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Thermite Reactions in the Mixtures of Magnesium with Lunar and Martian Regolith Simulants

Armando Delgado and Evgeny Shafirovich

Center for Space Exploration Technology Research
Department of Mechanical Engineering
The University of Texas at El Paso

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  - Carlos Contreras
  - Israel Lopez

Agenda

- Introduction
- Previous Research
- Experimental Setup
- Microgravity Flight Experiments
- Differential Thermal Analysis
- Conclusions

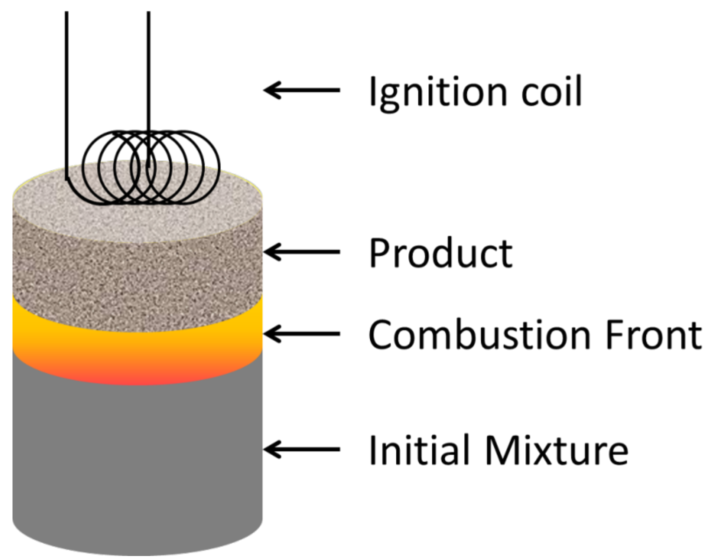
In-Situ Production

Construction Materials from Lunar and Martian Regolith

- Construction materials are needed for landing/launching pads, radiation shielding, and other structures.
- External heating of regolith
  - Needs lots of energy

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



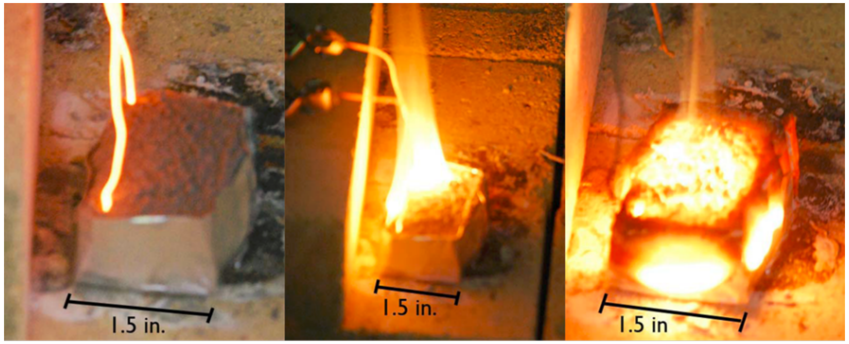
Objectives

- Explore the feasibility of producing construction materials by SHS on the Moon and Mars.
- Reveal the reaction mechanisms of regolith/magnesium mixtures.
  - Three regolith simulants:
    - JSC-1A lunar regolith simulant
    - JSC-Mars-1A Martian regolith simulant
    - Mars Mojave Martian regolith simulant

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

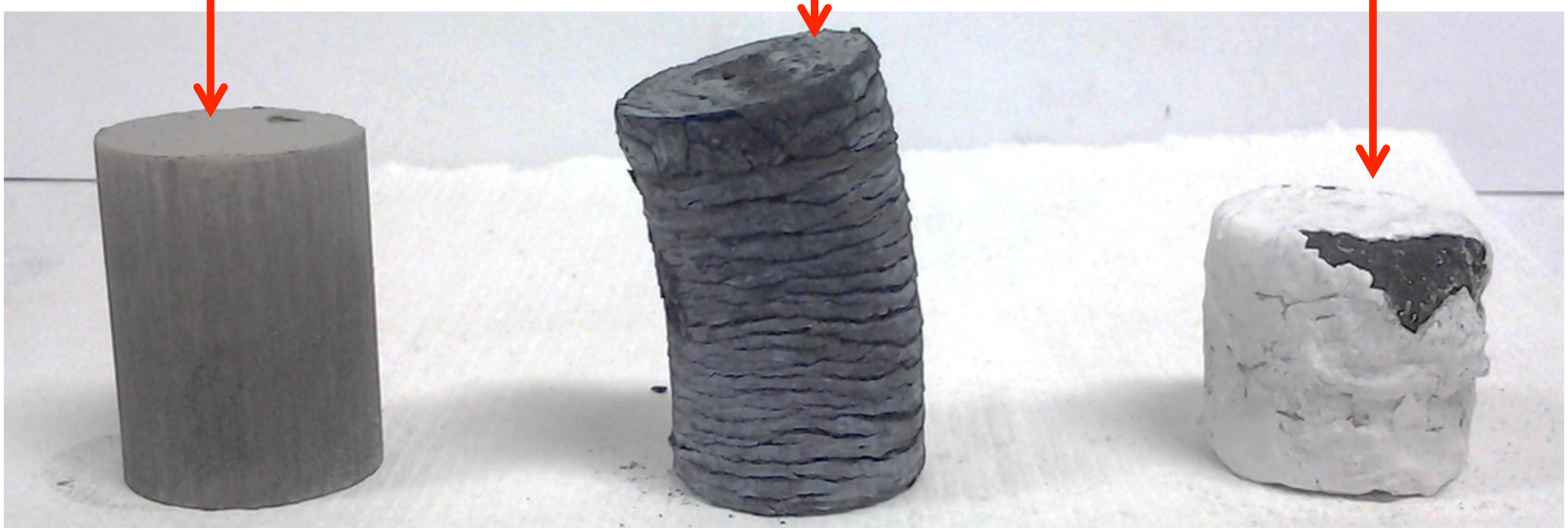
Producing stronger and denser products using SHS compaction

