# In-Situ Production of Construction Materials by Combustion of Regolith/Aluminum and Regolith/Magnesium Mixtures

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# Acknowledgment


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- ISRU is one of research topics studied at cSETR.

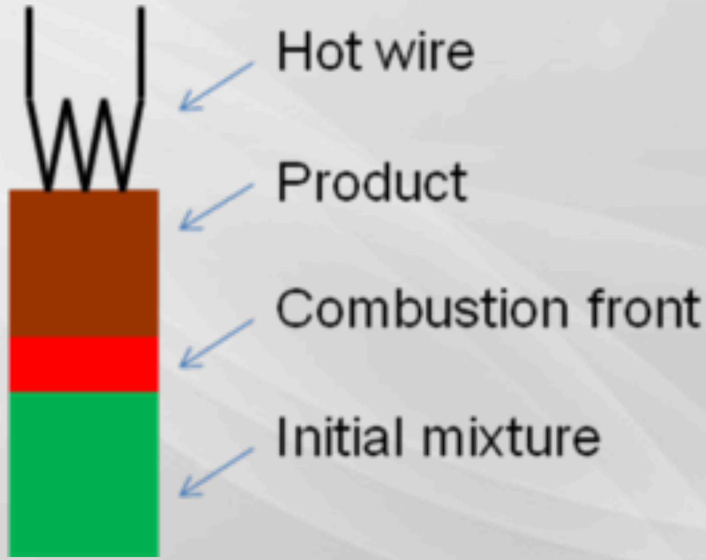
# In-Situ Production of Materials

- Construction materials for landing/ launching pads, radiation shielding, thermal wadis, etc., could be produced in situ from regolith, using sintering and other high-temperature methods.

- One such method is to apply self-propagating high-temperature synthesis (SHS), also called combustion synthesis.

# Combustion of Regolith Mixtures

- Regolith is mixed with either a pyrotechnic mixture (e.g., Ti + 2B) or a metal (e.g., Al or Mg) powder.
- Upon ignition, mixture exhibits




- Products can be used for construction applications.
- Advantage: small energy consumption

# Prior Research

- Martirosyan and Luss (University of Houston) studied combustion in mixtures of lunar regolith simulant with Ti + 2B.
  - The reaction is: $Ti + 2\,B \rightarrow TiB_2$
  - Regolith is inert
  - Successful ignition of 40 wt% (Ti/2B) / 60 wt% regolith mixtures.

# Prior Research

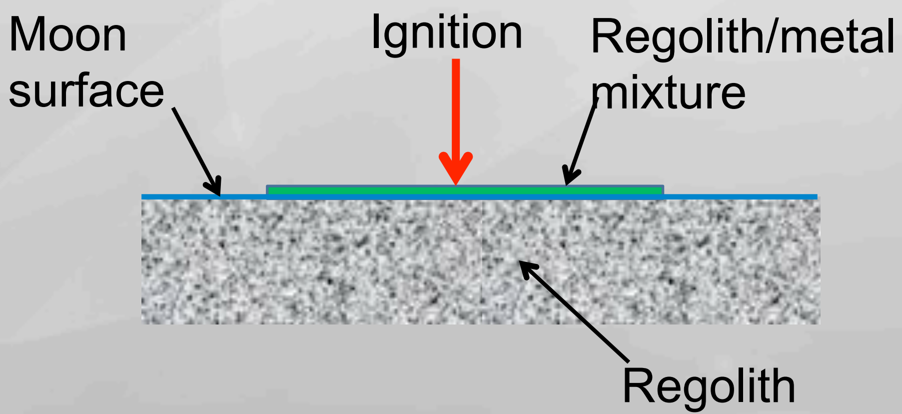
- Faierson et al. (Virginia Tech) demonstrated combustibility of regolith/Al mixtures.
  - The reaction is between Al and regolith (thermite)

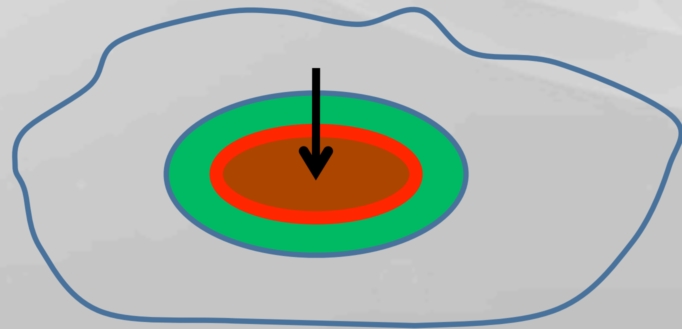


Images: E.J. Faierson, K.V. Logan, B.K.Stewart, M.P. Hunt, Acta Astronautica 67 (2010), 38-45

