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Fabrication of Construction Materials from Lunar and Martian Regolith Using Thermite Reactions with Magnesium

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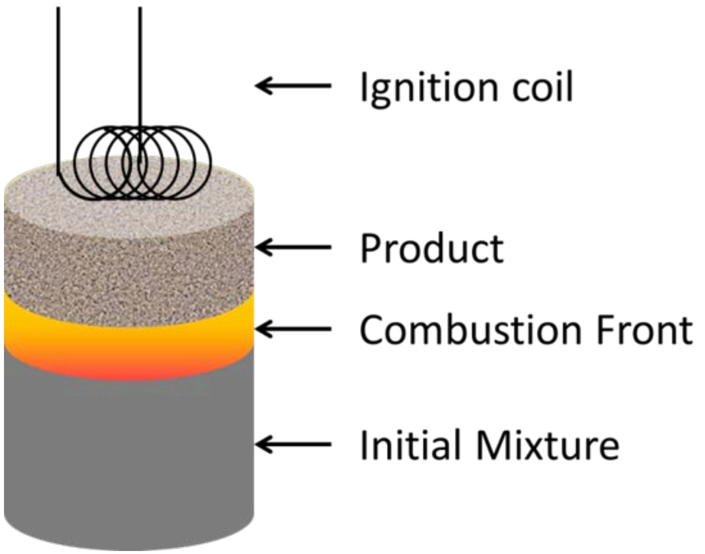
In-Situ Production of Construction Materials from Lunar and Martian Regolith

- 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

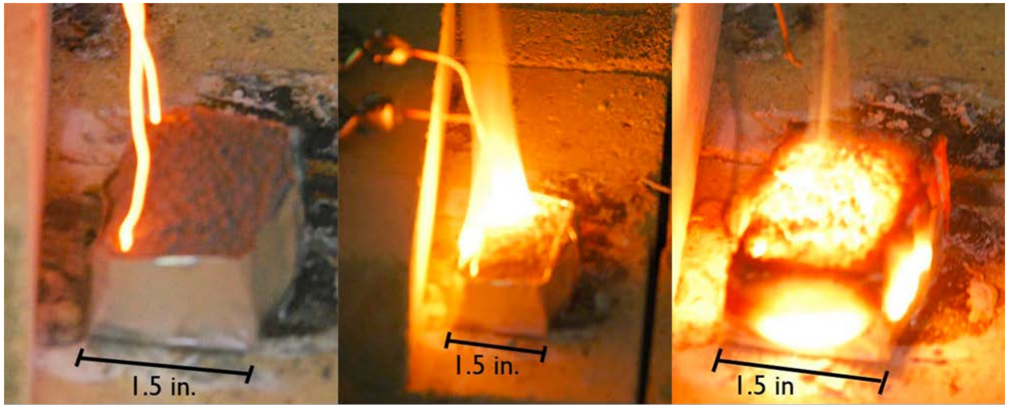
Self-Propagating High-Temperature Synthesis (SHS)

- Upon ignition of a mixture, exothermic reactions cause a self-sustained propagation of the combustion wave.
- Advantages:
  - Low energy for ignition
  - High temperatures generated by the reaction heat release
- Used for synthesis of many ceramic materials.



Combustion in Regolith-based Mixtures

Research Team	Energetic Additive	Additive Content (wt%)
Martirosyan and Luss (2006)	Ti + B	>40
Corrias et al. (2012)	$FeTiO_3$ + Al	>70
Faierson et al. (2010)	Al	>37



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Faierson et al., PISCES and JUSTSAP Conference, 2008.

- JSC-1A/Al mixture
- Large external energy is supplied by a long heating wire embedded in the mixture
- No self-sustained combustion

Prior Research of Our Team

- Combustion of mixtures of JSC-1A lunar regolith simulant with **magnesium**
- Magnesium is easier to ignite than aluminum
- 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)

White, Alvarez, and Shafirovich, *J. Thermophys. Heat Tr.* 25 (2011) 620−625.

Combustion at 26 wt% Mg

Prior Research of Our Team (contd.)

- Preheating (100°C) decreased content to **8 wt% Mg**.
- SHS compaction increased the density of the products by **66%** as compared to conventional SHS in argon.
- The compressive strength for SHS compaction products is about **10 MPa** – twice stronger than common bricks (5 MPa).

Delgado and Shafirovich, *Combust. Flame* 160 (2013) 1876−1882.

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.

Regolith Simulant Compositions

Mineral composition is known only for JSC-1A.
Simple oxide compositions are shown here:

