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Reaction Mechanisms in Combustible Regolith/Magnesium Mixtures

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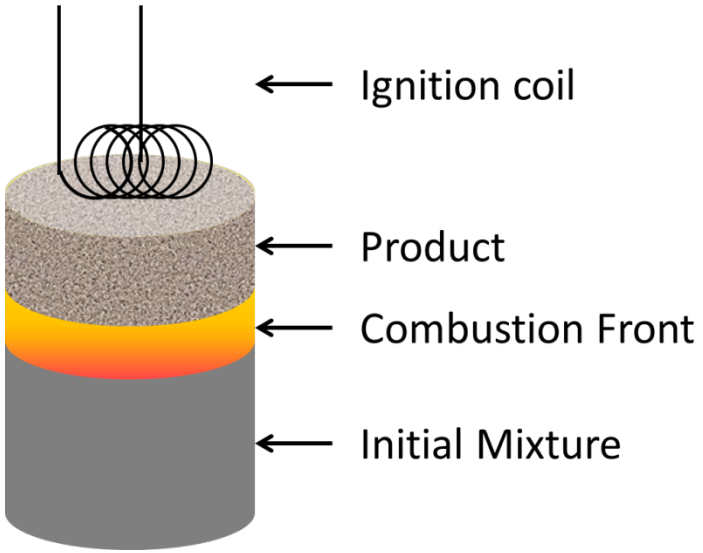
In-Situ Production

Construction Materials from Lunar and Martian Regolith

- In future lunar and Mars missions, construction materials will be needed for landing/launching pads, radiation shielding, and other structures.
- Fabrication methods:
  - Lunar concrete
    - Water or sulfur recovered from regolith
    - Thermoplastic brought from Earth
  - Microwave heating of regolith
    - Needs lots of energy
  - Energetic additives enabling a self-sustained combustion
    - Low energy needed

Self-Propagating High-Temperature Synthesis (SHS)

- Upon ignition of a mixture, exothermic reactions cause self-sustained propagation of the combustion wave.
- Advantages
  - Low energy for ignition
  - High temperatures generated by the reaction heat release.
- Used for synthesis of numerous ceramics and other compounds



Present Research: Objectives

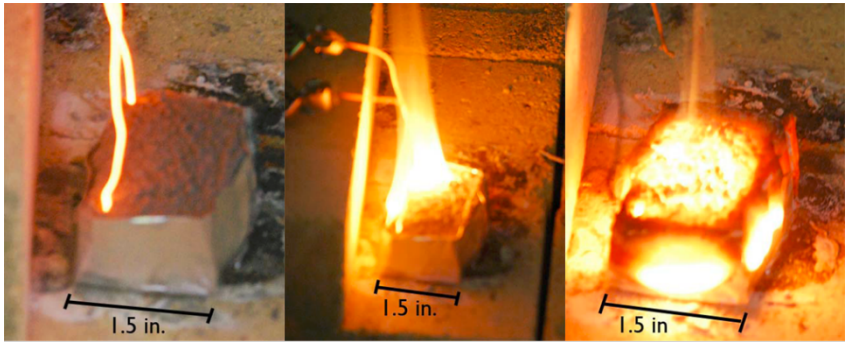
- Study combustion of **Martian** regolith simulants with Mg and compare it with combustion of JSC-1A **lunar** regolith simulant with Mg.
  - Martian regolith simulants: **JSC-Mars-1A** and **Mojave Mars**

- Clarify the **mechanisms of reactions** that occur during combustion of the lunar and Martian regolith simulants with Mg.

Combustion of Regolith-based Mixtures

Research Group	Energetic Additive	Role of Regolith	JSC-1A Content (wt %)
Martirosyan and Luss (2006)	Ti + B	Inert	<60
Corrias et al. (2012)	$FeTiO_3$ + Al	Inert	<30
Faierson et al. (2010)	Al	Active	<67

Combustion of Al/JSC-1A required significant preheating.



a b c

Faierson et al. PISCES and JUSTSAP Conference, 2008.

Prior Research of Our Team

- Thermodynamic calculations of the adiabatic flame temperatures and combustion products.
  - For Mg, the temperatures are higher than for Al
  - Maximum adiabatic temperature: 1417 °C at 26 wt% Mg (equal to the melting point of Si).
- Experiments demonstrated that mixtures of JSC-1A lunar regolith simulant with magnesium are combustible with no preheating.

C. White, F. Alvarez, E. Shafirovich, *J. Thermophys. Heat Tr.* 25 (2011) 620–625.

Prior Research of Our Team

Minimizing the wt% content of Magnesium

- Planetary Ball Milled (PBM) JSC-1A powder decreased Mg content to **13 wt%**.
- Mg wt% was **minimized to 8%** when preheating the mixture (PBM JSC-1A) to 100°C.