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

Original JSC-1A/Mg pellet

Argon product environment

SHS compaction product



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

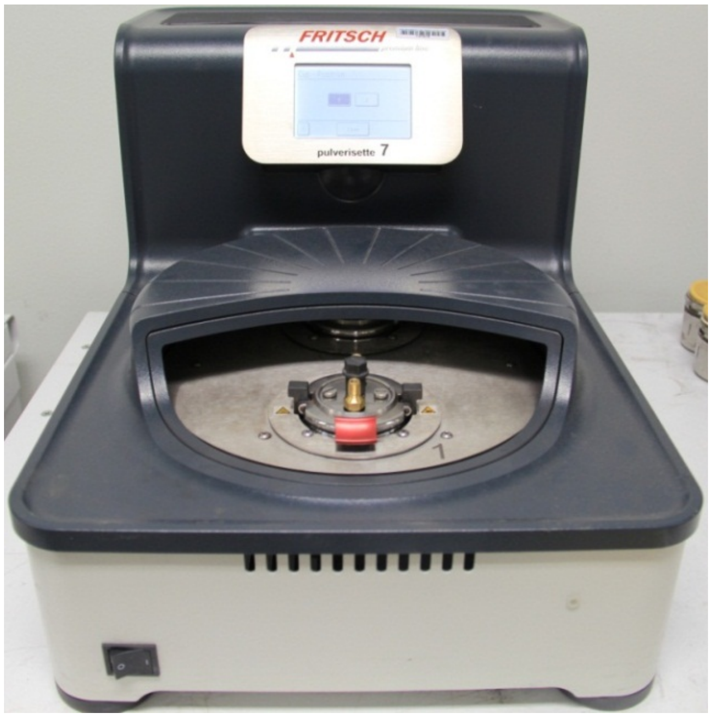
Simplified Compositions of Regolith Simulants

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

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

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

High-Energy Ball Milling

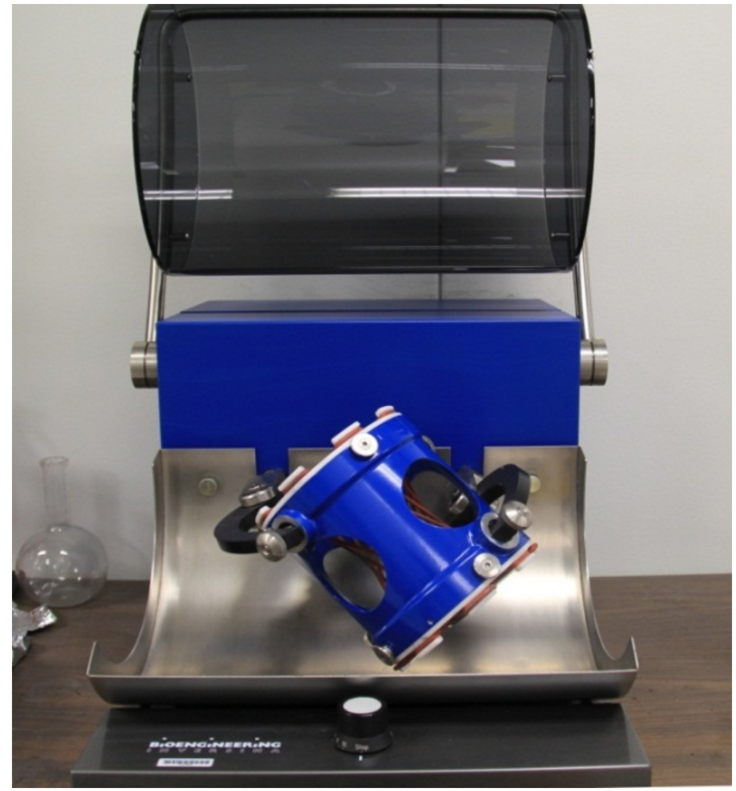


Planetary ball mill
(Fritsch Pulverisette 7 Premium Line)

- 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%).