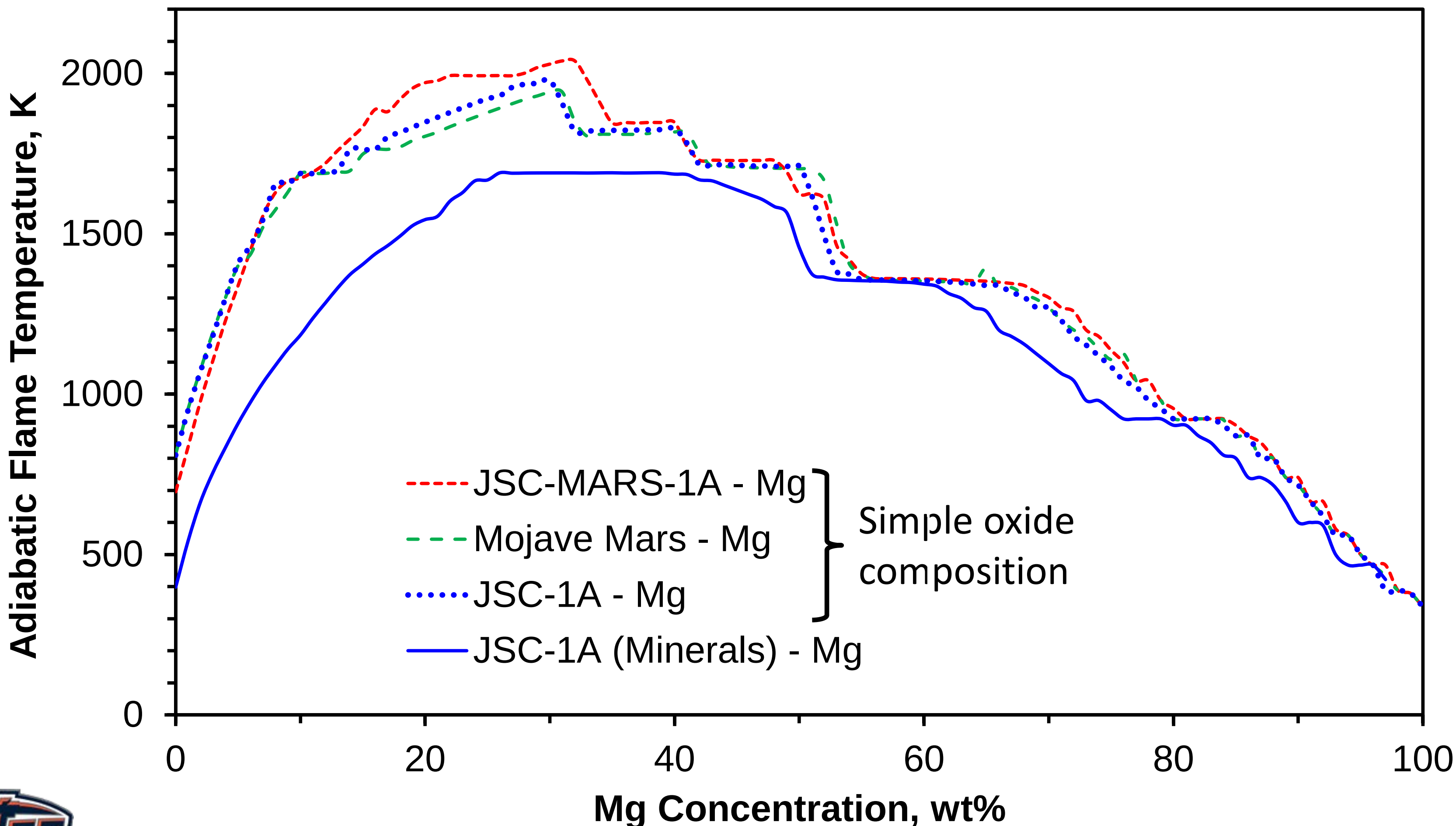
Compound	Concentration, wt%		
	JSC-1A	JSC-Mars-1A	Mojave Mars
SiO_2	**45.7**	**43.48**	**49.4**
Al_2O_3	16.2	22.09	17.1
Fe_2O_3	**12.4**	**16.08**	**10.87**
CaO	10	6.05	10.45
MgO	8.7	4.22	6.08
Na_2O	3.2	2.34	3.28
TiO_2	1.9	3.62	1.09

Main potential reactions:

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

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

Thermodynamic Calculations for Combustion of Regolith Simulants with Mg

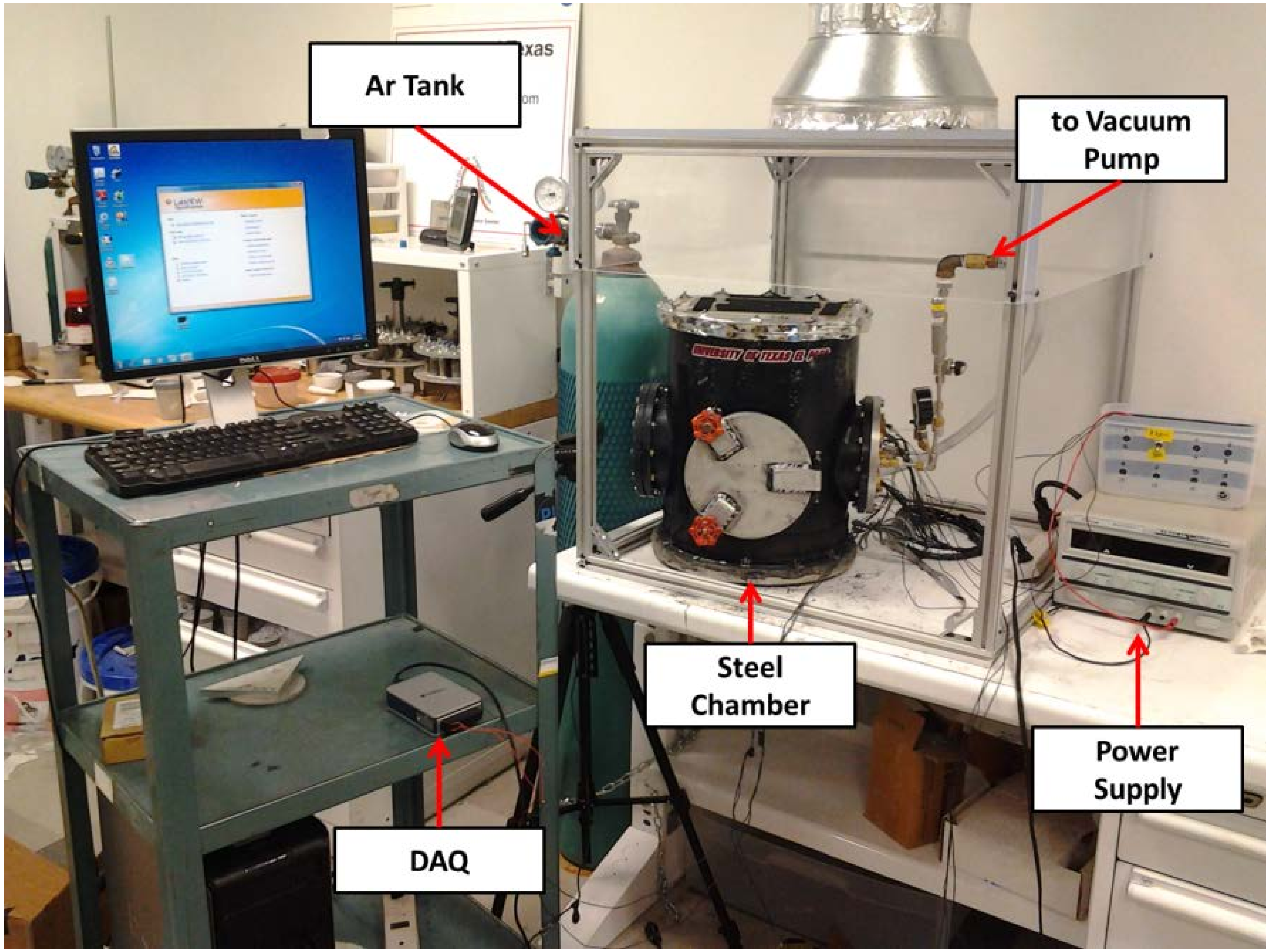


Sample Preparation

- Regolith is milled in a planetary ball mill (1100 rpm, 40 min).
- Regolith is mixed with Mg (10, 20, 30.., wt%).
- The mixtures are compacted into pellets.
  - Mass: 5 g
  - Diameter: 1.3 cm
  - Force: 2 metric tons
- Channel drilled for thermocouple.

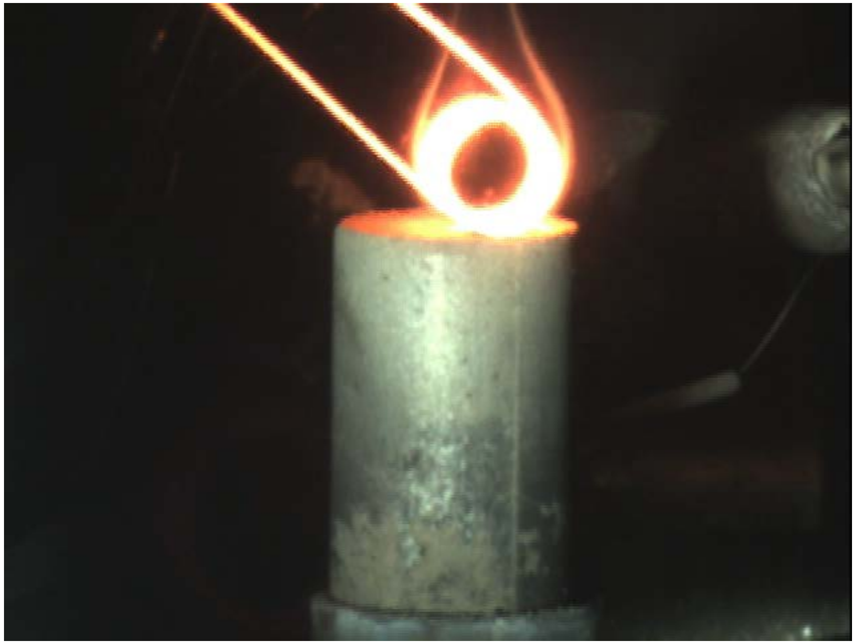
Compacted Powder

Experimental Setup



Mars Regolith/Mg Combustion

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



Mojave Mars/Mg pellet (30 wt% Mg)

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.

