Production of Structural Materials by Combustion of Lunar Regolith with Metals

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Introduction

- Future lunar activity will require construction materials for radiation shielding, landing pads, and thermal wadis.
  - Such materials could be produced *in situ* from lunar regolith, using sintering and other high-temperature methods.
    - One such method is to apply self-propagating high-temperature synthesis (SHS), using a metal/regolith mixture.

SHS Combustion of Lunar Regolith

- Regolith, which primarily consists of oxides, is first mixed with a metal powder to form a combustible thermite mixture.
  - Only a small amount of energy is required to ignite.
  - Upon ignition, mixture exhibits self-sustained propagation of the combustion wave.
    - No external energy required after ignition.
    - Oxygen comes directly from solid reactants.
- The result: Dense and strong materials which may be used for construction applications.

Past Research

- Experiments performed by Faierson & Logan at Virginia Tech demonstrated combustibility of aluminum & JSC-1AF mixtures.
  - Minerals were assumed to be simple oxides.
    - Gibbs free energy for reduction/formation of these oxides was compared.
  - Solid bricks were formed from the reaction.
  - Product composition & material properties were examined.

Current Research

- In addition to aluminum, magnesium will also be tested.

- Thermodynamic calculations for the mixtures have been performed which apply Gibbs Energy Minimization for varying metal concentrations.
  - Minerals were not assumed to be simple oxides.
  - Results of calculations suggest magnesium will yield more favorable reactions than aluminum.

- 2 sample shapes will be tested:
  - Circular layers of loose material
  - Cylindrical samples of compressed material

- We are interested in minimizing the metal content necessary for stable combustion.
  - Stable/unstable combustion region
  - Particulate size

Project Goals

- For both aluminum and magnesium powders, we will determine:
  - The minimum metal loading needed to ensure stable flame propagation for each type of sample.
  - Products of the combustion reaction.
  - Structural properties of the new material (compressive strength, impact testing, flexural strength).
  - Correlation between structural properties and chemical composition.

JSC-1A & JSC-1AF Composition

- QEMSCAN® modal analysis and electron-probe microanalysis were conducted by NASA and Orbitec at the Marshall Space Flight Center.
- Orbitec's findings for JSC-1AF's mineral chemistry were used to approximate the mineral content of JSC-1A.
  - Plagioclase:
    - 70% Anorthite
    - 29% Albite
    - 1% Orthoclase
  - Ca-Pyroxene
    - 45% Wollastonite
    - 38% Enstatite
    - 22$ Ferrosilite
  - Olivine
    - 73% Forsterite
    - 27% Fayalite

Minerals	JSC-1A	JSC-1AF
Plagioclase	37.83	48.47
Clinopyroxene	18.77	21.15
Orthopyroxene	0.66	1.62
Olivine	12.44	9.22
Glass	26.67	15.68
Magnetite	0.01	0.00
Chromite	0.00	0.00
Ilmenite	0.11	0.08
Sulphides	0.17	0.31
Iron	0.00	0.00
MgFeAl Silicate	3.06	3.09
K Feldspar	0.07	0.11
Quartz	0.01	0.04
Calcite	0.11	0.14
Others	0.07	0.08
Total	100.00	100.00

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  - Plagioclase:
    - 70% Anorthite
    - 30% Albite
    - ~~1% Orthoclase~~
  - Pyroxene
    - 40% Wollastonite
    - 38% Enstatite
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Thermodynamic Calculations

- THERMO software used to calculate adiabatic flame temperatures, products, and states.
  - Database includes approximately 3000 compounds.
  - Limited by the number of elements it can process in a given calculation.
  - 8 most abundant minerals were chosen for calculations.
    - Glass composition is assumed to be the same as the remaining mineral content.
    - Percent compositions were modified to account for missing minerals.