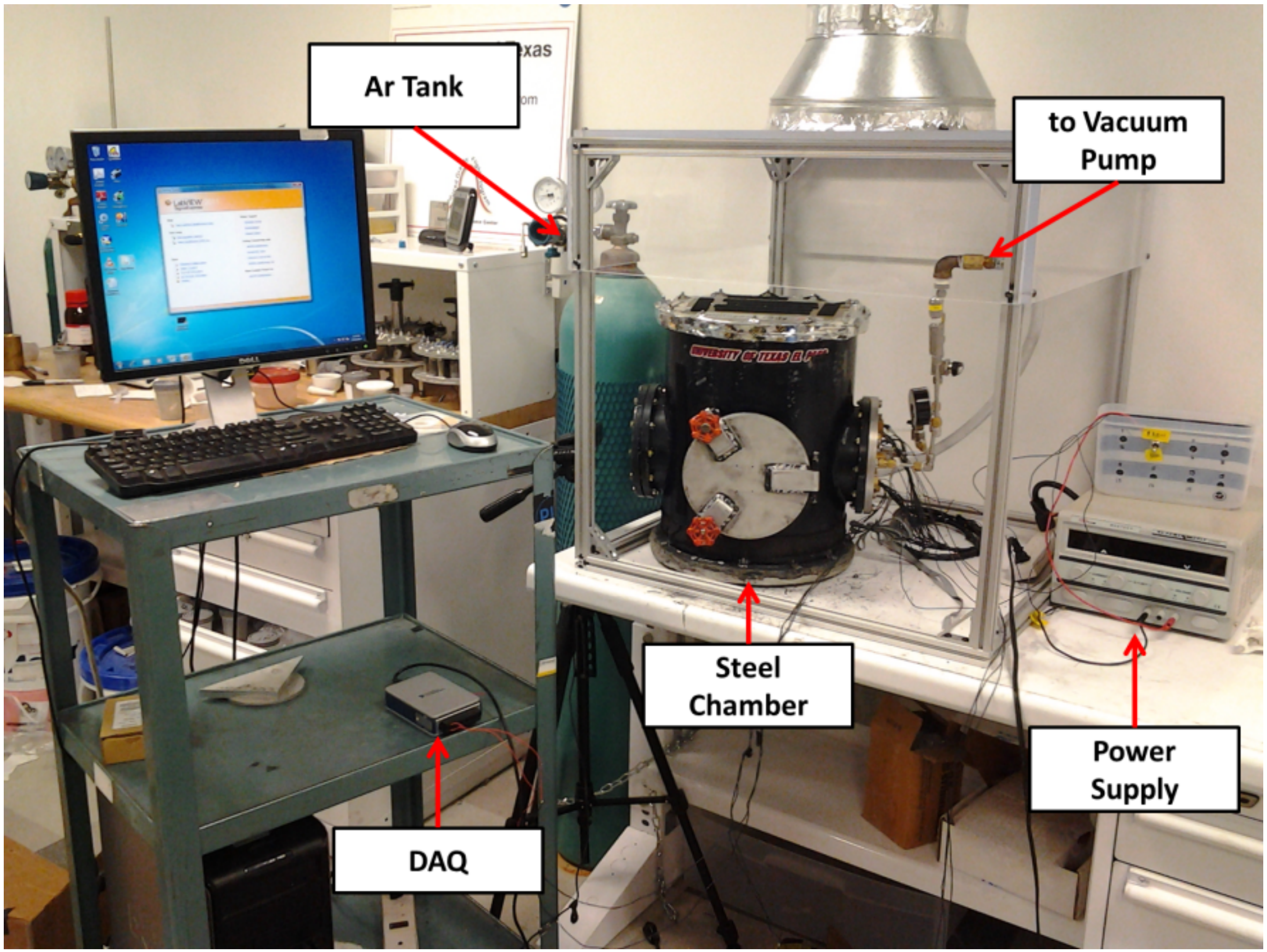
Inversina 2L Mixer

Preparation of Pellets

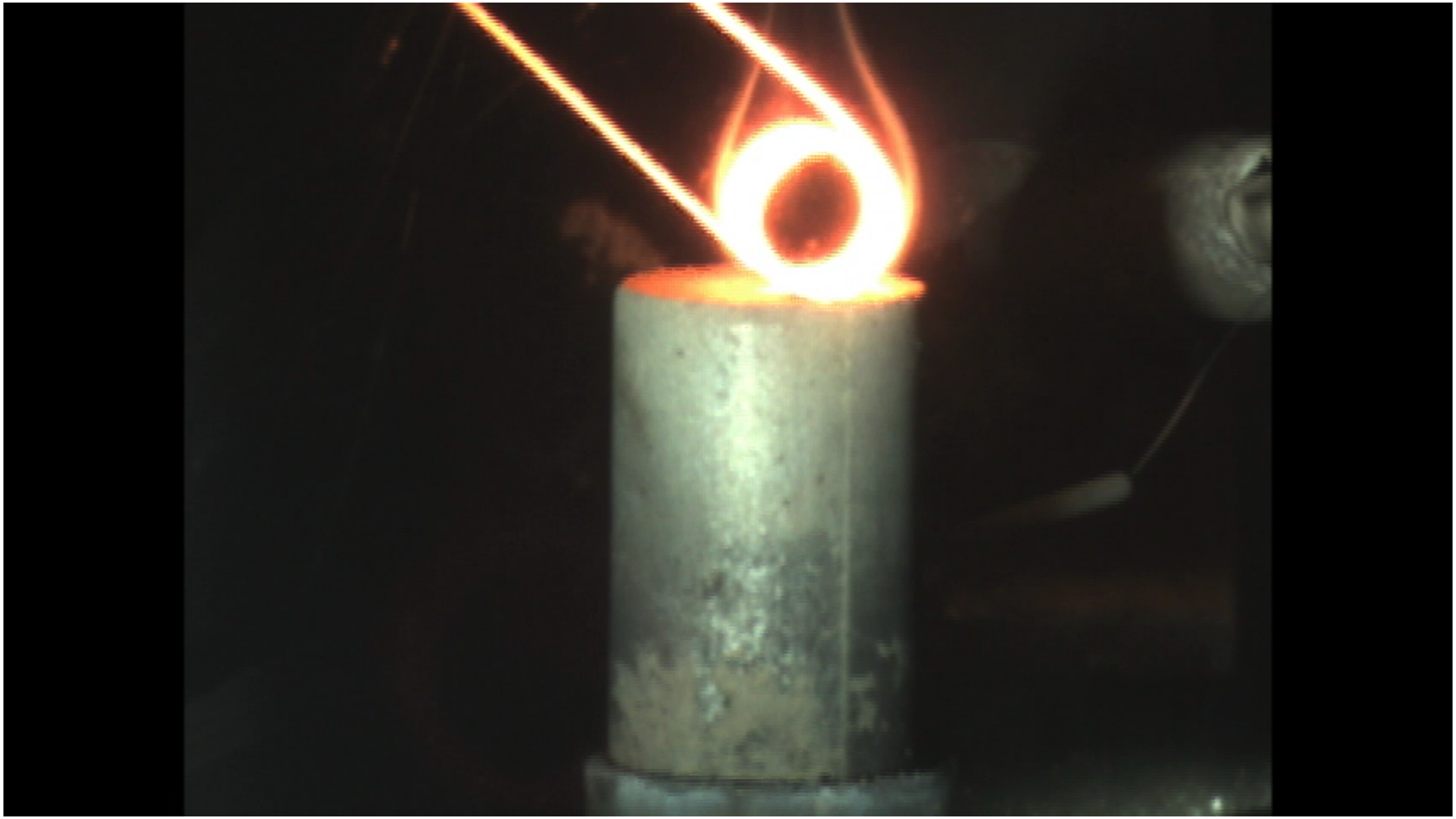
- Compaction in an uniaxial hydraulic press
  - Mass: 5 g
  - Diameter: 1.3 cm
  - Force: 2 metric tons
- Channel drilled for thermocouple

