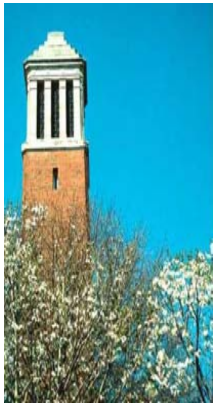


In-Situ Resources Utilization

Processing of Lunar Materials

(JSC-1 Lunar Simulant Materials)

R. G. Reddy[+], L. Tong[#] and S. Sen*

[+]ACIPCO Professor and Associate Director; [#]Graduate Student
Center for Green Manufacturing
Department of Metallurgical and Materials Engineering
The University of Alabama, Tuscaloosa, AL 35487

***BAE Systems, NASA /Marshall Space Flight Center**
Huntsville, Alabama 35812

E-mail: rreddy@coe.eng.ua.edu
Web: http://bama.ua.edu/~rreddy

Contents

- Introduction
- Research Projects
- Lunar Materials Research
  - Modeling
  - Experimental
- Conclusions
- Acknowledgments

Introduction

- **The ultimate success of space exploration and colonization of Moon will depend on the effective use of the available resources.**
- **Minerals and soils available on Moon are excellent sources for extraction of oxygen, water, and metals and alloys needed for extended human presence on Moon.**
- **Processing of lunar regolith into usable structural components to support the construction of advanced lunar bases and colonies will be essential for human habitation.**
- **It is economical to use locally produced metals and alloys.**

Objectives

The principal objectives of the research project are

- **exploring materials processes for the extraction of volatiles, metals and alloys from available resources on Moon and Mars**
- **advancing our current understanding of materials processing in a low gravity environment.**
- **developing process modules for materials processing on Moon and Mars**

Composition of JSC-1 Simulant Material

Phases	Temperature (^{0}C)	Amount (Wt %)	Amount (kmol)	Amount (at %)
SiO_2	25	47.71	0.794	52.057
TiO_2	25	1.59	0.02	1.311
Al_2O_3	25	15.02	0.147	9.638
Fe_2O_3	25	3.44	0.022	1.442
FeO	25	7.35	0.102	6.687
MgO	25	9.01	0.224	14.686
CaO	25	10.42	0.186	12.195
Na_2O	25	2.7	0.044	0.852
K_2O	25	0.82	0.009	0.590
MnO	25	0.18	0.003	0.197
Cr_2O_3	25	0.04	0	0.017
P_2O_5	25	0.66	0.005	0.328

Thermodynamic Modeling

Calculations were performed based on the method of Gibbs energy minimization under the condition of mass balance:

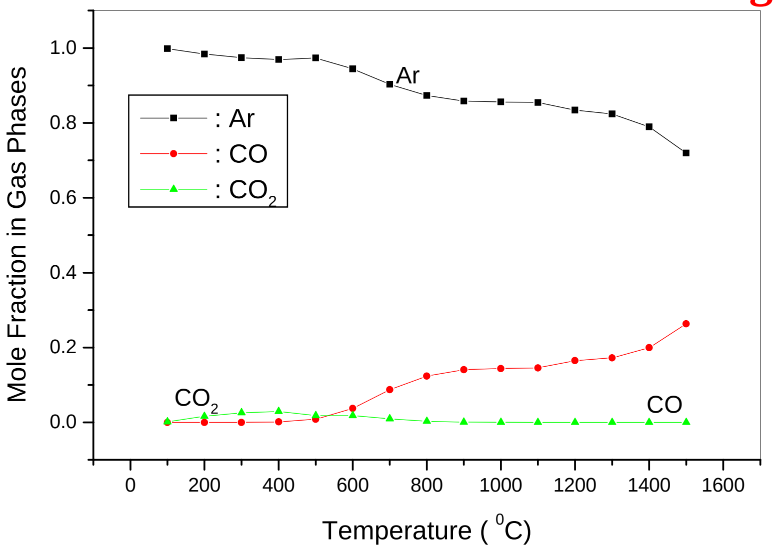
$$G = \sum_{gas} n_i (g_i^o + RT\ln P_i) + \sum_{\substack{pure\\condensed\\phase}} n_i g_i^o + \sum_{solution-1} n_i (g_i^o + RT\ln X_i + RT\ln\gamma_i)$$