JSC-1A and Model Composition

Mineral	Formula	wt% (JSC-1A)	wt% (Model System)
Anorthite	$CaAl_2Si_2O_8$	26.48	37.95
Albite	$NaAlSi_3O_8$	11.35	16.27
Orthoclase (K Feldspar)	$KAlSi_3O_8$	0.07	0.10
Wollastonite	$CaSiO_3$	7.77	11.14
Enstatite	$MgSiO_3$	7.38	10.58
Ferrosilite	$FeSiO_3$	4.28	6.13
Forsterite	Mg_2SiO_4	9.08	13.02
Fayalite	Fe_2SiO_4	3.36	4.81
Glass		26.67	0
MgFeAl silicate		3.06	0
Sulphides		0.17	0
Ilmenite	$FeTiO_3$	0.11	0
Calcite	$CaCO_3$	0.11	0
Magnetite	Fe_3O_4	0.01	0
Quartz	SiO_2	0.01	0
Others		0.07	0
TOTAL		99.98	100.00

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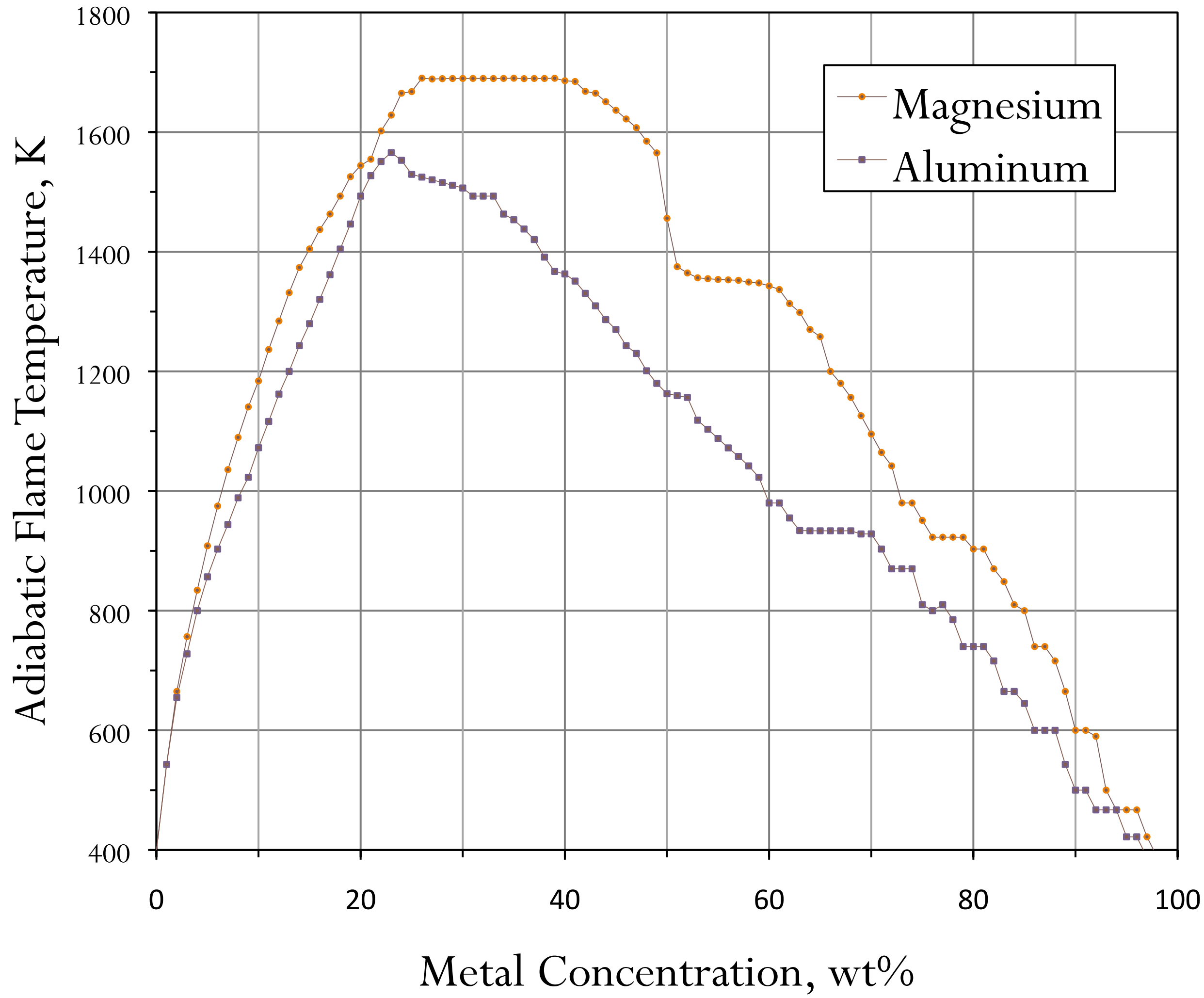
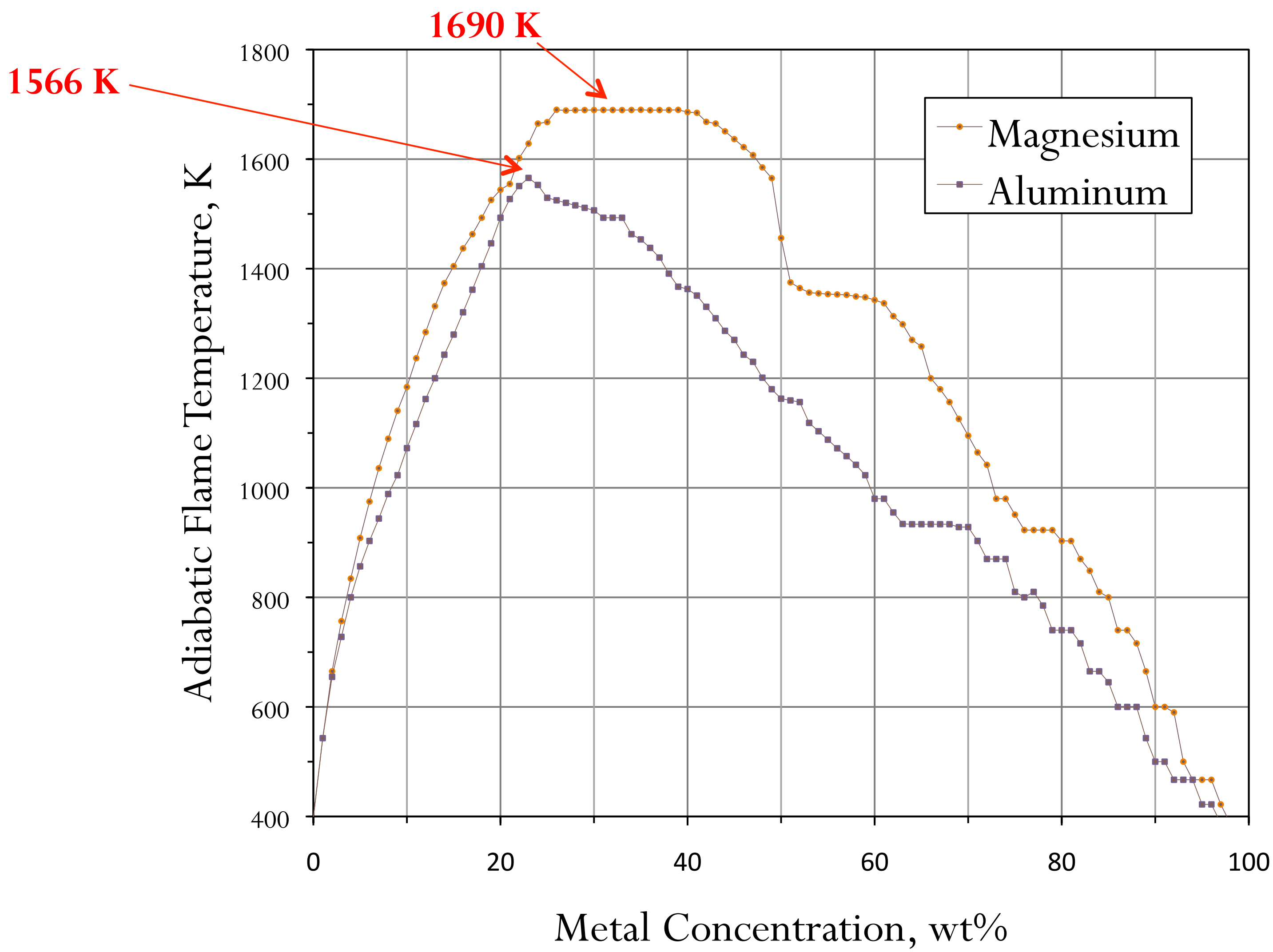
Thermodynamic Calculations