Compacted Powder

Experimental Setup

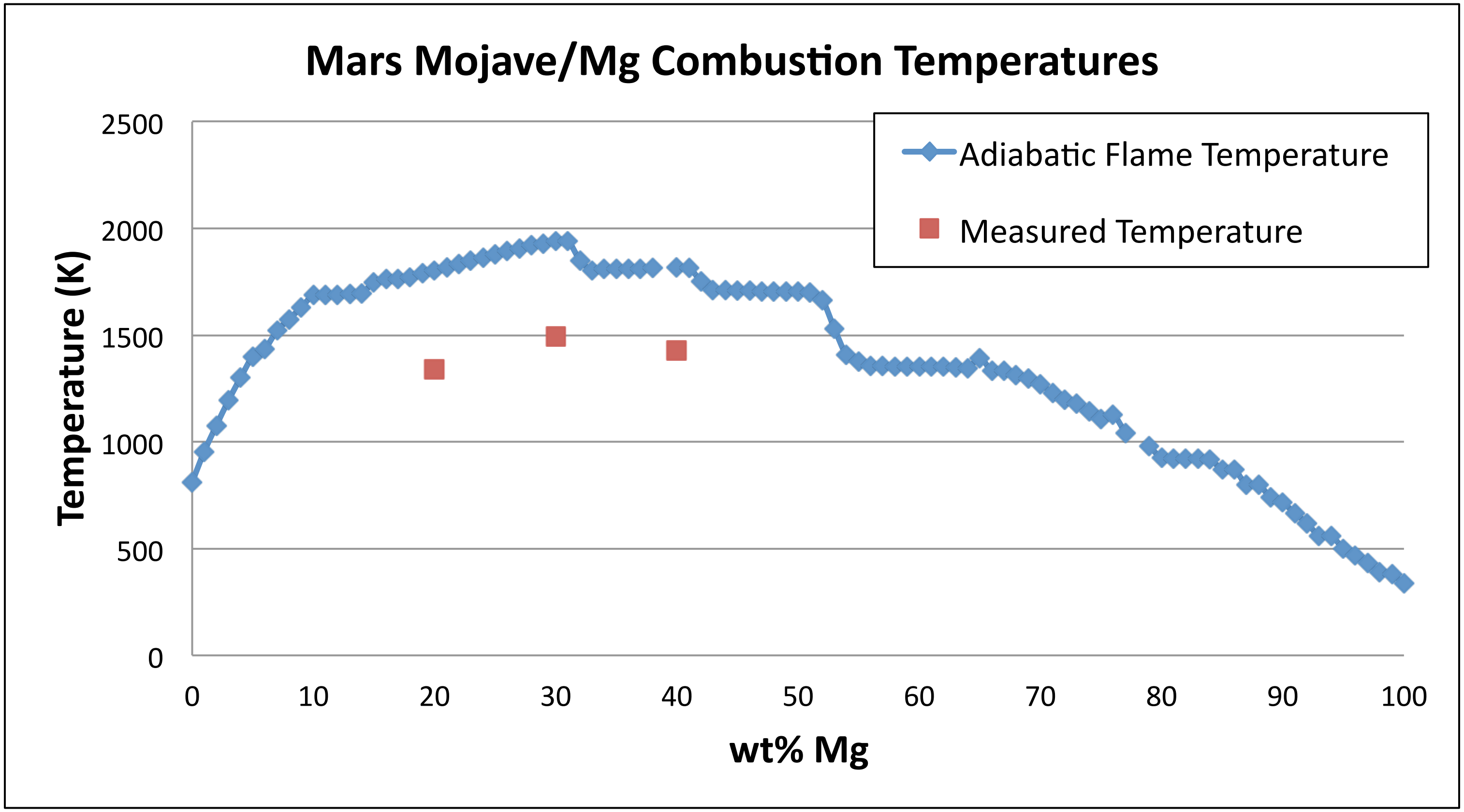


Mars Mojave/Mg Combustion



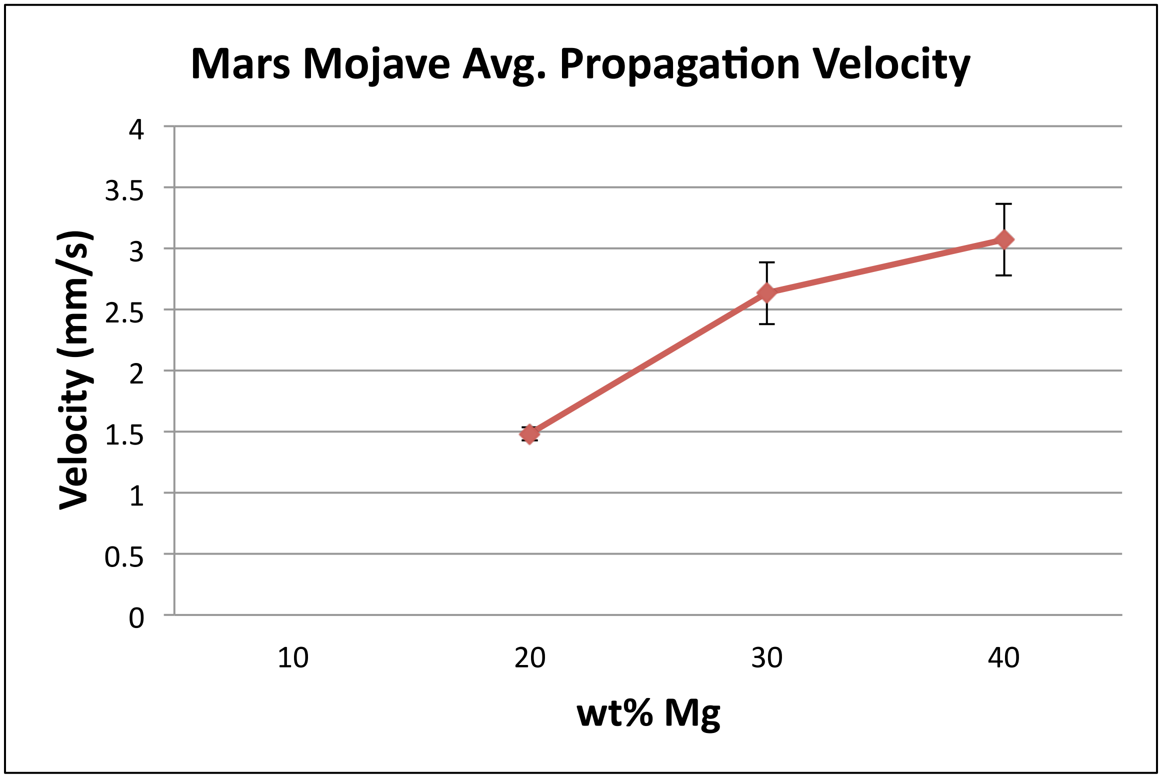
Mars Mojave/Mg pellet (30 wt% Mg)

Combustion Temperature



- Adiabatic flame temperatures were calculated using THERMO software
- Reasonable agreement between experimental and predicted data is observed for Mars Mojave simulant

Combustion Front Velocity



