Conceptual Design of an ISRU Metal-LOX Lunar Propulsion System. S. K. Hampl[1], C. Heng[2], S. Goroshin[3], J. Bergthorson[4], D. Austen[5], E. Shafirovich[6], [1-4] McGill University, Department of Mechanical Engineering, 817 Sherbrooke St W, H3A 0AC, Montréal (sebastian.hampl@mail.mcgill.ca), [5-6] The University of Texas, El Paso, 1981 Hawthorne St, El Paso, TX 79902

A permanent base on Moon will have a key strategic importance for space exploration [1,2] by enabling better access to Mars and other extraterrestrial bodies. In addition, the surface of Moon is of great interest for general scientific exploration, the installation of observatories and communication stations, and an easier access to lower-Earth orbit (LEO). While current programs such as the Lunar Reconnaissance Orbiter, Artemis, and some private ventures, are approaching their initial launch dates, increased efforts have been conducted to explore the possibility of supplying the missions directly with lunar material obtained via in-situ resource utilization (ISRU) processes. As shipping propellant from Earth is prohibitively expensive ($35,000/kg or more [3]), its production on the Moon in a cheaper manner could remove what is currently a major bottleneck for return missions, flights to Mars, and on-surface transportation. Since the terrain on the lunar surface is very rough and in the absence of any significant atmosphere, a lunar rocket hopper is believed to be the only fast and efficient mode of transportation.

The most considered in-situ option is the use of hydrogen-oxygen bipropellants, which can be derived from water detected on the Moon, whose actual quantities remain largely unknown ([4]), as well as from trace amounts of water molecules bonded to the regolith [5]. LH_2/LOX engines are a mature technology with a high efficiency. However, some factors may limit the feasibility of LH_2/LOX rockets in terms of ISRU technology. The first is the unproven quantity and most likely uneven distribution of water on the lunar surface. As a result of the uneven water distribution, propellant would have to be transported on the Moon between the production facilities and bases where water is available to other lunar bases without water access, where the hoppers and return rockets might be located. The infrastructure to sustain such an operation is difficult to establish. In addition to that, long-term storage of LH_2 is also very challenging due to its much higher volatility in comparison to LOX and extremely low density (0.07 g/cc). Thus, hydrogen storage would require well-insulated, large-size tanks or alternatively high-production-rate facilities to supply enough hydrogen just before utilization. And finally, the sustainability of using valuable water resources as a single-use non-recyclable propellant have also been questioned.

In this work, we examine an alternative ISRU-derived solution based on the use of Metal/LOX propellant mixtures, which can complement the LH_2/LOX technology. In this concept, both the oxidizer (LOX) and the fuel (powdered metal alloy) are extracted from the reduction of lunar regolith rock in a process powered by solar energy. The overwhelming abundance of metal oxides in the lunar soil may make it possible to set up a production facility on the surface of any celestial body with a hard, rocky surface. For example, on the Moon, the soil is primarily composed of oxides of light metals such as Si,Al,Ti, etc. [6]. The propellants can then be relatively easily stored for long periods and later used in specialized powdered rockets. Previous studies, performed in great part at NASA, analyzed the performance of such Metal/LOX propulsion systems both experimentally and theoretically. The results, based mainly on the use of aluminum powder as the fuel, confirmed the feasibility of the concept [5-8]

While most previous studies concentrated on pure metal fuels, the present paper examines the capabilities of a system using metallic alloys, whose composition reflects that of selected samples of lunar soil. It is assumed that such alloys will be the direct product of the reduction process and that the production of pure metallic powders would require further complex separation stages, whose inclusion would unnecessarily increase the costs of propellant production. The theoretical performance of the regolith-derived alloy/LOX propellant is analyzed with two different thermodynamic software, NASA CEA and Thermo (Version 3.4). Both have in common that they minimize the Gibbs free energy and even though Thermo was not specifically developed to calculate rocket performance, this capability was added by Shiryaev [9]. The study provides an estimate of the theoretical performance as well as the temperature in the thrust chamber. An important parameter is the oxidizer to fuel ratio (O/F), by mass, and we have calculated preliminary results for a 40%Al/ 60%Si mixture (their oxides being the most important components of many regolith samples [6]). The combustion chamber pressure is set at $p_c = 20$ atm and a pressure ratio of $p_c/p_e = 1000$ was utilized. The initial thermodynamic calculations of the vacuum specific impulse I_{sp} show that the performance of metal alloy/LOX propellants exceeds those of many standard aluminized composite propellants. The proposed system should theoretically be capable of achieving sufficient performance to reach lunar orbit and send the spacecraft onto a return trajectory to Earth. Both CEA and Thermo show good agreement of the performance and an analysis on the combustion products to assess potential problems for the engine and nozzle design will be performed.