Thermodynamic Calculations



Predicted Products

- For 23% aluminum composition:

Formula	Phase	Composition, wt%
$MgAl_2O_4$	Solid	31.81
$CaAl_4O_7$	Solid	30.24
Si	Solid	14.91
$Ca_2Al_2SiO_7$	Solid	8.58
FeSi	Solid	6.05
Al_2O_3	Solid	4.49
$NaAlO_2$	Solid	3.89
K	Gas	0.01
Na	Gas	0.01

- **Qualitative agreement with experiments conducted at Virginia Tech**

Predicted Products

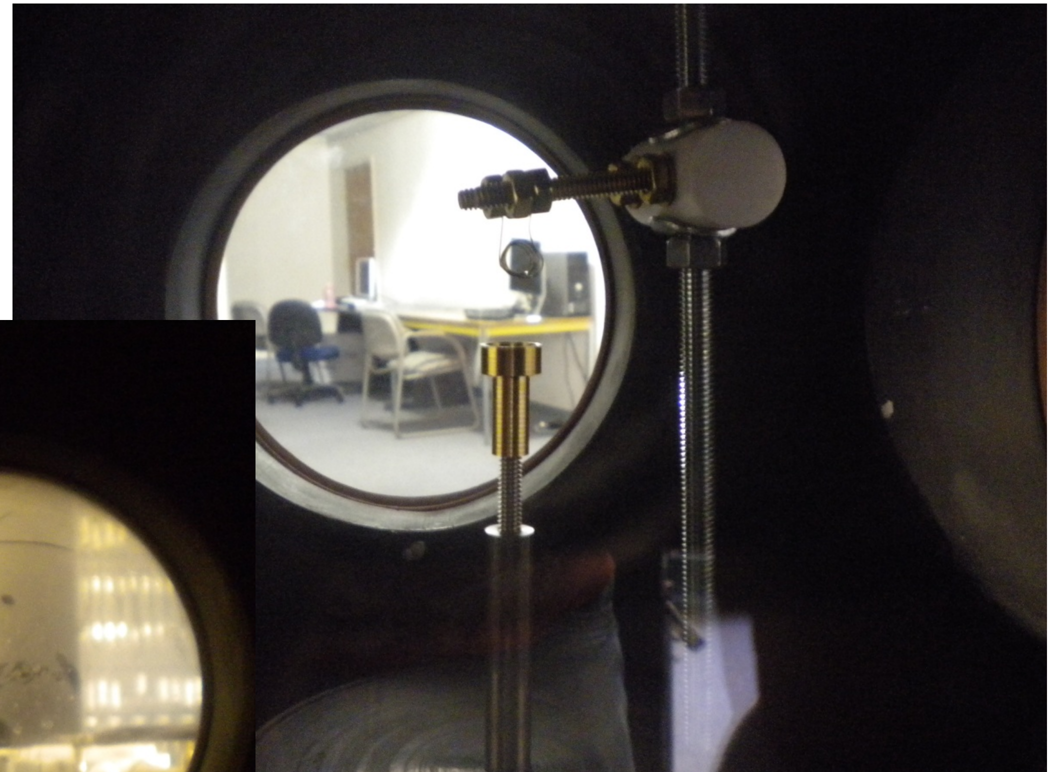
- For 26% magnesium composition:

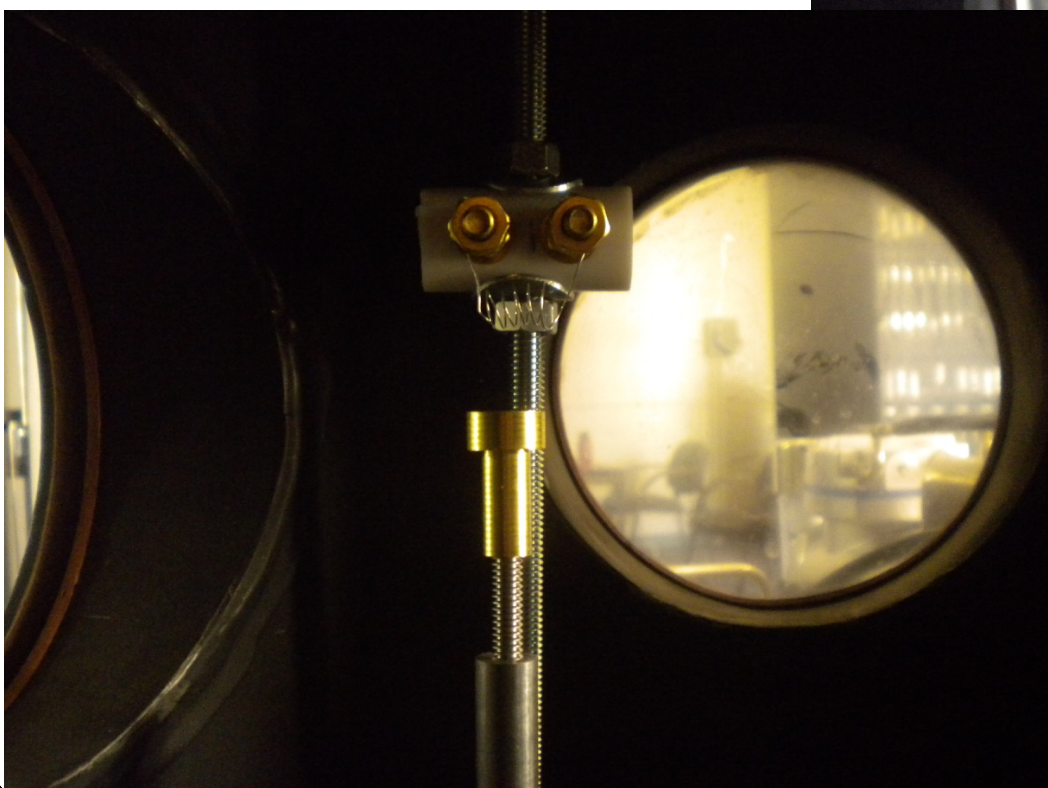
Formula	Phase	Composition, wt%
MgO	Solid	43.61
$MgAl_2O_4$	Solid	17.65
$Ca_3MgSi_2O_8$	Solid	16.04
Si	Solid	10.56
$FeSi$	Solid	5.82
$CaMgSiO_4$	Solid	3.99
Si	Liquid	1.16
Na	Gas	1.03
Mg	Gas	0.10
Na_2	Gas	0.02
K	Gas	0.01

Experimental Setup

- Steel combustion chamber, 30 cm x 40 cm.
- Experiments will be conducted with argon as inert atmosphere.
- First experiments will be conducted at 1 atm.
- Further experiments will be conducted in vacuum.