- The combustion front velocity increases with increasing Mg concentration

Microgravity Experiments

- Parabolic flights: NASA Johnson Space Center
  - June 2011: JSC-1A
  - June 2012: JSC-1A
  - July 2013: JSC-1A, JSC-Mars-1A, Mars Mojave

Microgravity Experiments in July 2013

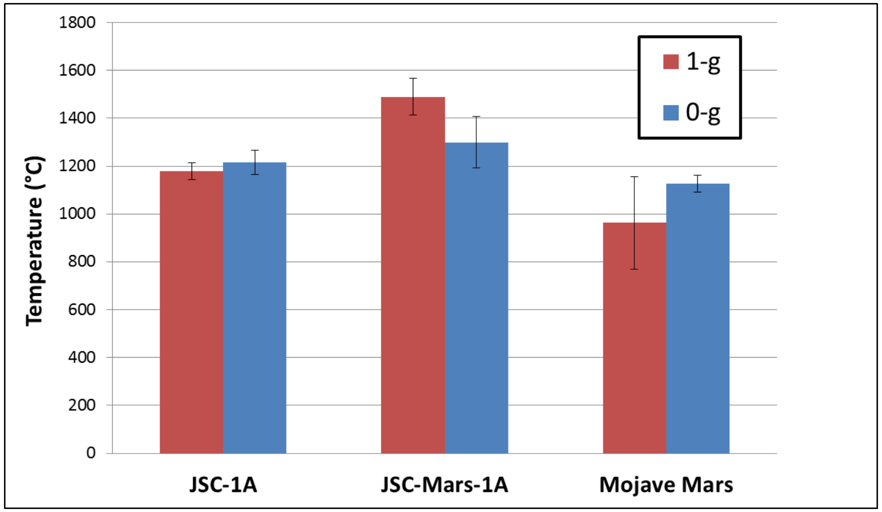
- Samples made with 25 wt% Mg
- Lunar and Martian simulants
  - JSC-1A
  - JSC-Mars-1A