Thermoanalytical Experiments

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

Regolith Simulant Mixtures

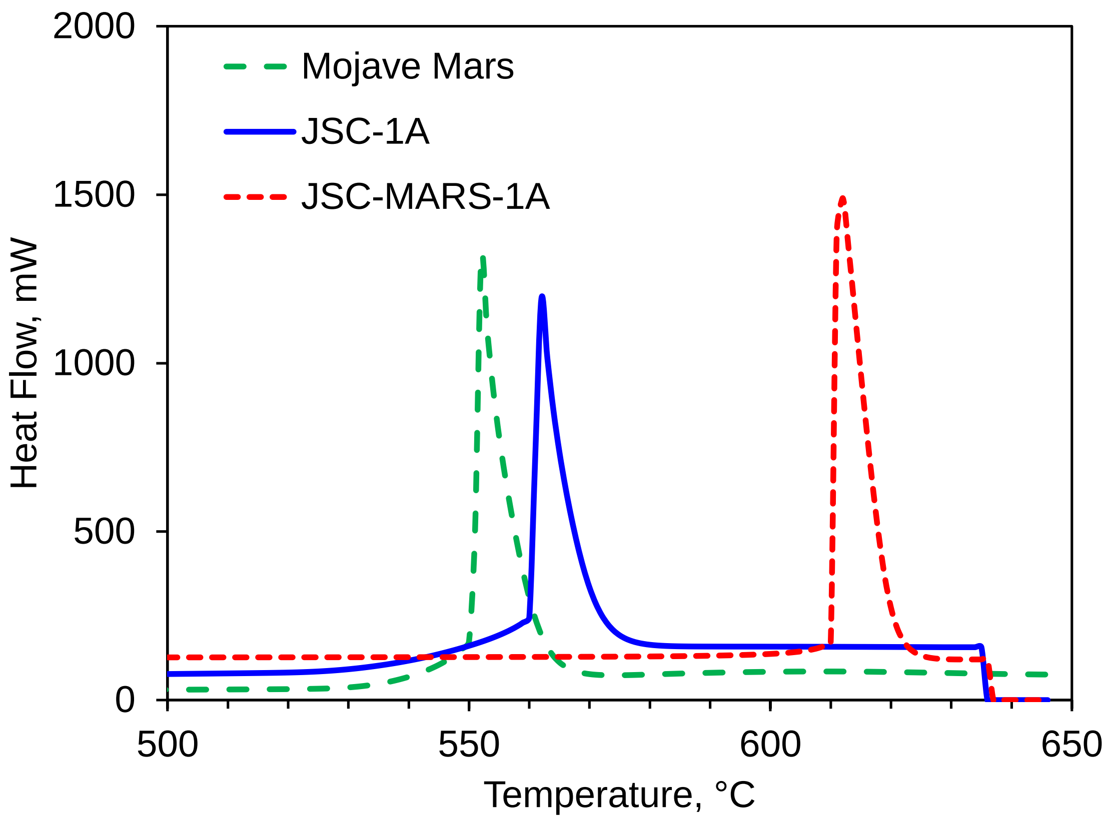
- 26 wt% Mg / 74 wt% JSC-Mars-1A
- 26 wt% Mg / 74 wt% JSC-1A
- 26 wt% Mg / 74 wt% Mojave Mars

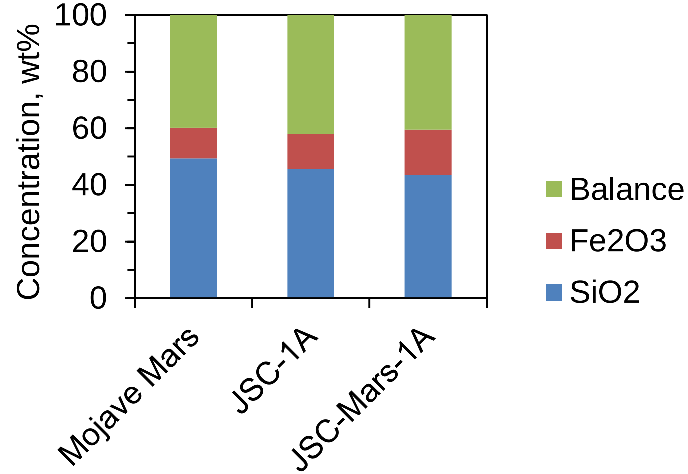
Simple Oxide Mixtures

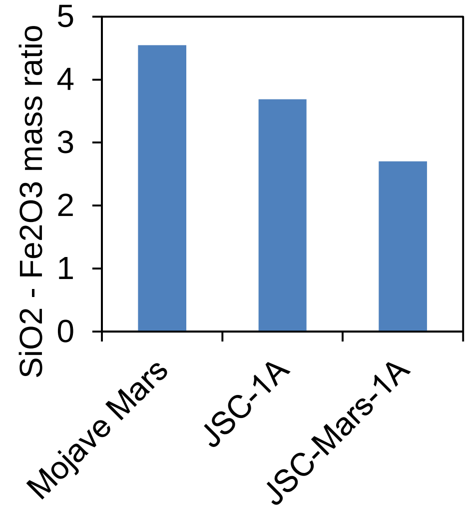
- Mg / SiO_2-Fe_2O_3 (SiO_2-Fe_2O_3 ratio: 0.5)
- Mg / SiO_2-Fe_2O_3 (SiO_2-Fe_2O_3 ratio: 1)
- Mg / SiO_2-Fe_2O_3 (SiO_2-Fe_2O_3 ratio: 2)

