SINTERING OF REGOLITH BY ACTIVATED THERMITES: A NOVEL APPROACH FOR LUNAR IN SITU RESOURCE UTILIZATION. M.A. Hobosyan[1] and K. S. Martirosyan[2], Department of Physics and Astronomy, University of Texas at Brownsville, 80 Fort Brown, Brownsville, Texas 78520, ([1]Mkhitar.Hobosyan108@utb.edu, [2]Karen.Martirosyan@utb.edu).

Introduction: Human exploration of Space is continuing with NASA's anticipated return to the Moon by 2020 and establishing of permanent lunar bases to support long term missions. For operation efficiency the subsequent development of lunar *in situ* resource utilization technologies are critical. The surface of Moon, which is covered with thick layer of lunar dust, is one of the major sources to fabricate solid and dense structural materials for future outposts and permanent lunar bases for space operation programs. For construction of permanent structures it is highly desired to have regular shaped sintered regolith with utilization of local materials by minimum consumptions of energy and materials or components delivered from Earth. There are several methods for fabrication of sintered regolith on the Moon by different techniques, among them sintering of lunar regolith with radiant and microwave heating, regolith thermopolymer compacting and fiberglass fabrication. However, as mentioned, the energy efficiency is critical on the Moon, where only solar source of energy is available. Recently, it was demonstrated that the compacting of regolith into dense ceramic bricks by using combustion synthesis, by using regolith exothermic mixtures like Ti-B-regolith [1, 2] or aluminum-regolith [3] can be achieved. However, the maximum utilization of regolith was less than 60 wt % and in case of aluminum-regolith system the initial heating of sample was required to generate reaction.

In the present work the concept of sintering of lunar regolith with thermite reactions activated by fluorocarbons is proposed to increase of regolith utilization and overcome the initial heating. The thermodynamic calculations of regolith thermite reactions as well as the experimental procedures are provided to demonstrate the effectiveness of new route of lunar soil simulant (regolith) sintering under the lunar environment. We obtained hard porous ceramics with improved thermal insulation properties, which can be used as a structural materials on the Moon.

Thermodynamic calculation and estimation of the systems regolith-aluminum-activator: Our simulant of regolith has the following molar composition (according to the weight percentages): $1.26SiO_2+0.19Al_2O_3+0.03Fe_2O_3+0.13FeO+0.2CaO+$ $+0.24MgO$. The system by itself contains some energetic reserves due to interaction between some oxides. According to thermodynamic calculations, adiabatic temperature (T_{ad}) was about 1500K. The HSC-7 Software suggests for Regolith - Al stoichiometric system reaction enthalpy of ΔH = - 5.44kJ/cc. We investigated the following system:

$$(1.26SiO_2+0.19Al_2O_3+0.03Fe_2O_3+0.13FeO+ +0.2CaO+0.24MgO) + nAl \quad (1)$$

where n is stoichiometric coefficient matching the moles of Al added to initial regolith powder. According to thermodynamic calculations (Fig. 1) the maximum adiabatic temperature 1700K generated at n=1.05 mol (22 wt % Al). Several intermediate substances were formed in this system. The temperature remains at highest value in range of 22-28 wt % Al.

The lowest amount of Al with maximum adiabatic temperature was 22 wt %. However, the experiments show that this system cannot ignite in self-assisting mode. Probably, due to oxygen diffusion limitation through the Al oxide layer on the aluminum particles. To remove the oxide layer during combustion and allow aluminum to react with regolith, we added tetrafluoroethylene $(-C_2F_4-)_n$, Teflon, into the exothermic mixture.

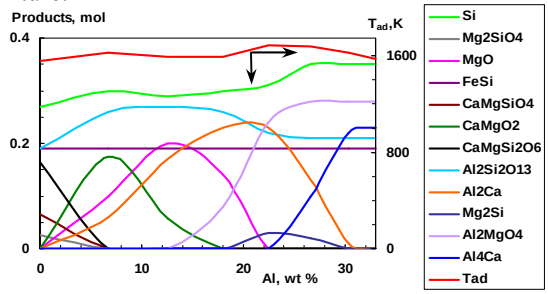

Fig. 1. Thermodynamic calculations of the system (1).

It is beneficial to use a small amount of Teflon~2 wt %, to achieve only chemical activation mode. The experiments show that the system (1) at 20 wt % of Al reacts in self-propagating mode with minimum amount of 1.5 wt % Teflon in initial mixture. The calculation shows that gaseous substances such as AlF_3, SiF_4 and SiO is generated during the combustion. These substances greatly affect on reaction mechanism, shifting it from solid-solid to solid-gas mode, according to the following schemes:

$$Al+(-C_2F_4-)n \rightarrow AlF_3(g)+C \quad (2)$$

$$Al_2O_3+(-C_2F_4-)n \rightarrow AlF_3(g)+CO(g) \quad (3)$$

$$SiO_2+(-C_2F_4-)n \rightarrow SiF_4(g)+CO(g)+SiO(g) \quad (4)$$

$$MgO+(-C_2F_4-)_n \rightarrow MgF_2(g)+CO(g) \quad (5)$$

The reactions (2) and (3) are main leading reactions. In case of 4 wt % Teflon the reaction (4) can be generated. There is always small possibility of reaction (5).