Mars Mojave

Combustion Characteristics at Reduced and Normal Gravity

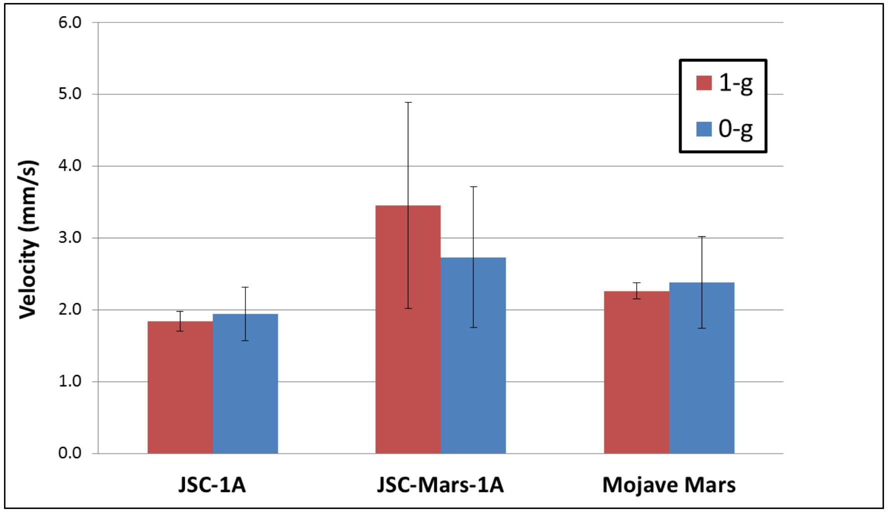
Temperature

- Combustion temperatures measured by thermocouples



Front Velocity

- The combustion front velocity determined from video records.



- Virtually no gravity effect.
- Mars-1A has the best combustion characteristics.

Simplified Compositions of Regolith Simulants

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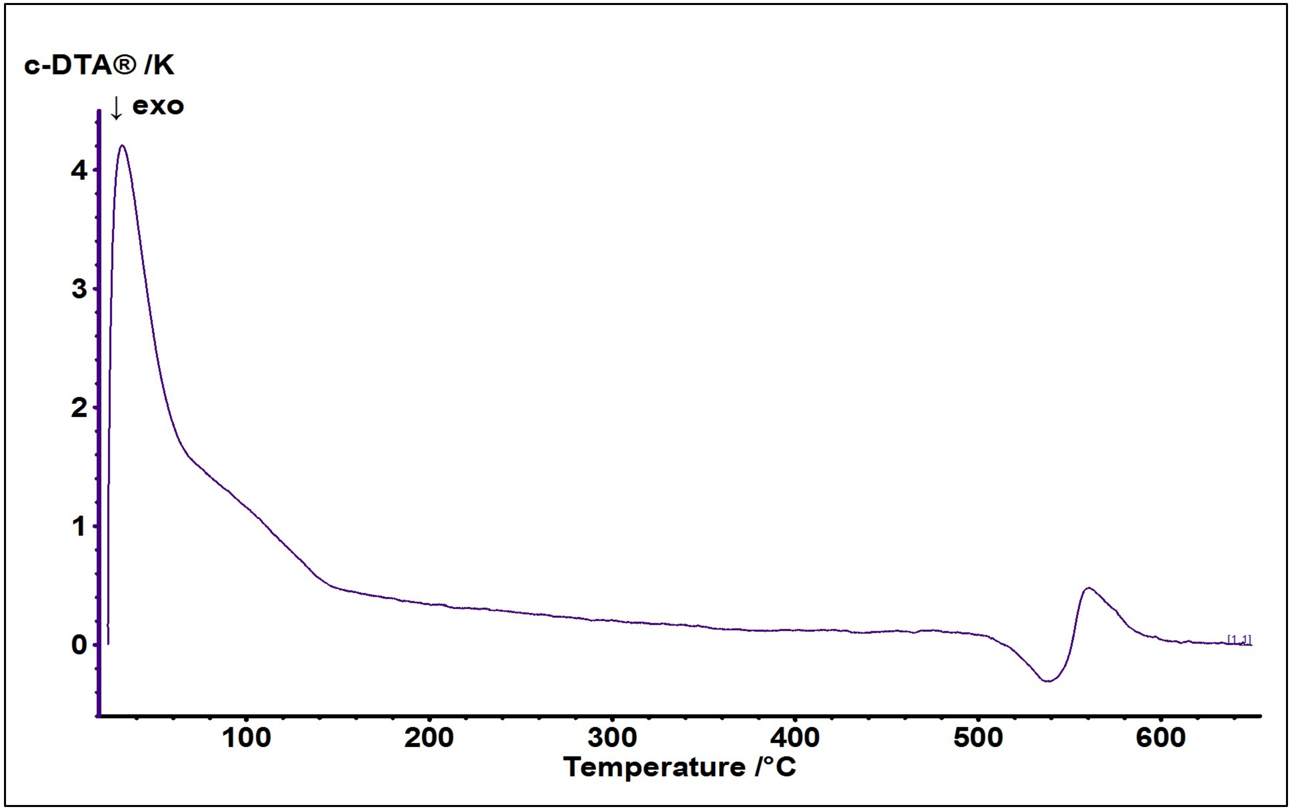
$$SiO_2 + 2\ Mg \rightarrow 2\ MgO + Si$$