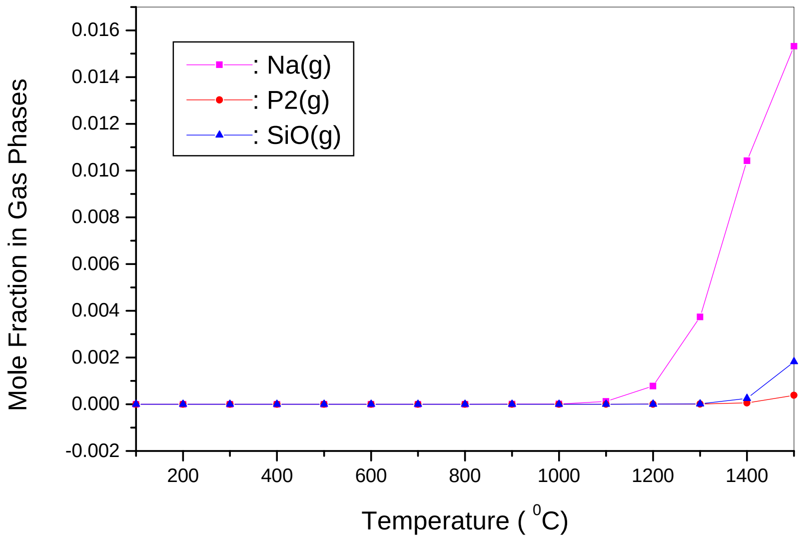
$$+ \sum_{solution-2} n_i (g_i^o + RT\ln X_i + RT\ln\gamma_i) + \ldots$$

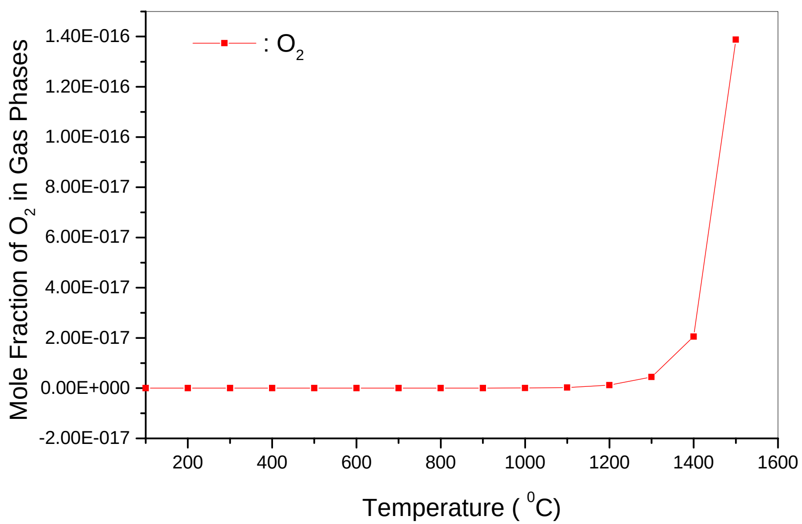
Where G - total Gibbs energy of the system; g_i^o - standard molar Gibbs energy of species i at T and P; n_i - number of mole of species i; P_i - partial pressure of species i=$(n_i/n_t)P_{total}$; X_i - mole fraction of species i; and ,γ_i - activity coefficient of species i. We will find n_i which minimize G subject to mass balance constraints.