# Potential Construction Elements

- Bricks
- Tiles
- Ceramic layer on the Moon surface for landing/launching pads and thermal wadis



# Research Objectives

- Comparative analysis of different additives to regolith (Al, Mg, Ti/2B) with the goal to minimize the amount of additive that is required for stable combustion
- Determination of the effect of mixture density on the combustion characteristics and product properties
- Determination of the effects of vacuum and reduced gravity
- For disks, determination of the minimum thickness that is required for stable combustion

# Approach

- Thermodynamic calculations
- Combustion experiments
- Characterization and testing of the products
- Modeling

# Thermodynamic Calculations (Al and Mg)

- THERMO software used to calculate adiabatic flame temperatures and combustion products.
  - Uses minimization of the Gibbs free energy.
  - Database includes approximately 3000 compounds.
  - 8 most abundant minerals were chosen for calculations.
  - Glass composition is assumed to be the same as the remaining mineral content.

# Regolith Simulant 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 | $KAlSi_3O_8$ | 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 |

# Predicted Temperatures

Temperatures for Mg are higher than

# Predicted Products

- For 23 wt% Al 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 wt% Mg 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 |

# Thermodynamic Calculations (Ti + 2B)

- The number of possible compounds is too large for THERMO.
- HSC Chemistry 7 includes 25,000 compounds but it  cannot determine the adiabatic temperature if the product composition is unknown.
- Solution: use HSC chemistry 7 to determine equilibrium compositions at different temperatures; then use these results to select compounds for THERMO and determine the adiabatic flame temperature.

# Predicted Temperatures

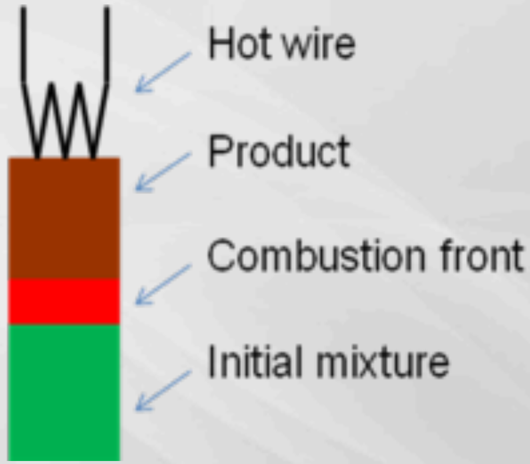
Mg is the best additive!

# Experimental Setup

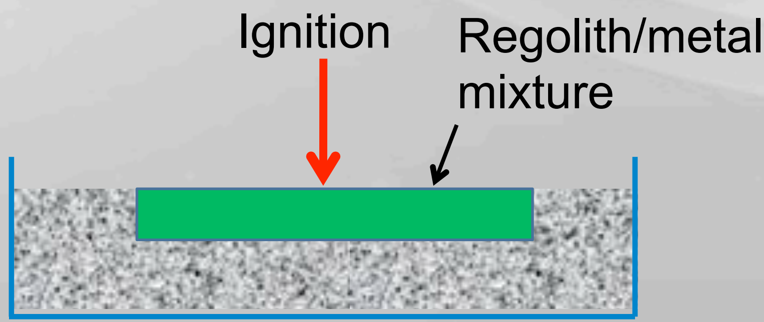
- Steel combustion chamber with inserts for pellets and layers
- Igniter: NiCr wire
- Environment:
  - Argon at 1 atm
  - Vacuum