F. Álvarez, C. White, A.K. Narayana Swamy, E. Shafirovich, *Proc. Combust. Inst.* 34 (2013) 2245–2252.
A. Delgado, E. Shafirovich, *Combust. Flame* 160 (2013) 1876−1882.

Prior Research of Our Team

Producing stronger and denser products using SHS compaction

- **66% increase** in density
- Compression stress: **11.8 MPa**
  - Typical strength of common bricks: **9.5 MPa**

A. Delgado, E. Shafirovich, *Combust. Flame* 160 (2013) 1876–1882.

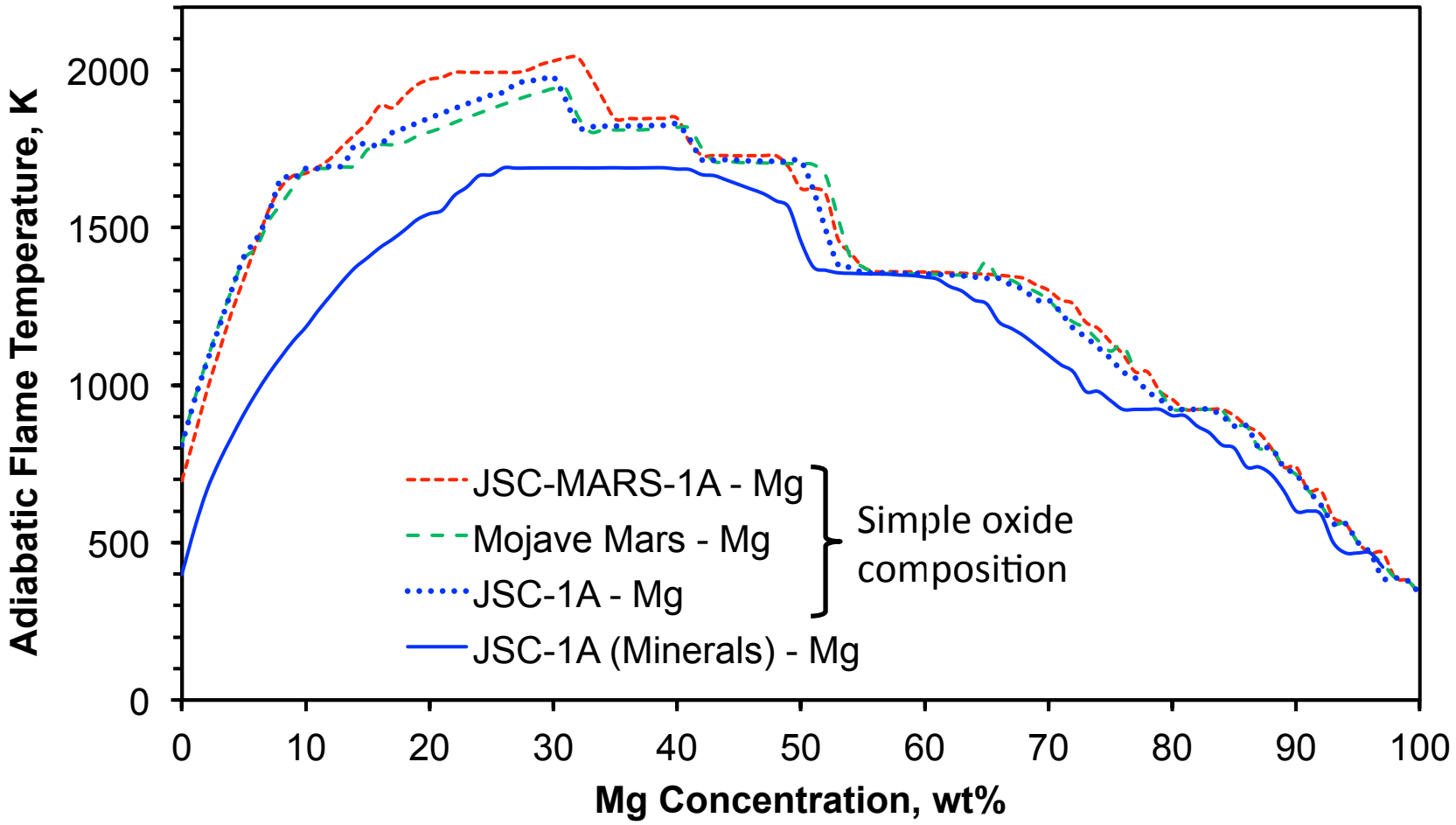
Simplified Compositions of Regolith Simulants