N.A. Gokcen and R.G. Reddy, Thermodynamics, Plenum Press, 1996

Material Balance for JSC-1 Lunar Simulant Material in Reducing Medium of Carbon





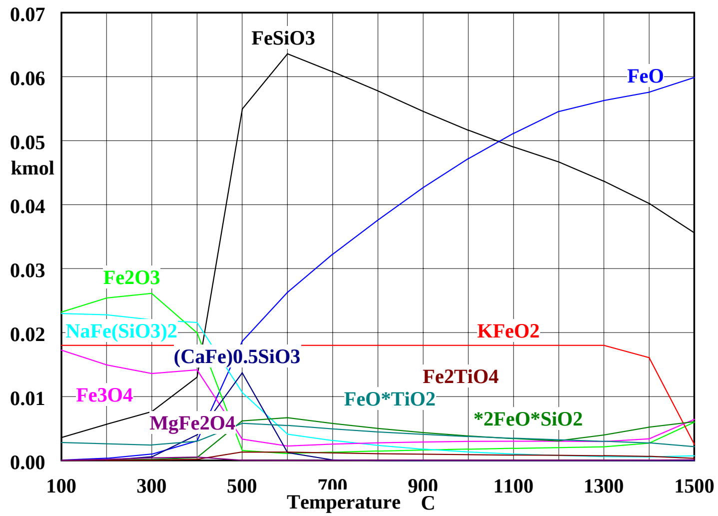


Argon gas: 1 kmol, Carbon: 1 kmol

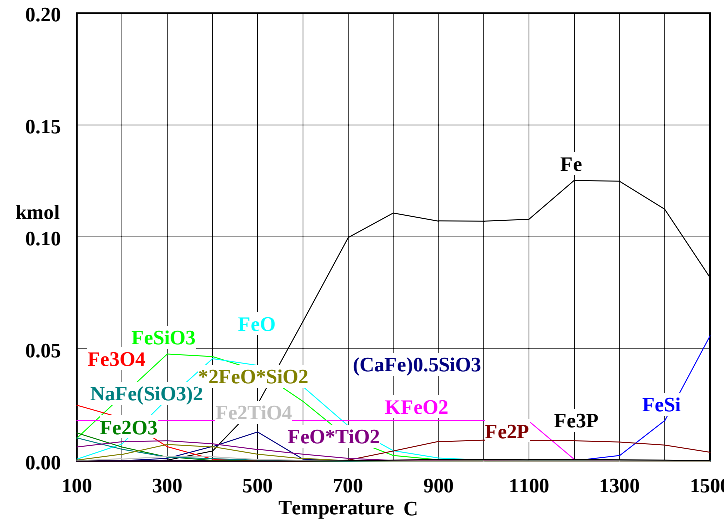
Mole fraction of gas phases as a function of temperature for JSC-1 lunar simulant materials with argon gas in reducing medium of carbon

