

the temperatures for SiO₂/Mg mixtures are higher than those for SiO₂/Al mixtures, which explains why Mg exhibits higher temperatures than Al in mixtures with regolith simulants. It is also interesting that the maximum temperatures for regolith-based mixtures are similar to those for SiO₂-based mixtures, but they are achieved at low metal concentrations. This is explained by the significant energy release of the reactions between the metal and Fe₂O₃, which is available in the regolith simulants.

3.2. Combustion experiments with Martian regolith simulants

Experiments with mixtures of the Martian regolith simulants with magnesium were conducted at concentrations of Mg from 10 wt% to 80 wt%, with an increment of 10 wt%. The experiments have shown that the mixtures are combustible at Mg concentrations from 20 through 70 wt%. The front propagation velocities were in the range from 1.5 to 5 mm/s, which is similar to the observations for JSC-1A/Mg mixtures [4-7]. In all experiments, significant expansion of the sample occurred during combustion. For Mojave Mars, combustion was accompanied by oscillations in the front motion and by the formation of a layered structure of the product. This effect was more significant at lower concentrations of Mg. Figure 4 shows combustion of Mojave Mars simulant mixed with magnesium at 20 wt% Mg (see also video 1 in Supplemental Material). Note that oscillating combustion of pellets has been predicted in the theory of heterogeneous combustion and observed in combustion experiments with many low-exothermic mixtures [26, 27]. For JSC-Mars-1A, at 20 wt% Mg and 30 wt% Mg, combustion was much more vigorous than for Mojave Mars, with a relatively fast, steady motion of the front and a uniform structure of the product (see images in Fig. 5 and video 2 in Supplemental Material).

Figure 6 shows the maximum temperatures measured during combustion of JSC-Mars-1A and Mojave Mars simulants with magnesium. For convenience, the calculated temperature curves for these two simulants, shown in Fig. 2a, are repeated in Fig. 6. It is seen that the experimental values are lower than the predicted ones. This is explained by heat losses in the experiments and by the assumption of simple oxide compositions in the calculations, which, as mentioned above, leads to increased temperatures. The fact that at Mg concentrations of 20 wt% and 30 wt% the measured temperatures for JSC-Mars-1A were higher than those for Mojave Mars accords with the difference between the adiabatic flame temperatures of these materials,

discussed in Section 3.1 and explained by the higher concentration of Fe_2O_3 in JSC-Mars-1A. The higher temperatures for JSC-Mars-1A also correlate with the faster combustion of this material, mentioned above.

The expansion of samples during combustion was apparently caused by Mg vapor, formed in the combustion front. As seen in Fig. 6, the maximum temperatures in the combustion front were in a range from 1100 K to 1700 K. Since the boiling point of Mg at 1 atm is 1368 K, significant amounts of Mg vapor could form during combustion, leading to the expansion of solid products. The obtained porous products are fragile and unsuitable for use as construction materials. As noted in the Introduction, to obtain stronger products, SHS compaction could be used as was demonstrated for JSC-1A/Mg mixtures [7]. SHS compaction, however, was beyond the scope of the present work.

Figure 7 shows XRD patterns of the combustion products for mixtures of the three regolith simulants with magnesium (20 wt% Mg and 26 wt% Mg), while Table 3 shows the results of the peak identification. Note that some of the peaks may belong to more than one compound. Comparison of the obtained XRD patterns between each other has not indicated any significant trend. It is seen that MgO has the highest peaks in all patterns, which is in agreement with the results of thermodynamic calculations (see Table 2). MgAl_2O_4 and FeSi are also present in both experimental data and calculations. However, two minerals based on Ca, Mg, and Si – akermanite $\text{Ca}_2\text{MgSi}_2\text{O}_7$ and montecillite CaMgSiO_4 – are present in XRD patterns, but they were not predicted by thermodynamic calculations. Instead, the software predicted the formation of Mg_2SiO_4 , Ca_2SiO_4 , and $\text{CaMgSi}_2\text{O}_6$. This discrepancy may be caused partly by the use of simple oxides instead of mineral phases. Indeed, when the mineral composition of JSC-1A is used in calculations, the predicted products contain Mg_2SiO_4 and CaMgSiO_4 for the mixture with 20 wt% Mg and Mg_2SiO_4 , CaMgSiO_4 , and $\text{Ca}_3\text{MgSi}_2\text{O}_8$ for the mixture with 26 wt% Mg. Also, the discrepancy may be associated with differences between the databases used by THERMO [28, 29] and XRD [30] software. Note, however, that simple oxide representations of akermanite and montesillite are $(\text{CaO})_2(\text{MgO})(\text{SiO}_2)_2$ and $(\text{CaO})(\text{MgO})(\text{SiO}_2)$, respectively. Comparison with simple oxide representations of predicted phases (Table 2) shows that all discussed mineral phases are formed by the same simple oxides mixed in different ratios.

3.3. Thermal analysis of reactions between regolith simulants and magnesium

Figure 8 shows the DSC curve obtained for the mixture of 26 wt% Mg and 74 wt% JSC-1A at a heating rate of 10 °C/min. The curve has a distinct exothermic peak at 560 °C, which indicates that the reaction occurs at temperatures below the melting point of magnesium (650 °C).