Compound	Concentration, wt%		
	JSC-1A [6]	JSC-Mars-1A [7]	Mars Mojave [7]
SiO_2	**45.7**	**43.48**	**49.4**
Al_2O_3	16.2	22.09	17.1
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

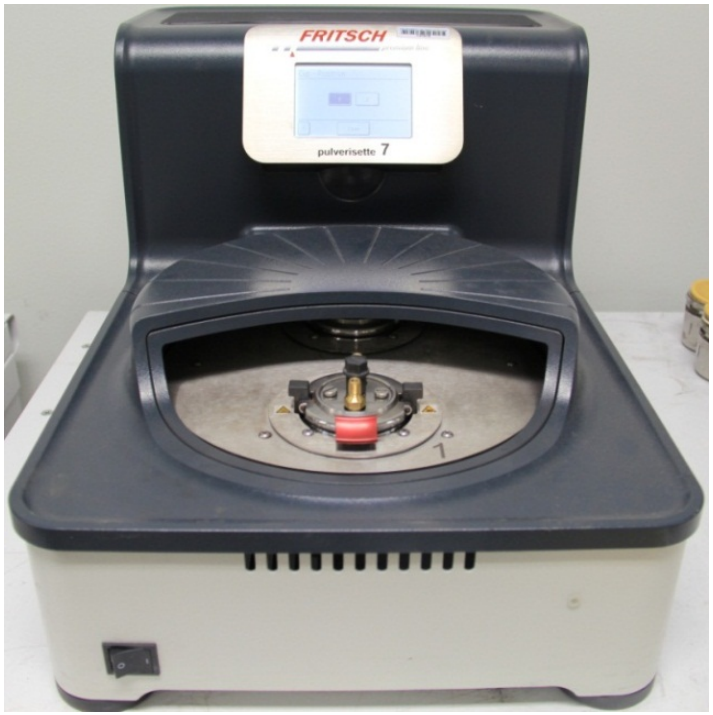
$$SiO_2 + 2\ Mg \rightarrow 2\ MgO + Si$$

$$Fe_2O_3 + 3\ Mg \rightarrow 3\ MgO + 2\ Fe$$

Thermodynamic Calculations for Combustion of Regolith Simulants with Mg



High-Energy Ball Milling

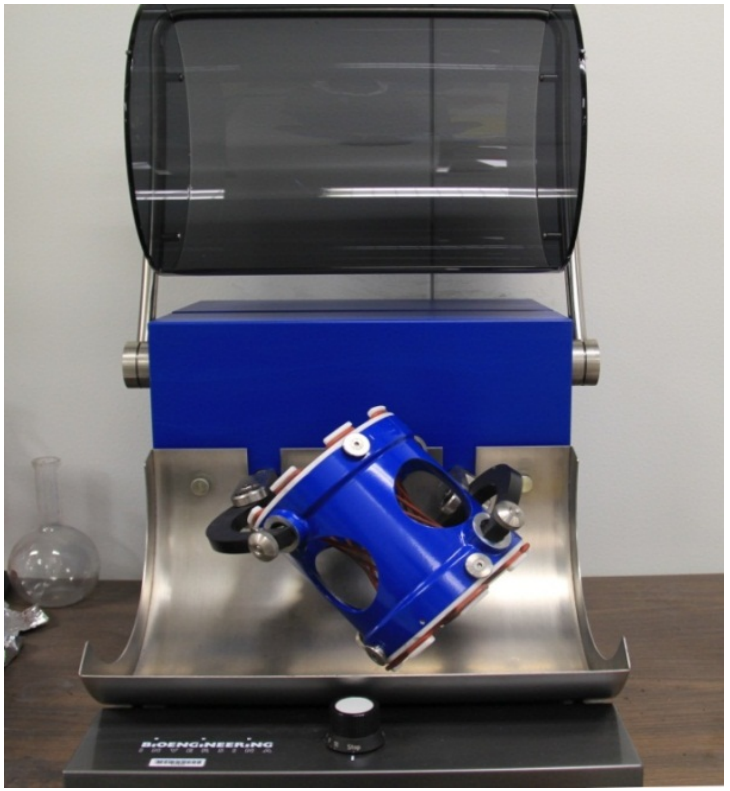


Planetary ball mill
(Fritsch Pulverisette 7 Premium Line)

- Zirconia-coated bowls and zirconia grinding balls
- Argon environment
- Mixture-ball mass ratio: 1:4
  - 1100 rpm
  - 4 milling-cooling cycles (10-min milling and 75-min cooling)

Mixing

- Three-dimensional inversion kinematics tumbler mixer
- Regolith is mixed with Mg (10, 20, 30.., wt%).