Material Balance for JSC-1 Lunar Simulant Material

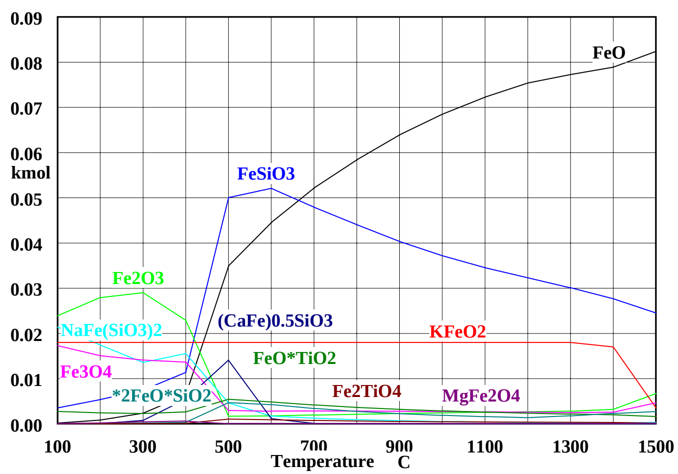
a



c



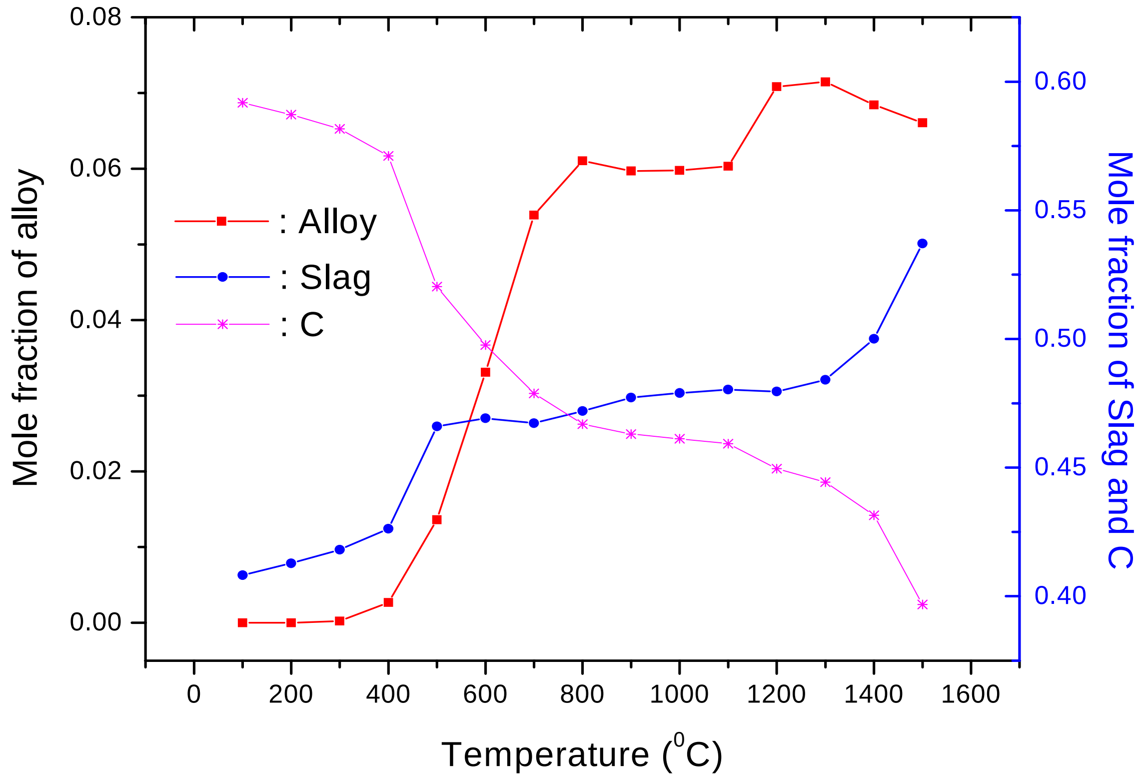
b



a: without argon gas
b: with argon gas
c: with argon gas and carbon

Equilibrium composition of product phases with Fe for JSC-1 Lunar simulant material in the temperature range of 100 ^{0}C-1500 ^{0}C