Comparable composition with simple oxides

DSC of Regolith Simulants Mixed with Mg

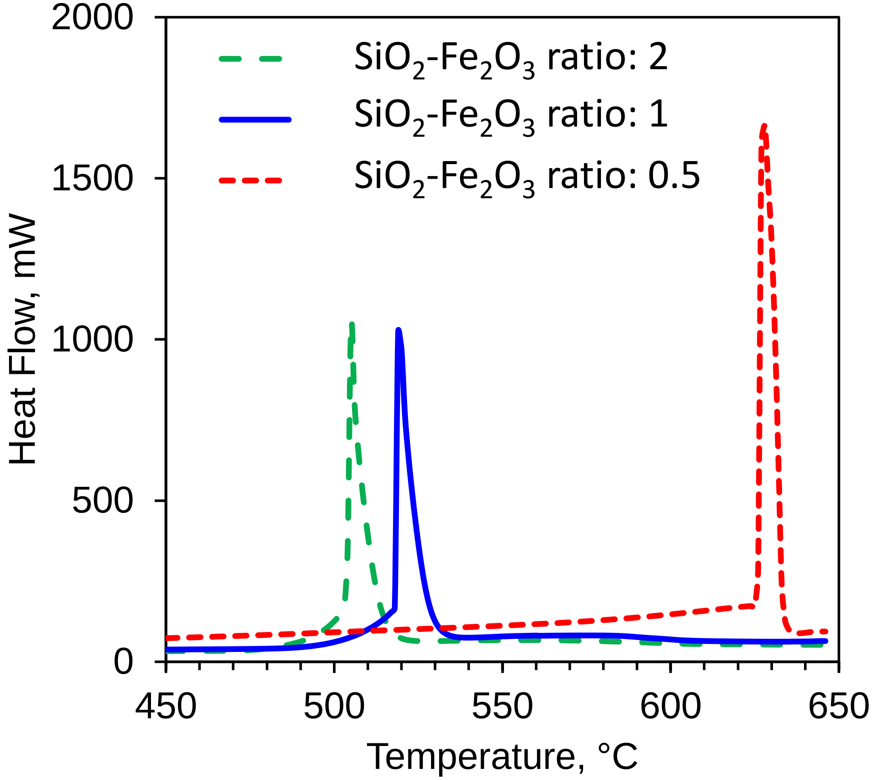


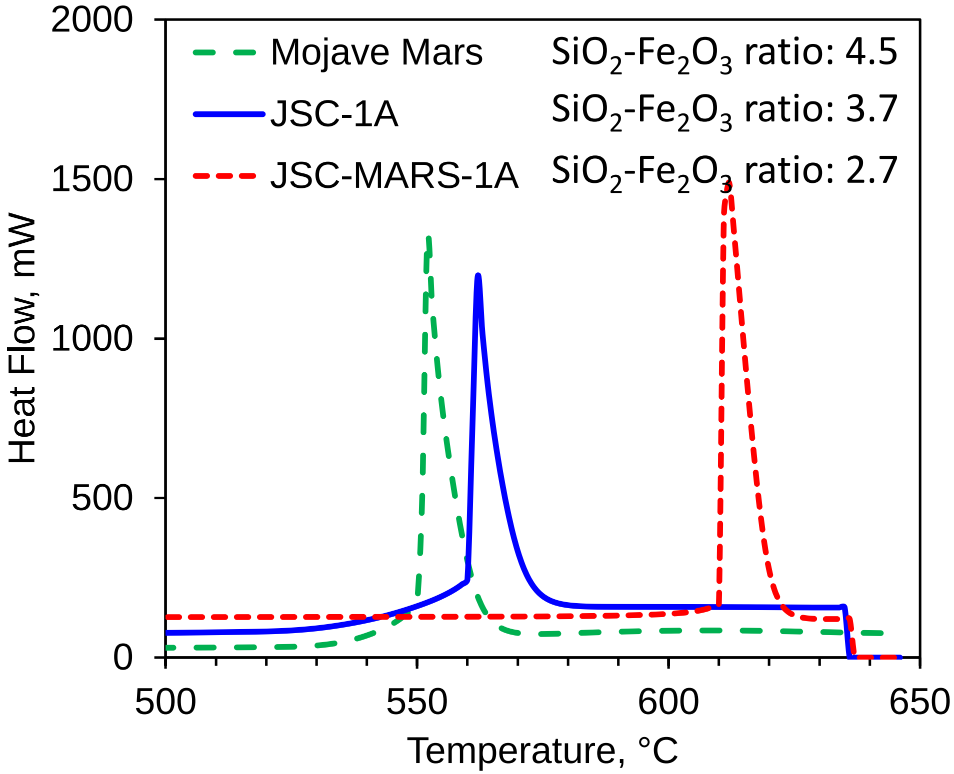




DSC peaks correlate with SiO_2-Fe_2O_3 ratio: Increase in this ratio decreases the temperature of the peak.

DSC of Mg-Fe_2O_3-SiO_2 Thermites





Temperature order of the peaks correlates with SiO_2-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.

Acknowledgements

- The NASA Office of Education for support of this research
- The Solar System Exploration Research Virtual Institute (SSERVI) for support of my travel here

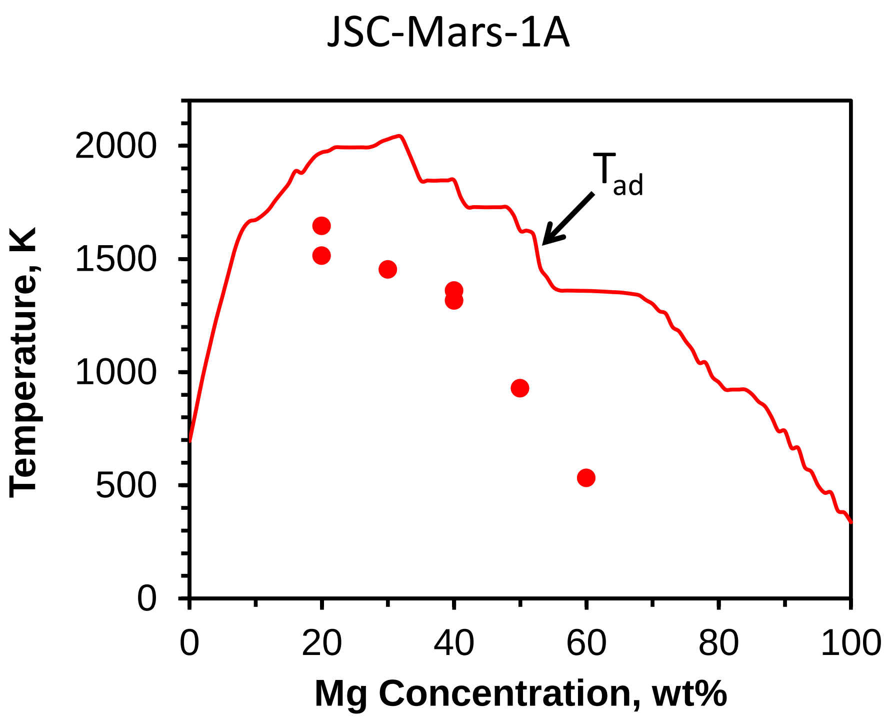
Thank you!