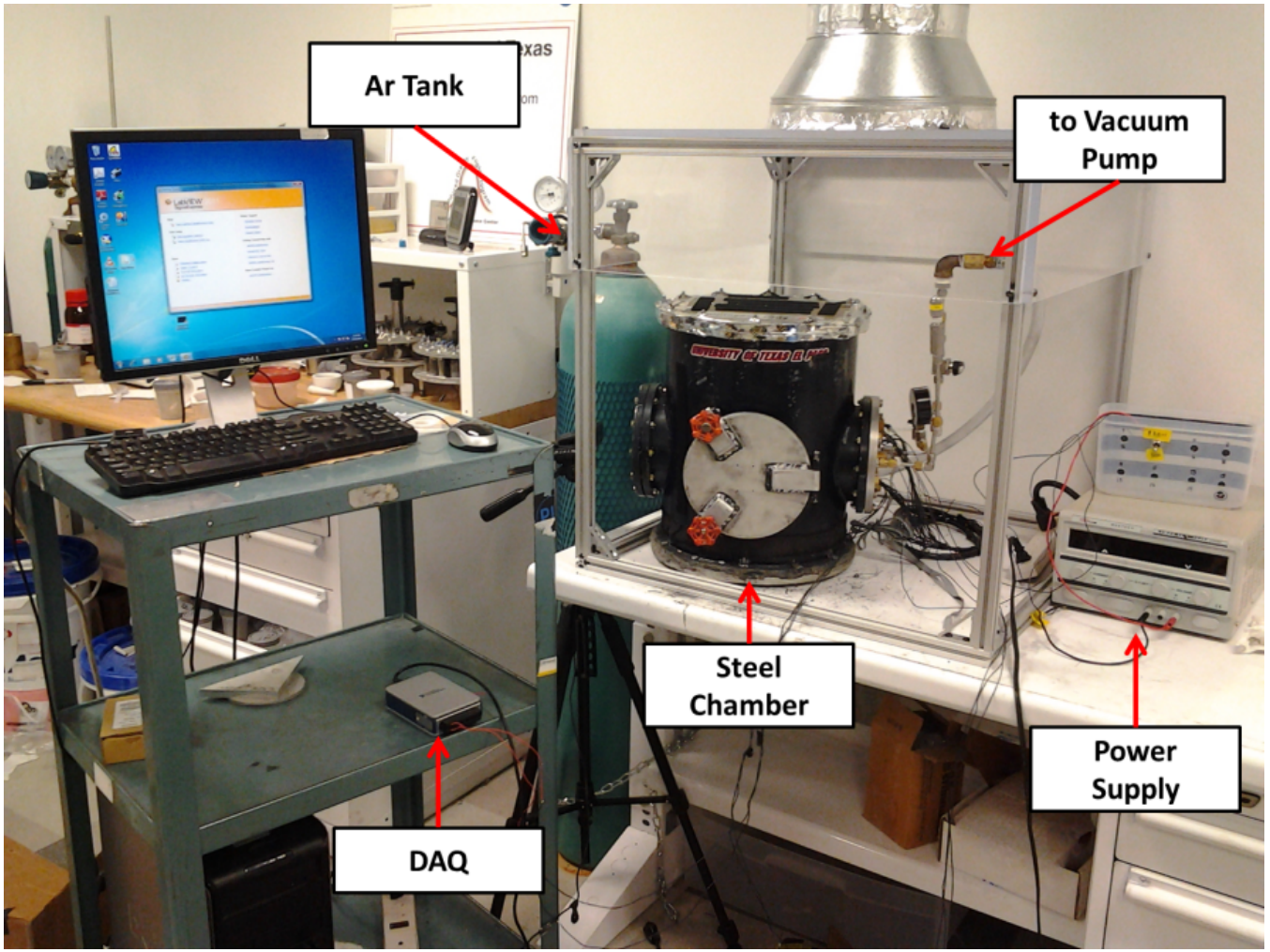
Inversina 2L Mixer

Preparation of Pellets

- Compaction in an uniaxial hydraulic press
  - Mass: 5 g
  - Diameter: 1.3 cm
  - Force: 2 metric tons
- Channel drilled for thermocouple