# Sample Types

- Pellet
  - diameter 1.3 cm, height 3 cm




- Disk
  - diameter 5-10 cm






Saturday, November 20, 2010

# Effect of Milling on Particle Size of JSC-1A

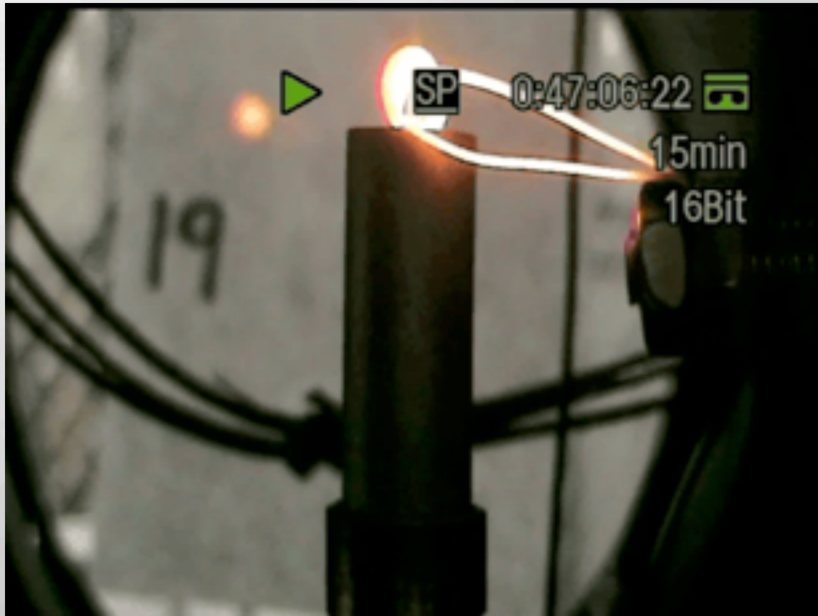
# Experimental Results

- Pellets compacted from the mixtures of original JSC-1A (mean size 300 μm) with Al or Mg did not ignite.
- Milled JSC-1A (mean size 110-120 μm) does not ignite with Al but it ignites with Mg.
- For mixtures of milled JSC-1A with Mg, in some runs pulsations were observed while in other runs combustion was steady.

# Combustion of Regolith/Mg Mixture

Steady combustion


Pulsating combustion



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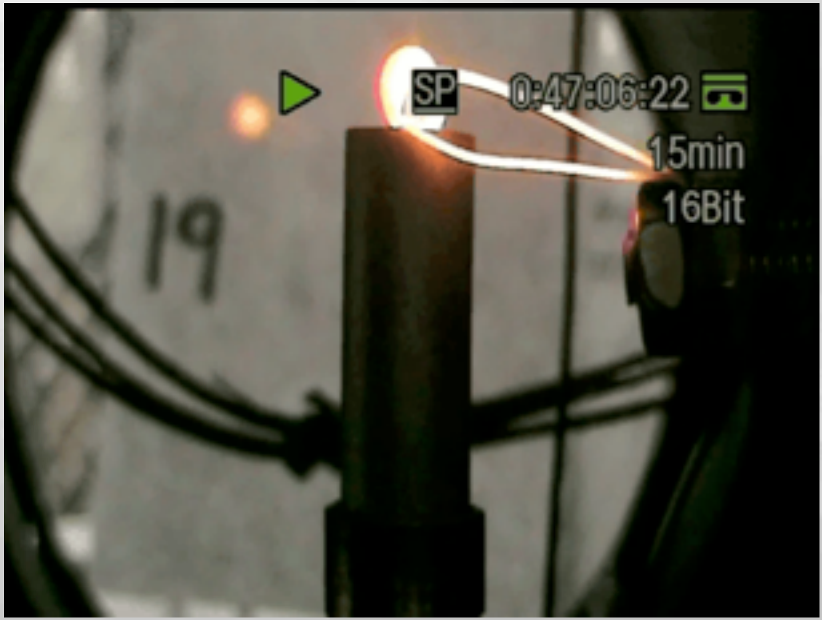

# Conclusions

- Thermodynamic calculations of the adiabatic flame temperature and combustion products have been conducted for mixtures of regolith simulant with Al, Mg, and Ti + 2B.
  - At the same wt% addition, Mg additive provides higher temperatures than Al.
  - Much larger amounts of Ti + 2B mixture are required for combustion.
- Combustion of regolith/Mg mixtures has been demonstrated experimentally (steady and pulsating regimes).

# Ongoing and Future Work

- Use a planetary ball mill (Fritsch Pulverisette 7) to further decrease the particle size of JSC-1A and determine the minimum amounts of Mg and Al for steady and unsteady combustion regimes.
- Along with pellets, study combustion of disks.
- Study combustion products
  - XRD, SEM, EDS
  - mechanical properties
  - testing by rocket plume at Kennedy Space Center