Results and Discussion: To prepare the samples the powders of lunar soil simulant JSC-1A (mainly consisting of SiO_2-47.7 wt %, Al_2O_3-15.02 wt %, Fe_2O_3-3.44 wt %, FeO-7.35 wt %, CaO-10.42 wt %, MgO-9.01 wt %), aluminum and Polytetrafluoroethylene, were mixed in High Speed Ball Mill for 2 min to receive homogeneous mixture. The cylindrical samples with 13 mm in diameter and 30 mm in height were prepared using uniaxial press. The relative density of the samples was about 70 %. Combustion experiments were conducted in a reactor with V=0.5L under vacuum (10^{-3} torr). During a typical experiment a sample was placed into the reactor and combustion was initiated by electrical micro heater located on the upper surface of the sample. A high-temperature flame propagated spontaneously through all the mixture with constant velocity. The maximum combustion temperature was measured by K-type micro thermocouples embedded in the center of the sample at predefined distances from each other. The output signals from the thermocouples were transformed by a data acquisition board at the rate of 1 kHz, and then recorded.

Fig. 2 shows the dependence of combustion temperature and product relative porosity on Teflon concentration in the mixture. The combustion products have a hard and highly porous structure with micropores that were formed due to escaping of gaseous phases (AlF_3, CO, SiF_4, MgF_2) from reaction zone. The minimal content of Teflon at which the combustion wave propagates spontaneously in system (1) at n=1.5 (12 wt % Al) is 1.5 wt %. The theoretical density of samples was 4.3 g/cc, while the real density of samples varied in the range of 1.7-2.6 g/cc and was proportional to the amount of Teflon, giving 40 – 60 % porosity for 1.5 – 7 wt % of Teflon, respectively. The Knoop hardness was in the range of 750 (100 gf) to 850 (1kgf). As we noticed earlier, the system is not combustible at lower (<12 wt %) amount of Al.

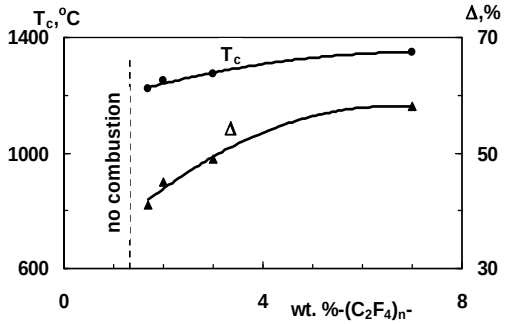

Fig. 2. Combustion temperature and product porosity as a function of Teflon concentration in the mixture.

Thus, we used Teflon as an additive for chemical activation of the reaction. The Teflon with content less than 10 wt % will play the role of chemical activator, i.e. it will activate Al with removing the oxide layer from its particles. The combustion reaction in Regolith-Al-$(-C_2F_4-)_n$ in low amounts of Teflon (less than 7 wt %) has calm character. The moving temperature front propagated in stable layer-by-layer mode with an average velocity of about 2 mm/s. The maximum combustion temperature was about 1400 °C. The temperature increseas drastically in a short time with the average rate of temperature rise of 500 K/s. The extensive set of experiments revealed that the self-sustaining reaction can be achieved for a minimum concentration of Al at 12 wt % with adding 1.5 wt % of Teflon.

Fig. 3 shows sintered samples morphology with various Teflon concentrations. Higher Teflon concentration leads to higher porosity, where inter-connected pore sizes varied in range of 20-200 μm.

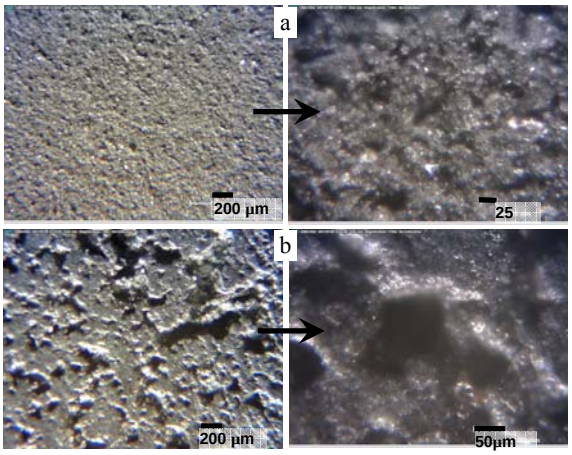

Fig. 3. Microstructure of sintered regolith at 20 wt % Al with (a) 2 wt % Teflon and (b) 7 wt % Teflon.

Thus, the use of local lunar resources with low concentration of aluminum (about 12 wt %) will allow to utilize more than 85 wt % of regolith component and fabricate dense and solid ceramic materials for building of vital structures of the future permanent lunar bases. The thermite method is proved to be much more energy efficient than the other sintering methods suggested in literature.

Acknowledgment

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References: [1] Martirosyan K.S., and Luss D. (2006), Lunar and Planetary Science XXXVII, paper 1896. [2] Martirosyan K.S.,and Luss D. (2008), Lunar and Planetary Science XXXIX, paper 1689. [3] Faierson E.J., Logan K.V, Stewart B.K., Hunt M.P. (2010), Acta Astronautica, 67, 38-45.