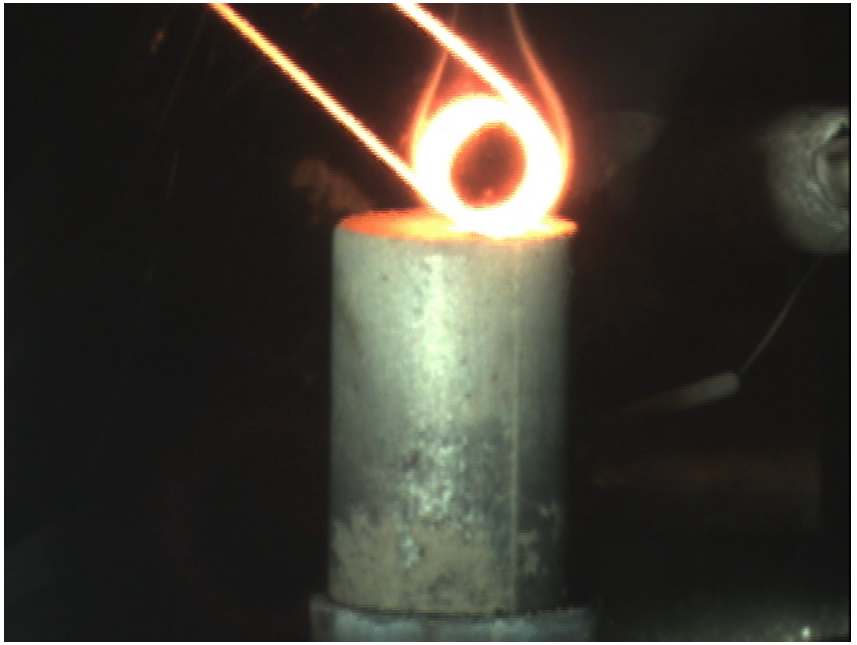
Compacted Powder

Experimental Setup



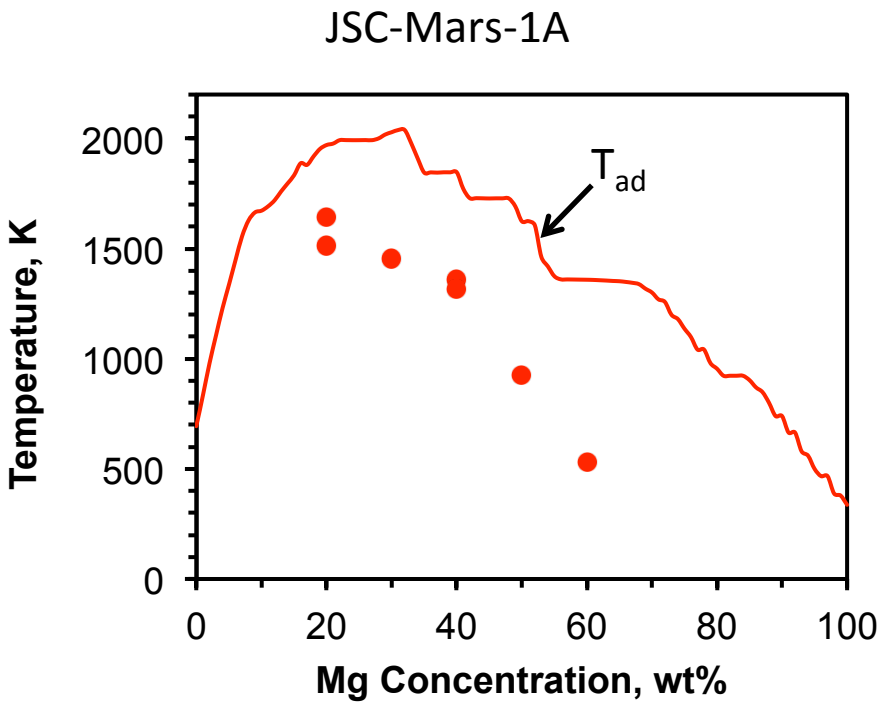
Mars Regolith/Mg Combustion

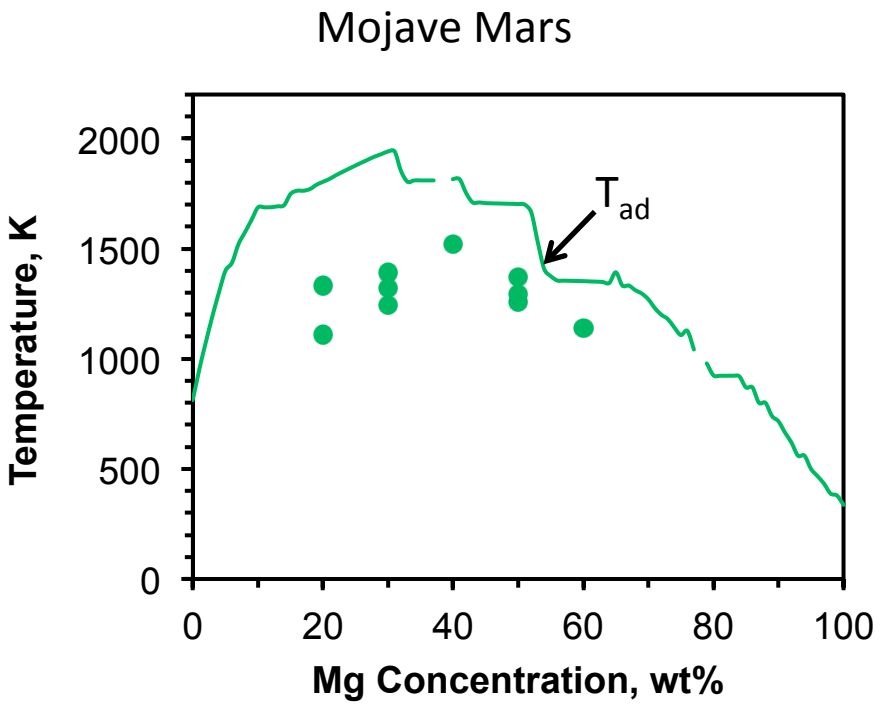
JSC-Mars-1A/Mg pellet (30 wt% Mg)



Mojave Mars/Mg pellet (30 wt% Mg)

Maximum Temperature in the Combustion Wave





- Reasonable agreement between experimental values and calculated adiabatic flame temperatures

Conclusions from Combustion Experiments

- JSC-Mars-1A combustion was much more vigorous than for Mojave Mars.
  - Relatively fast, steady propagation of combustion and a uniform structure of the product
- Different combustion behaviors may be related to different **SiO_2/Fe_2O_3 ratios**.