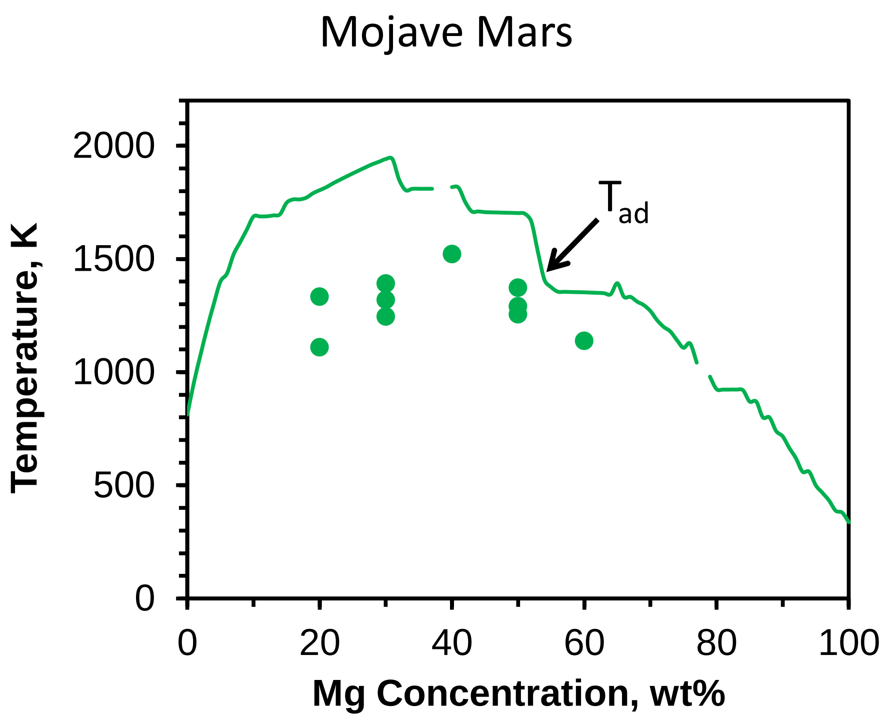
BACK-UP SLIDES

Spin Combustion

- Two counter-propagating hot spots

Maximum Temperature in the Combustion Wave



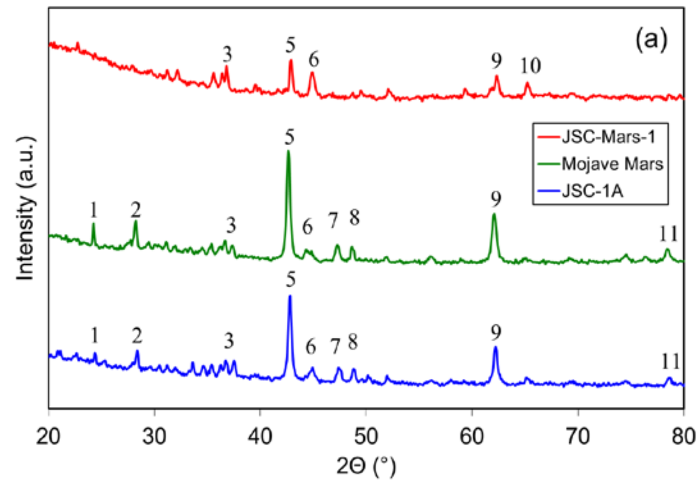


- Reasonable agreement between experimental values and calculated adiabatic flame temperatures

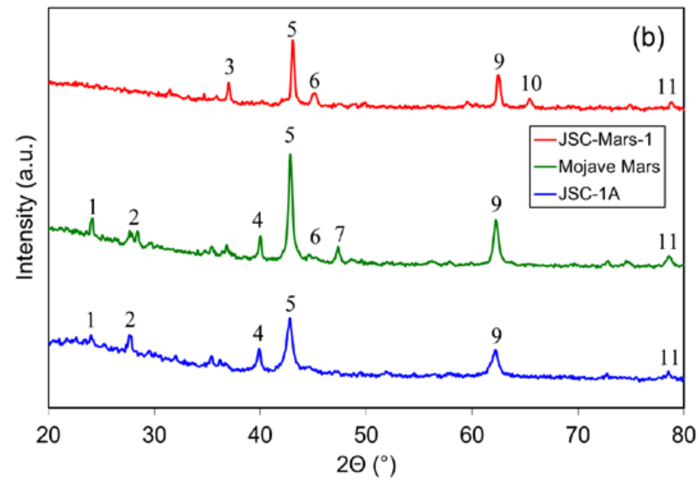
XRD of Combustion Products

Peak	Phases			
1	$Ca_2MgSi_2O_7$	$CaMgSiO_4$	Mg_2Si	
2	$MgAl_2O_4$	$CaMgSiO_4$	FeSi	Mg_2Si
3	$MgAl_2O_4$	MgO	MgO_2	
4	Al_2O_3	FeSi	Fe	Mg_2Si
5	**MgO**			
6	$MgAl_2O_4$	FeSi		
7	Al_2O_3	Mg_2Si		
8	Al_2O_3			
9	**MgO**	FeSi		
10	$MgAl_2O_4$	$Ca_2MgSi_2O_7$	Al_2O_3	Fe
11	**MgO**			