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

Differential Thermal Analysis (DTA)

- Employed to investigate reaction mechanisms of regolith/magnesium mixtures
- Examined mixture composed of JSC-1A lunar regolith with 26 wt% Mg
- Samples cooled in argon flow (20 mL/min)
- X-ray diffraction analysis (XRD) employed to examine the products

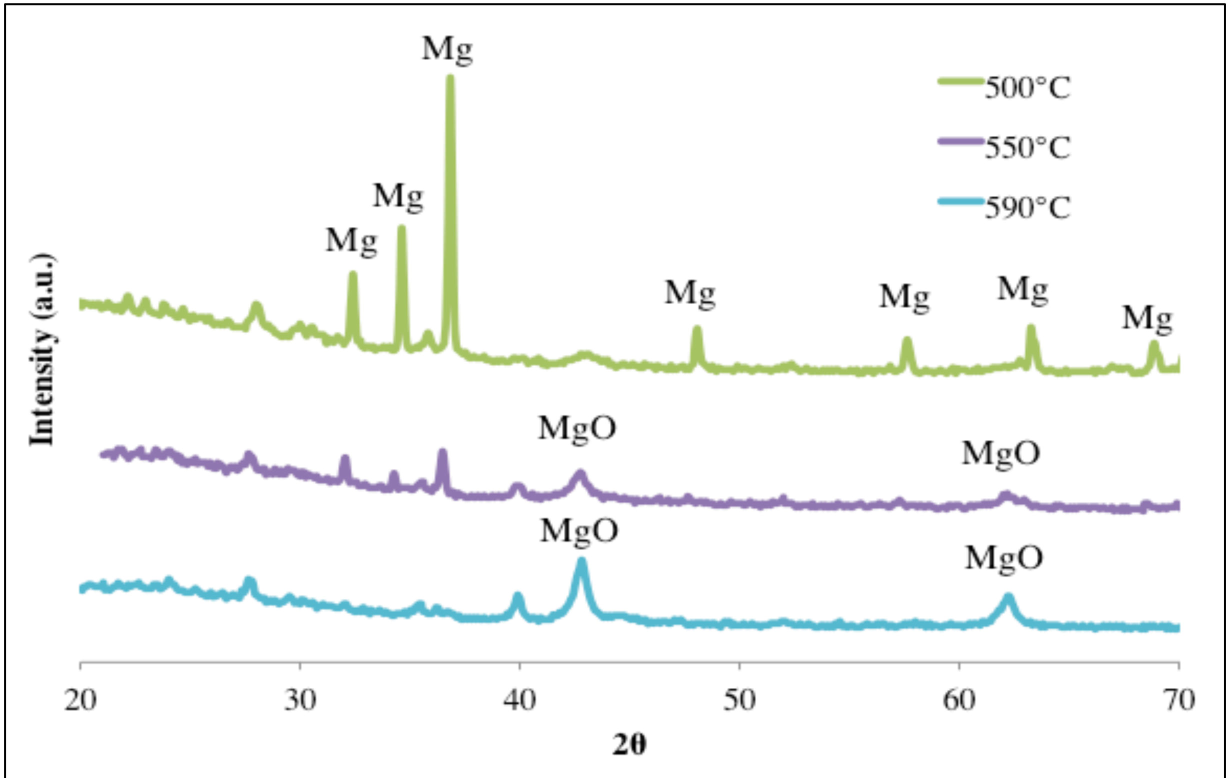
Differential Thermal Analysis (DTA)