- To clarify reaction mechanisms in regolith/Mg mixtures, thermoanalytical experiments should be conducted.

Simplified Compositions of Regolith Simulants

Compound	Concentration, wt%		
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SiO_2	**45.7**	**43.48**	**49.4**
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$$SiO_2 + 2\ Mg \rightarrow 2\ MgO + Si$$

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Thermoanalytical Experiments

- To investigate reaction mechanisms of regolith/Mg mixtures.
  - Differential scanning calorimeter (Netzsch DSC 404 F1 Pegasus)
- Examined mixtures:

Regolith Simulant Mixtures

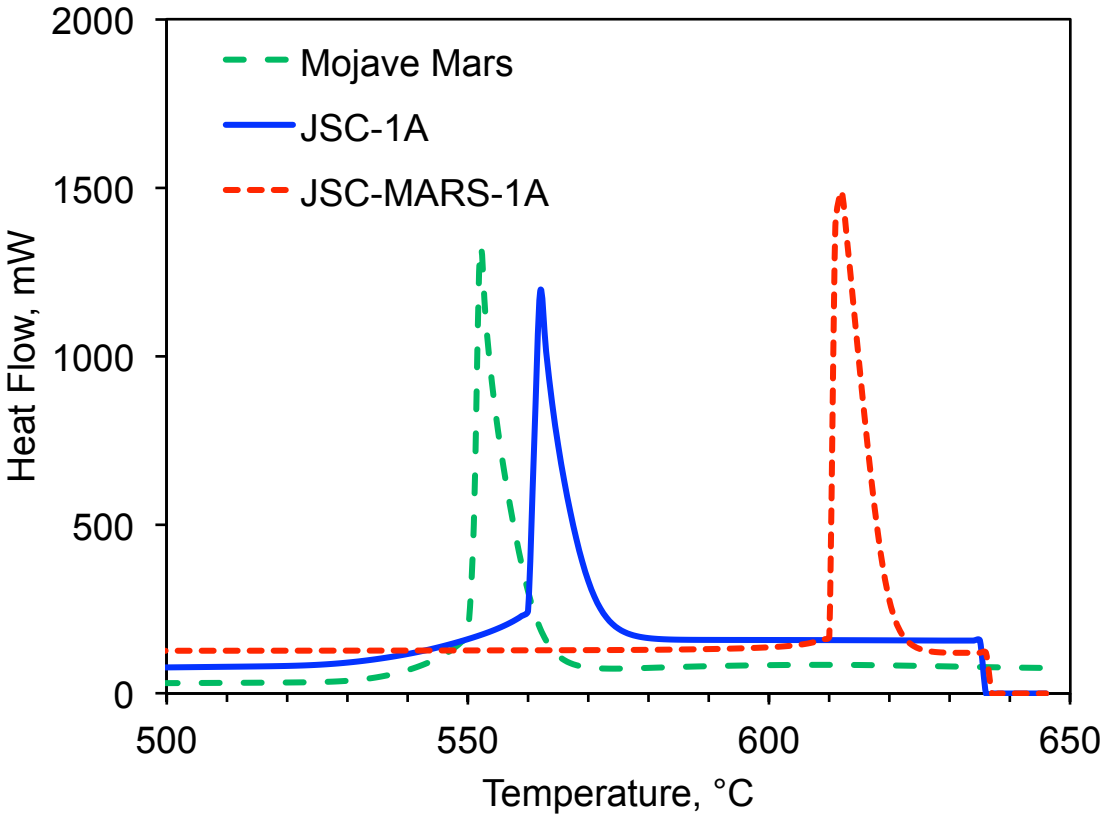
- 26 wt% Mg / 74 wt% JSC-Mars-1A
- 26 wt% Mg / 74 wt% JSC-1A
- 26 wt% Mg / 74 wt% Mojave Mars