20 wt% Mg / 80 wt% Regolith



26 wt% Mg / 74 wt% Regolith

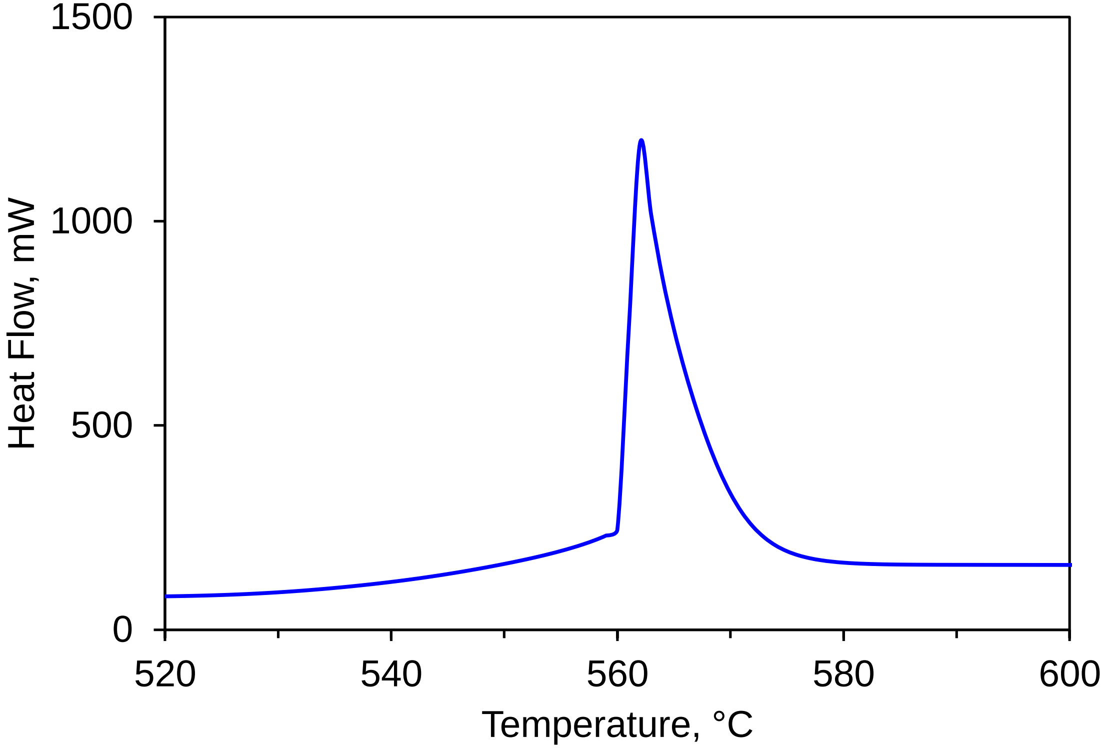


Combustion Products from THERMO

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	29.4	2.0	7.9	32.8	30.4	31.3
$Al_2Si_2O_{13}$	$Al_2O_3\cdot(SiO_5)_2$	S	31.0	-	-	25.7	-	-
Al_2MgO_4	$Al_2O_3\cdot MgO$	S	-	25.2	19.3	-	23.3	17.9
Mg_2SiO_4	$(MgO)_2\cdot SiO_2$	S	-	45.8	42.5	-	9.9	18.3
Ca_2SiO_4	$(CaO)_2\cdot SiO_2$	S	-	7.6	13.0	-	2.5	12.0
$CaMgSi_2O_6$	$CaO\cdot MgO\cdot(SiO_2)_2$	L	-	-	-	-	11.5	-
$CaMgO_2$	$CaO\cdot MgO$	S	10.9	-	-	9.2	-	-
FeSi		S	10.6	-	-	9.8	-	-
FeSi		L	-	13.8	9.3	-	12.8	8.6
Si		S	8.1	-	-	5.5	-	-
Si		L	-	0.9	4.8	-	5.0	8.6
Si_3Ti_5		S	1.3	2.4	0.7	1.2	2.2	0.7
Mg_2Si		L	-	-	-	6.8	-	-
Al_2Ca		L	3.0	-	-	3.7	-	-
Mg		G	3.8	0.7	0.2	3.5	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