Material Balance for JSC-1 Lunar Simulant Material in Reducing Medium of Carbon



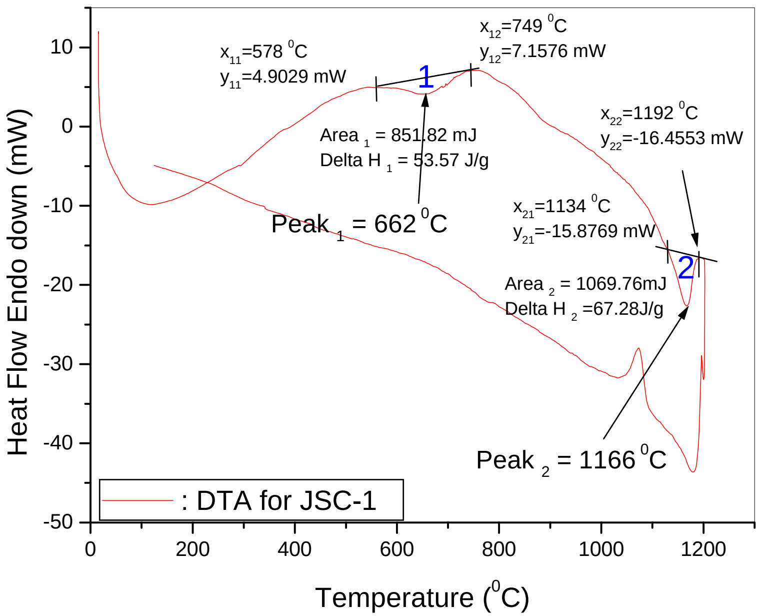
Mole fraction of Fe-P-Si alloy, slag and carbon as a function of temperature for JSC-1 lunar simulant materials with argon gas in reducing medium of carbon

Preparation of Sample Pellets for DTA and TGA Experiments

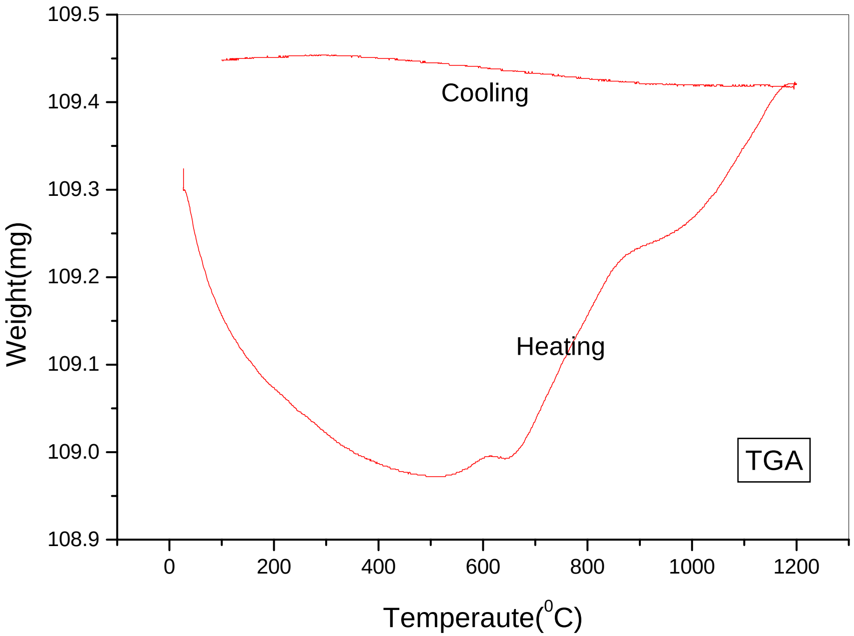
One gram of JSC-1 powders was pressed at a pressure of 6000 psi to make a sample pellet with the diameter of 1 cm as shown. Six sample pellets were prepared. Four pellets were used for thermal gravimetric analysis in an indigeneous TGA setup at 500 °C, 800 °C, 1000 °C and 1100°C, and one pellet was used for sintering experiment at 1200 °C. In addition, one pellet was broken into several small pieces to fit into a small platinum pan. One small piece was used for thermal gravimetric analysis in Perkin-Elmer TGA-7 equipment. JSC-1 powders were directly used to do differential thermal analysis in Perkin-Elmer DTA-7 equipment.

After the thermal gravimetric analysis and sintering experiments, the sample pellets were broken and ground for X-ray diffraction analysis in Philips X-rays diffractometer PW-1710 and SEM observation in Philips XL30 scanning electron microscope equipped with the DX-41 energy-dispersive spectrometer.