- DTA curve shows exothermic peak at 550°C
- Melting point of Mg: 650°C

XRD Analysis of Quenched Products

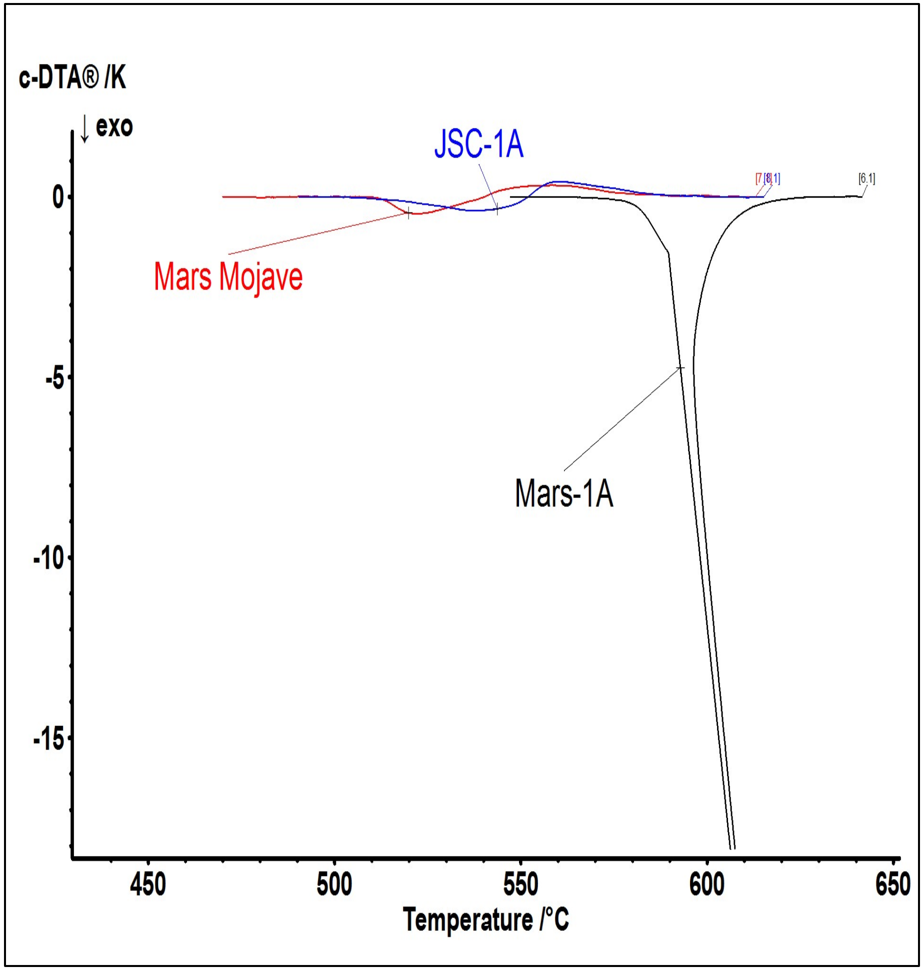
- To investigate reaction, analysis was stopped at 500°C, 550°C, and 590°C



- The reaction is complete at a temperature between 550 C and 590 C
- Magnesium is solid throughout reaction ($T_{melting,Mg}$ = 650°C)

DTA of Regolith/Mg Mixtures

Regolith Simulant	SiO_2 wt%	Fe_2O_3 wt%
Mars Mojave	49.4	10.87
JSC-1A	45.7	12.4
JSC-Mars-1A	43.48	16.08



DTA of Mg/SiO2 and Mg/Fe2O3 Mixtures

- **Mixture 1**

41 wt% Mg / 20 wt% Fe_2O_3 / 39 wt% SiO_2

  - 71 Mg/SiO_2
  - 29 Mg/Fe_2O_3

- **Mixture 2**

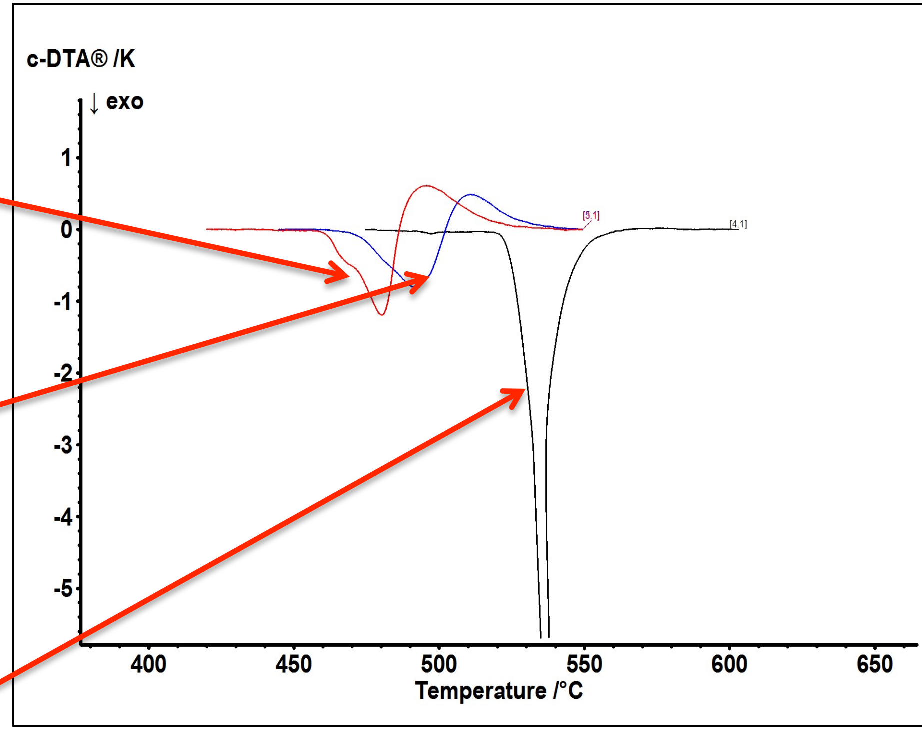
38 wt% Mg / 31 wt% Fe_2O_3 / 31 wt% SiO_2

  - 55 wt% Mg/SiO_2
  - 45 wt% Mg/Fe_2O_3

- **Mixture 3**

37 wt% Mg / 42 wt% Fe_2O_3 / 21 wt% SiO_2

  - 38 wt% Mg/SiO_2
  - 62 wt% Mg/Fe_2O_3



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

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

Conclusions

- Martian regolith simulants form combustible mixtures with Mg.
- JSC-Mars-1A exhibits the best combustion characteristics.
  - JSC-Mars-1A is characterized by the highest concentration of iron oxide.
- DTA and XRD have shown that Fe_2O_3 may play a more important role than SiO_2 in the combustion of lunar and Martian regolith simulants with Mg – **Iron-rich regoliths are recommended**.

Thank you!