To further investigate this reaction, the heating process, conducted at 5 °C/min, was stopped at three different temperatures (500 °C, 550 °C, and 590 °C). XRD of the obtained products (Fig. 9) revealed that there was no MgO at 500°C, while all Mg was converted to MgO at 590 °C. At 550 °C, a partial conversion of Mg to MgO was observed. These results confirm that the reaction between JSC-1A and Mg occurs when Mg is still solid.

Mixtures of 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 10 shows the DSC curves for these mixtures and for JSC-1A/Mg mixture for comparison. It is seen that the temperature of the peak is the highest for the mixture based on JSC-Mars-1A and the lowest for the mixture based on Mojave Mars.

To explain this order of the peaks, compositions of the three simulants (Table 1) should be analyzed focusing on the concentrations of silica and iron oxide. For clarity, for each simulant, Table 1 shows SiO₂–Fe₂O₃ mass ratio. It is seen that the order of the DSC peaks in Fig. 10 correlates with the SiO₂–Fe₂O₃ ratio: an increase in this ratio decreases the temperature of the peak.

To better understand this result, we have conducted DSC tests with binary Fe₂O₃/Mg and SiO₂/Mg mixtures under the same conditions. Iron oxide (Fe₂O₃, >2 µm, 99%, Sigma-Aldrich) and silica (SiO₂, –400 mesh, i.e., less than 37 µm, 99.5%, Alpha Aesar) were used in these tests. The obtained DSC curves are shown in Fig. 11. It is seen that Mg/SiO₂ mixture ignites at a temperature lower by approximately 100°C than for Mg/Fe₂O₃. Note that the peak in the mixture based on iron oxide is at about the same temperature as for the mixture based on JSC-Mars-1A (where the concentration of iron oxide is the highest), while the peak in the mixture based on silica is at a lower temperature than for mixtures with two other simulants. This implies that iron oxide plays a dominant role in the reaction between JSC-Mars-1A and Mg, while for two other regolith simulants the increased concentration of silica decreases the temperature of the reaction.

To further verify this conclusion, DSC tests were conducted with ternary SiO₂/Fe₂O₃/Mg mixtures. Three ternary mixtures had different SiO₂–Fe₂O₃ mass ratios (2, 1, and 0.5), while the

concentration of Mg was determined to simultaneously provide stoichiometry for both reactions described by Eqs. 1 and 2. Thus, in other words, the mixtures had different ratios between Mg/SiO₂ and Mg/Fe₂O₃ thermites:

- SiO₂–Fe₂O₃ mass ratio: 2 (71 wt% Mg/SiO₂ and 29 wt% Mg/Fe₂O₃)
- SiO₂–Fe₂O₃ mass ratio: 1 (55 wt% Mg/SiO₂ and 45 wt% Mg/Fe₂O₃)
- SiO₂–Fe₂O₃ mass ratio: 0.5 (38 wt% Mg/SiO₂ and 62 wt% Mg/Fe₂O₃)

Figure 12 shows DSC curves obtained for the three mixtures. It is seen that the temperature order of the peaks correlates with the SiO₂–Fe₂O₃ mass ratio. This confirms the conclusion that iron oxide plays a primary role in combustion of iron-rich JSC-Mars-1A simulant with Mg, while the effect of silica is significant in combustion of iron-lean JSC-1A and Mojave Mars simulants. Thus, the iron-rich regolith exhibits higher temperatures and more vigorous combustion owing to the higher exothermicity of Mg–Fe₂O₃ reaction (Eq. 2), but it may be easier to ignite the iron-lean regolith simulants because Mg–SiO₂ reaction (Eq. 1) becomes significant at a lower temperature.

4. Conclusions

Thermodynamic analysis has shown that mixtures of Martian regolith simulants (JSC-Mars-1A and Mojave Mars) with Mg exhibit higher adiabatic flame temperatures than their mixtures with Al (at the same concentration of the metal). Comparison with the data for JSC-1A lunar regolith simulant shows that JSC-Mars-1A exhibits higher temperatures than Mojave Mars and JSC-1A, which correlates with Fe₂O₃ concentrations in these materials.

Experiments have confirmed that JSC-Mars-1A and Mojave Mars simulants form combustible mixtures with magnesium. The measured combustion temperatures and identified product compositions are in reasonable agreement with thermodynamic predictions. The mixtures of JSC-Mars-1A with magnesium at 20-30 wt% Mg exhibit higher temperatures and burn more vigorously than mixtures based on Mojave Mars. For Mojave Mars, combustion is accompanied by oscillations in the front motion and by the formation of a layered structure of the product. This effect is more significant at lower concentrations of Mg.

Thermoanalytical studies have shown that iron oxide plays a dominant role in the combustion of JSC-Mars-1A simulant with magnesium. However, Mg/SiO₂ mixture ignites at a temperature lower by approximately 100°C than for Mg/Fe₂O₃. For Mojave Mars material and JSC-1A lunar

regolith simulant, which include more silica and less iron oxide, silica exhibits a significant effect on the combustion, promoting reactions at lower temperatures.