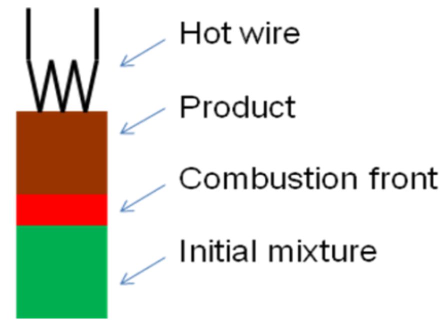
Experimental Setup



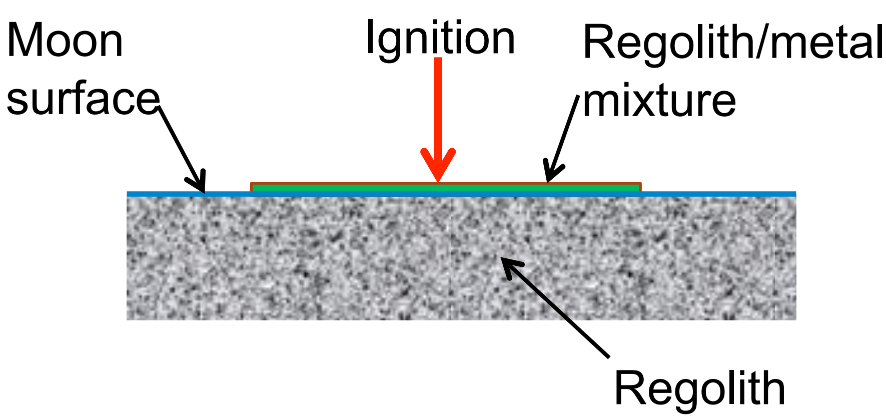


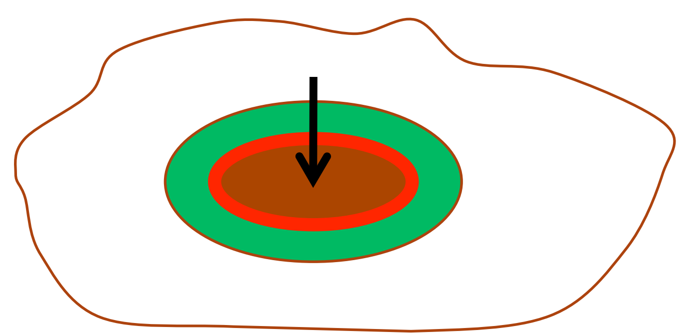
Sample Types

- Mixture pellets (1.3 cm x 2.5-4 cm)



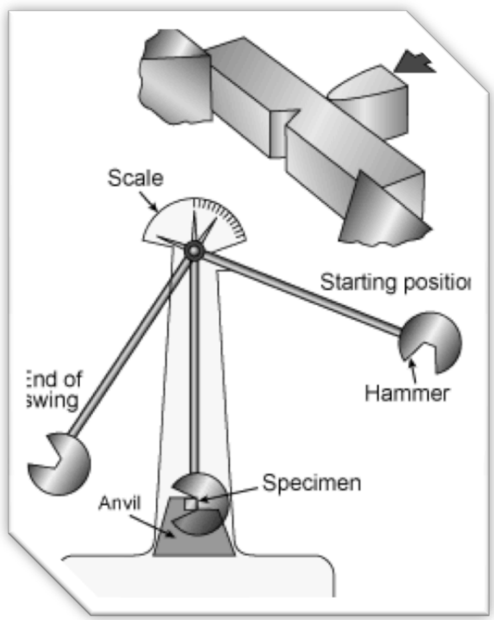
- Mixture layer (up to 20 cm in diameter and up to 5 cm deep)





Testing

- Compression, impact, and bending tests to be conducted with UTEP's Civil Engineering Department.



Conclusion

- Thermodynamic calculations of the adiabatic flame temperature and combustion products have been conducted for metal concentrations from 0-100%.
  - Expected products of Al-based mixtures agree with prior experimental data.
  - Higher temperatures predicted for Mg-based mixtures.

- An experimental setup has been constructed to study combustion of mixture pellets and layers.

Acknowledgements

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Questions