DTA and TGA Results for JSC-1 Lunar Simulant Material



DTA Curve for JSC-1 Lunar Material in argon atmosphere in the temperature range of 100-1200 ^{0}C.

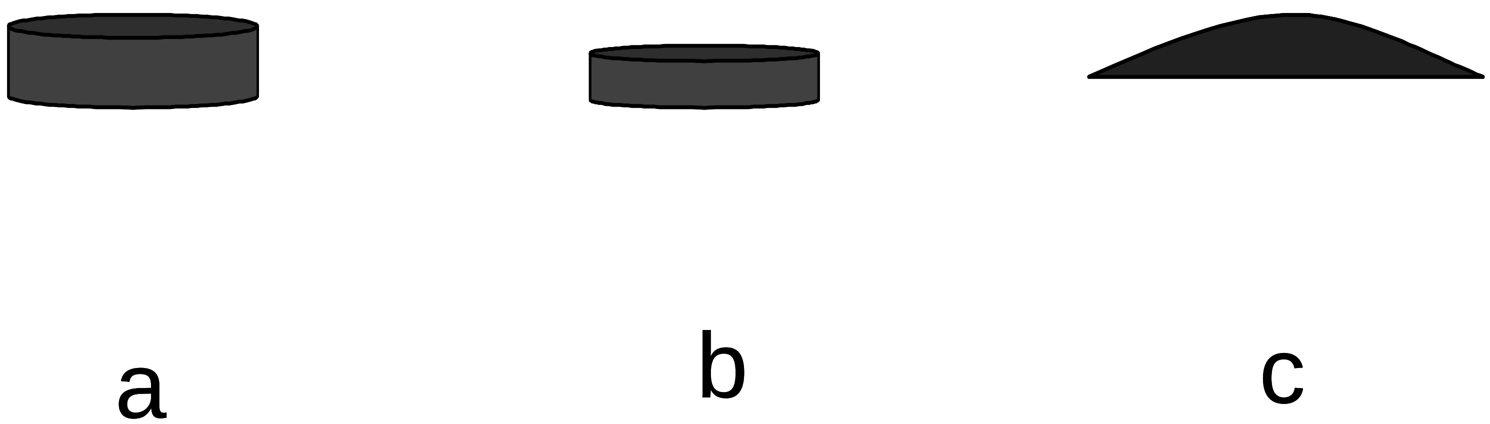


TGA Curve for JSC-1 Lunar Material in argon atmosphere in the temperature range of 100-1200 ^{0}C