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Table 1. Simple oxide compositions of regolith simulants.

Regolith simulant	Concentration, wt%							SiO₂/Fe₂O₃ mass ratio	Ref.
	SiO₂	Al₂O₃	Fe₂O₃	CaO	MgO	Na₂O	TiO₂		
JSC-1A	45.7	16.2	12.4	10.0	8.7	3.2	1.9	3.69	[16]
JSC- Mars-1A	43.48	22.09	16.08	6.05	4.22	2.34	3.62	2.70	[18]
Mojave Mars	49.4	17.10	10.87	10.45	6.08	3.28	1.09	4.54	[18]

Table 2. Calculated compositions of combustion products for mixtures of JSC-1A, JSC-Mars-1A, and Mojave Mars with magnesium (20 wt% Mg and 26 wt% Mg).

Compound		State	Concentration, wt%					
			20 wt% Mg			26 wt% Mg		
			80 wt% JSC-1A	80 wt% JSC- Mars- 1A	80 wt% Mojave Mars	74 wt% JSC-1A	74 wt% JSC- Mars- 1A	74 wt% Mojave Mars
MgO		S	12.2	2.0	7.9	35.1	30.4	31.3
MgAl ₂ O ₄	Al ₂ O ₃ ·MgO	S	18.4	25.2	19.3	17.1	23.3	17.9
Mg ₂ SiO ₄	(MgO) ₂ ·SiO ₂	S	39.1	45.8	42.5	15.4	9.9	18.3
Ca ₂ SiO ₄	(CaO) ₂ ·SiO ₂	S	12.5	7.6	13.0	11.6	2.5	12.0
CaMgSi ₂ O ₆	CaO·MgO·(SiO ₂) ₂	L	-	-	-	-	11.5	-
FeSi		L	10.6	13.8	9.3	9.8	12.8	8.6
Si		L	3.7	0.9	4.8	7.6	5.0	8.6
Si ₃ Ti ₅		S	1.3	2.4	0.7	1.2	2.2	0.7
Mg		G	0.3	0.7	0.2	0.6	0.9	0.5
Na		G	1.9	1.4	2.3	1.8	1.3	2.1
SiO		G	-	0.2	-	-	0.2	0.1

Table 3. Identifications of peaks in XRD patterns shown in Fig. 7.

Peak	Phases			
1	Ca ₂ MgSi ₂ O ₇	CaMgSiO ₄	Mg ₂ Si	
2	MgAl ₂ O ₄	CaMgSiO ₄	FeSi	Mg ₂ Si
3	MgAl ₂ O ₄	MgO	MgO ₂	
4	Al ₂ O ₃	FeSi	Fe	Mg ₂ Si
5	MgO			
6	MgAl ₂ O ₄	FeSi		
7	Al ₂ O ₃	Mg ₂ Si		
8	Al ₂ O ₃			
9	MgO	FeSi		
10	MgAl ₂ O ₄	Ca ₂ MgSi ₂ O ₇	Al ₂ O ₃	Fe
11	MgO			

FIGURE CAPTIONS

Fig. 1. Particle size distribution for the milled JSC-Mars-1A simulant.

Fig. 2. Adiabatic flame temperatures for the mixtures of JSC-Mars-1A, Mojave Mars, and JSC-1A regolith simulants with (a) magnesium and (b) aluminum.

Fig. 3. Adiabatic flame temperatures for the mixtures of Fe_2O_3 and SiO_2 with (a) magnesium and (b) aluminum.

Fig. 4. Combustion propagation over a compacted mixture of Mojave Mars regolith simulant with magnesium (20 wt% Mg).

Fig. 5. Combustion propagation over a compacted mixture of JSC-Mars-1A regolith simulant with magnesium (20 wt% Mg).

Fig. 6. Maximum combustion temperatures for mixtures of JSC-Mars-1A and Mojave Mars simulants with Mg, in comparison with the adiabatic flame temperatures.

Fig. 7. XRD patterns of products obtained after combustion of JSC-Mars-1A, Mojave Mars, and JSC-1A regolith simulants mixed with magnesium at (a) 20 wt% Mg and (b) 26 wt% Mg.

Identified phases are shown in Table 3.

Fig. 8. DTA curve for 74 wt% JSC-1A and 26 wt% Mg.

Fig. 9. XRD patterns of 74 wt% JSC-1A and 26 wt% Mg.

Fig. 10. DSC curves for mixtures of JSC-1A, JSC-Mars-1A, and Mojave Mars simulants with Mg.

Fig. 11. DSC curves for $\text{Fe}_2\text{O}_3/\text{Mg}$ and SiO_2/Mg mixtures.

Fig. 12. DSC curves for $\text{SiO}_2/\text{Fe}_2\text{O}_3/\text{Mg}$ mixtures with $\text{SiO}_2\text{--Fe}_2\text{O}_3$ mass ratios of 2, 1, and 0.5.

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Fig. 4. Combustion propagation over a compacted mixture of Mojave Mars regolith simulant with magnesium (20 wt% Mg). Time zero was selected arbitrarily.

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