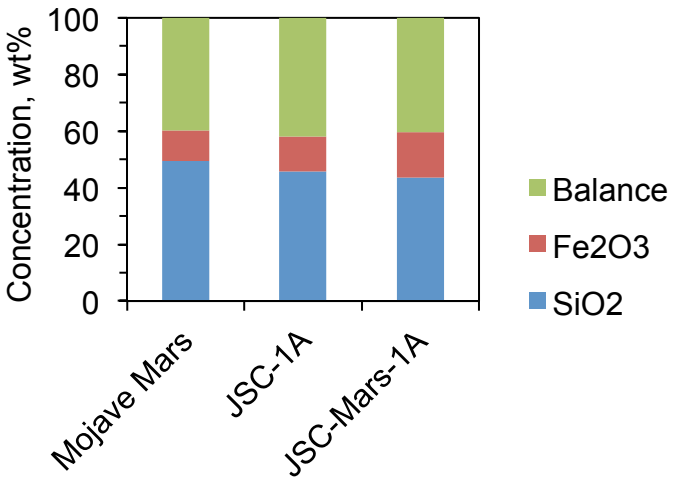
Simple Oxide Mixtures

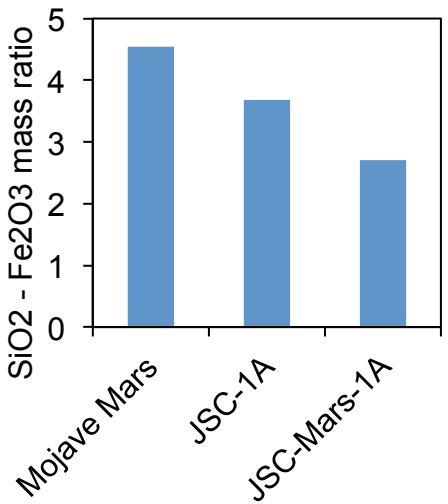
- Mg / SiO_2-Fe_2O_3 (SiO_2-Fe_2O_3 ratio: 0.5)
- Mg / SiO_2-Fe_2O_3 (SiO_2-Fe_2O_3 ratio: 1)
- Mg / SiO_2-Fe_2O_3 (SiO_2-Fe_2O_3 ratio: 2)