Peak 1: Area = 851.82 mJ, Delta H = 53.57J/g
Peak = 662 ^{0}C

Peak 2: Area = 1069.76 mJ, Delta H = 67.28J/g
Peak = 1166 ^{0}C

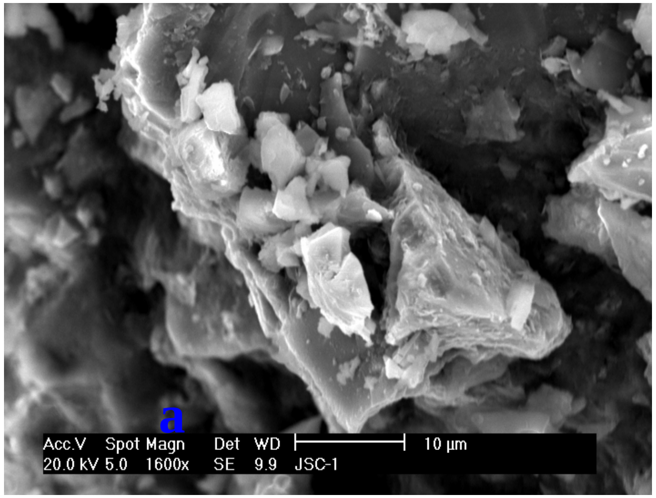
Shape of JSC-1 Sample Pellet

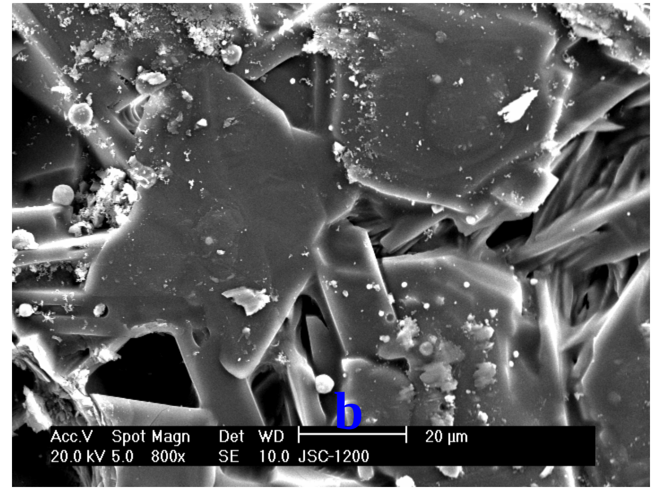


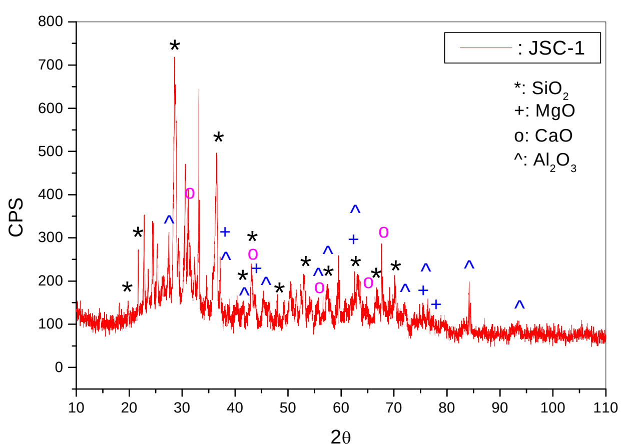
a: Initial sample
b: Sample after sintering for 30 minutes at 1100 °C
c: Sample after sintering for 30 minutes at 1200 °C

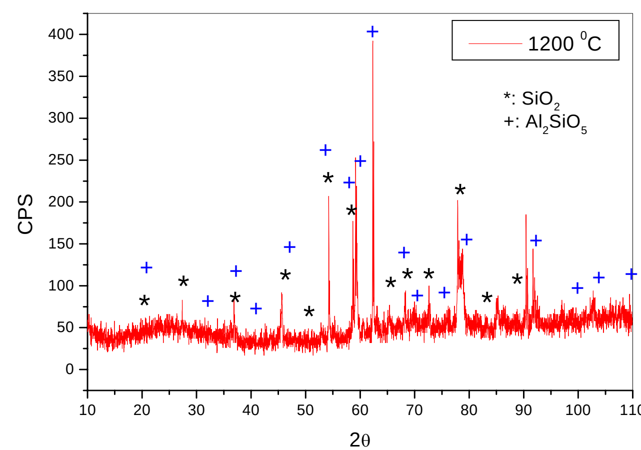
Sample before and after sintering

Characterization









a: Initial JSC-1 Lunar material **b: 1200 ^{0}C**

SEM Images and XRD of JSC-1 Lunar Materials

Summary

- When carbon was used as reducing medium, results of thermodynamic analysis show that Fe is stable above 300 °C and Na, Si and P are stable above 1100 °C. Therefore, JSC 1 Lunar Simulant Materials can be reduced using carbon to produce Fe, Na, Si and P. Results of thermodynamic analysis in argon show that no reduction was occurred in the temperature range of 100 °C -1500 °C.