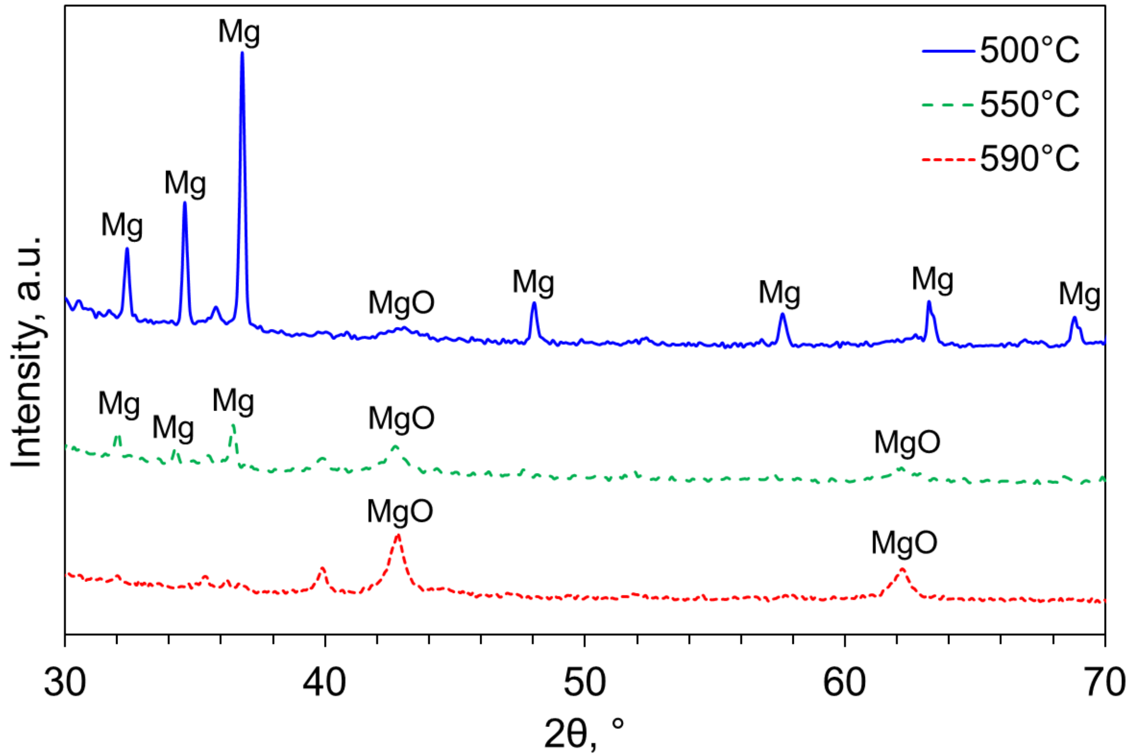
DSC of JSC-1A/Mg (26 wt% Mg)

- Differential scanning calorimetry (DSC) curve
- Heating rate: 10°C/min
- DSC curve shows exothermic peak at 560°C.

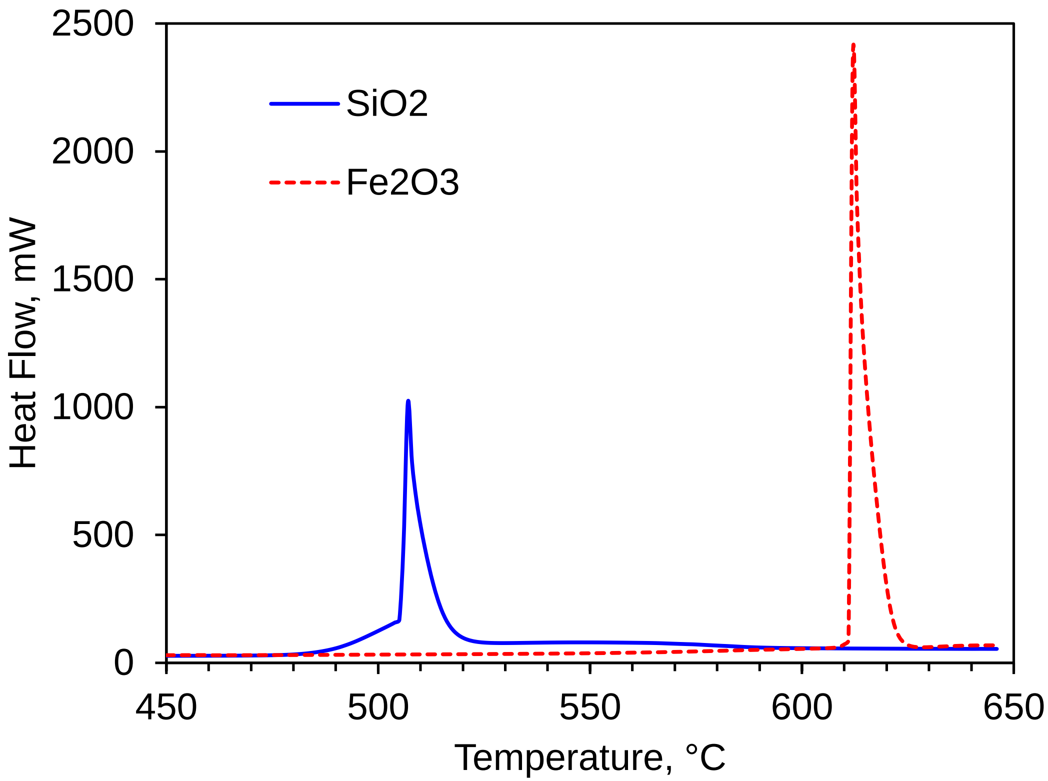


XRD of Reaction Products at Different Temperatures

- To investigate reaction, analysis was stopped at 500°C, 550°C, and 590°C.
- Heating rate: 5°C/min
- The reaction is complete at a temperature between 550°C and 590°C.
- Magnesium is solid throughout reaction ($T_{melting,Mg}$ = 650°C).



DSC of Mg-Fe_2O_3 and Mg-SiO_2 Thermites



Stoichiometric mixtures of

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

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

The peak temperature for Mg-Fe_2O_3 is higher than for Mg-SiO_2.