Comparable composition with simple oxides

DSC of Regolith Simulants Mixed with Mg

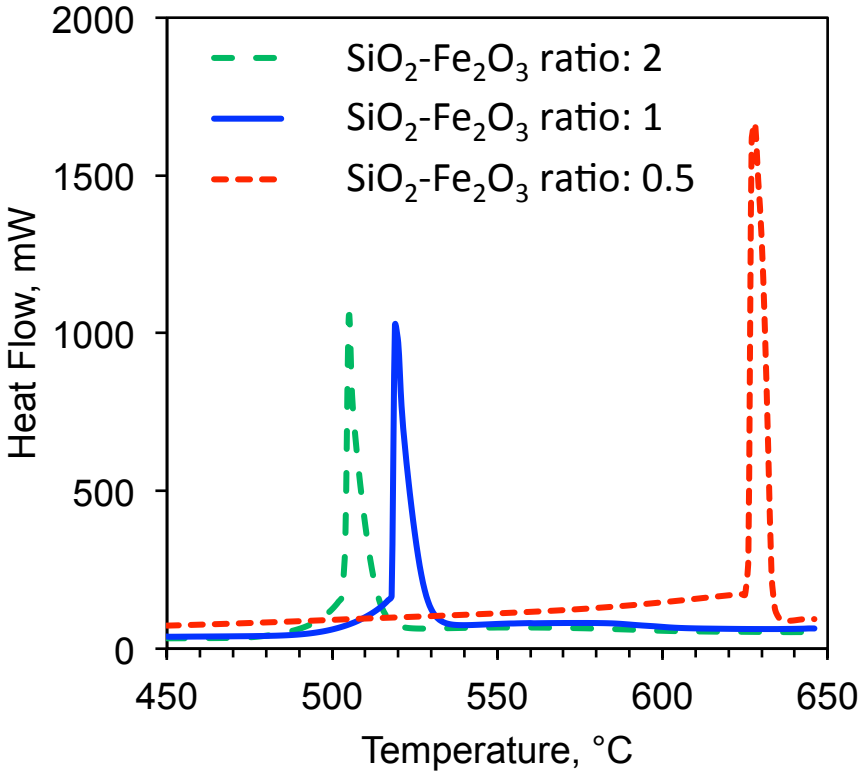


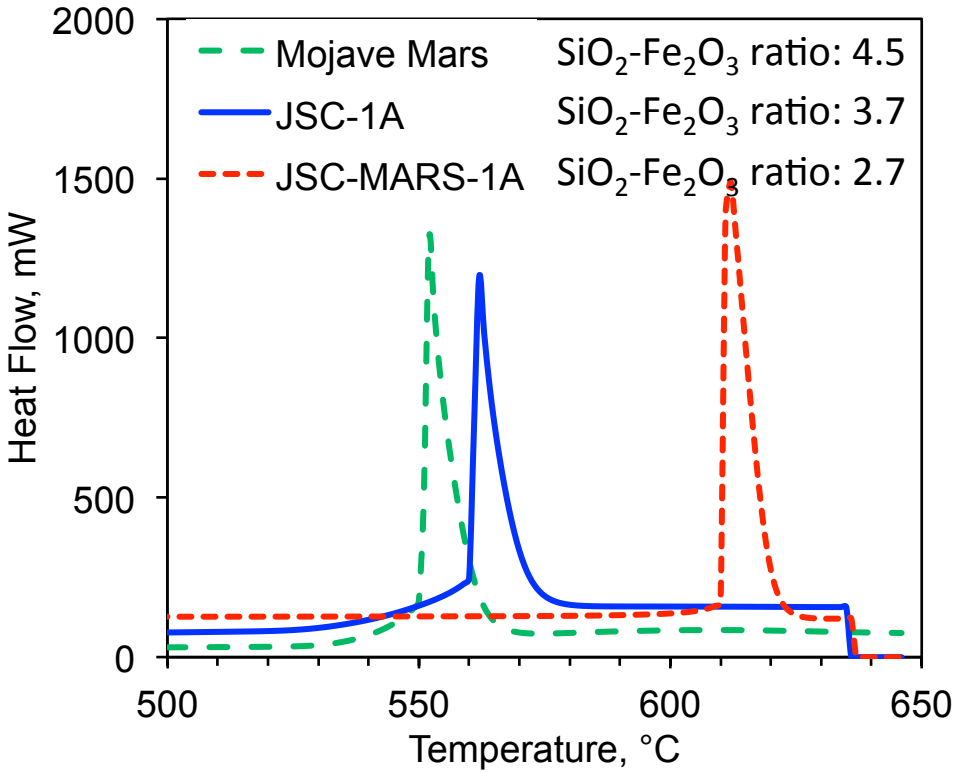




DSC peaks correlate with SiO_2-Fe_2O_3 ratio: Increase in this ratio decreases the temperature of the peak.

DSC of $Mg\text{-}Fe_2O_3\text{-}SiO_2$ Thermites





Temperature order of the peaks correlates with $SiO_2\text{-}Fe_2O_3$ ratio.
This explains the different peak temperatures of the three simulants.

Conclusions from Thermoanalytical Experiments

- Iron oxide plays a primary role in combustion of **iron-rich** JSC-Mars-1A simulant with Mg.
  - The iron-rich regolith exhibits higher temperatures and more vigorous combustion owing to the higher exothermicity of Mg–Fe_2O_3 reaction.
- The effect of silica is significant in combustion of **iron-lean** JSC-1A and Mojave Mars simulants
  - It is easier to ignite the iron-lean regolith simulants because Mg–SiO_2 reaction occurs at a lower temperature.

Summary

- Combustion-based methods for the fabrication of construction materials from lunar and Martian regolith have an advantage of low energy consumption.
- Mixtures of lunar and Martian regolith simulants with Mg exhibit a self-sustained combustion, leading to formation of ceramic materials.
- The reaction mechanisms in these mixtures involve thermite reactions of Mg with silica and iron oxide.
  - Iron oxide ensures intensive combustion.
  - Silica facilitates the ignition.

Thank you!