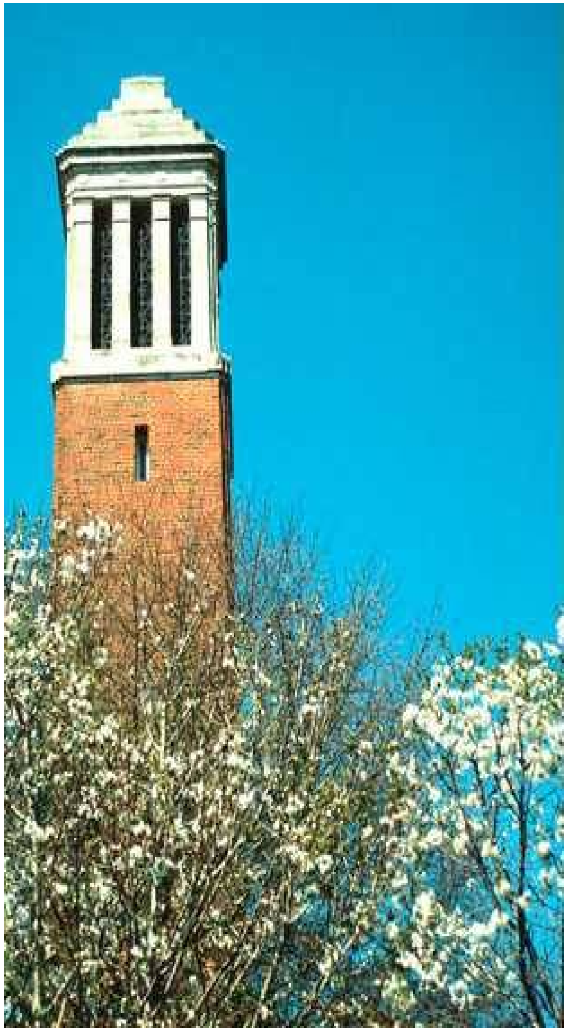
- Moles of only SiO_2, TiO_2, Fe_2O_3, FeO and MgO major element compositions are more than 10^{-4} kmol; moles of the other compounds are less than 10^{-4} kmol in the temperature range of 100 °C – 1500 °C in product compositions. Results of thermodynamic analysis in argon show similar results .

- Oxygen gas is still not significant (less than 10^{-5} kmol) in reducing medium, but mole fraction of CO and CO_2 gases are up to 26 % and 2.9 % in gas phases respectively. These results obviously differ from the results of thermodynamic analysis in argon. There is only $MgSiO_3$ liquid phase in the product compositions. Major compounds are solid phases which have three or more than three elements.

- The temperature range of 300 °C to 600 °C is suggested to be paid more attention because the moles of many product compounds reached the maximum in the temperature range of 300°C to 600°C. Results of thermodynamic analysis in argon show similar trend .

Summary

- TGA results show that the weight of JSC-1 lunar materials did not significantly change from 25 °C to 1200 °C. The maximum weight change observed for samples is less than 2%. Therefore, no phase change is said to have occurred in the temperature range of 25 °C to 1200 °C.
- DTA result shows that one phase change occurred at about 1160 °C. The phase change may be related with the melting of Na_2O(metling point of Na_2O is : 1131.9 °C).
- At 500 °C and 800 °C, the shape and size of particles of tested samples remain unchanged as that of untested samples. At 1000 °C and 1100 °C, SEM images show that some particles appear to be fused. But at 1200 °C, SEM images show that particles have been fused, and the sample shape was changed.
- At 500 °C, 800 °C, 1000 °C and 1100 °C, XRD patterns show that peak positions (2θ value) of tested samples remain the same, but relative values of some peaks has little difference. The XRD pattern of the tested sample at 1200 °C is significantly different from that of tested samples at 500 °C, 800 °C, 1000 °C and 1100 °C.
- Thermodynamic analysis shows that association reactions among /between some oxides in JSC-1 lunar materials are feasible in the temperature range of 100 °C - 1500°C, but XRD results show that temperature is one of the most important factors which influence on kinetics of association reactions.



Thank you