The work also addresses various design aspects of the rocket engine, including a broad discussion of the feed system, the nozzle design, and the storage of the propellants. The design is based on the dispersion of the metal/LOX mixture into the combustion chamber and the stabilization of a turbulent heterogeneous flame.

First, the performance of the feed system is evaluated, with two main options discussed in literature. The metal and LOX can either be stored together and fed into the system as a premixed propellant or can be provided separately [10]. In the first case, the oxygen can either be pressure-fed or an electrical pump system like in the Electron rockets [11] could be used, because traditional methods like a staged combustion cycle cannot be implemented in the proposed engine. Since the predicted combustion temperatures are relatively high, protective measures, such as the use of a sheathing cooling flow of oxygen close to the walls or the installation of an ablating nozzle, will have to be implemented. Both feed designs have their respective drawbacks (detonation risk for the premixed concept [12] and complexity for the separate feeding) and advantages (simplicity for the premixed concept and the ability to throttle for the separate feeding) that will be presented in the design section of this work.

As for the combustion chamber, previous work by our group has shown that an aluminum flame is significantly easier to stabilize and to control in fuel-rich conditions [13]. Thus, the primary injection system will consist of a dense suspension, which will burn in a first flame. The remaining, unburnt fuel will then be consumed in a staged process by additional oxygen, which is provided through flow from the aforementioned sheathing oxygen inlets. The latter will also supply a sufficient amount of gas to maintain a high I_{sp}. In the same analysis, two-phase losses, mainly present in the nozzle section, will also be quantified, and their impact on engine performance will be studied.

The work will also include concepts of possible missions that would benefit from this novel propulsion system. These would pertain to both intra-planetary travel and return-to-Earth missions. For the first, hopper concepts have been proposed [14]. These had also been previously discussed for missions on Mars, albeit with atmospheric CO_2 as the oxidizer [15]. Insights from these studies as well as from those pertaining to similar CO_2/magnesium gas-breathing systems [16] will also be used in the analysis. A return mission from the Moon surface to Earth requires a $\Delta v \approx 6$ m/s [17] and with the different specific impulses of our propulsion systems aw well as assumptions about a standard rocket, we will infer the design constraints for the propulsion system.

Several additional challenges are also addressed in the paper. These include the long-term storage of the metallic powder, since metal particles have been sometimes observed to weld in vacuum [18]. This may be resolved by storing the powdered fuel in either hydrogen or oxygen. The feasibility of the concept will also depend on the establishment of successful space mining operations. Several concepts, advanced by both public and private organizations, have already been proposed, and NASA has awarded contracts to companies to extract the first traces of regolith by 2024 [19].

References

[1] NASA, online (2020)
[2] NASA, online (2020)
[3] Sowers, G. F. *(2016)*, *Space Policy*, 37, 103–109
[4] Hayne, P.O. et al. (2015), *Icarus*, 255, 58–69
[5] Hepp, A. et al. (1991), *JPP,* 10
[6] Schreiner, S. S. et al. (2016), *Adv. Space Research*, 57, 5, 1209–1222.
[7] Linne, D. L., and Meyer, M. L. (1992), NASA/TM 105262
[8] Meyer, M. L. (1993), NASA/TM 106439
[9] Shiryaev, A. A. (1995), *Int. J. of Self-Propagating High-Temperature Synthesis*, 351–362
[10] Meyer, M. L. (1992), NASA/TM 105433
[11] Rocketlabs, online (2022)
[12] Austin, C. M. et al. (1959), *J. of Chem. Ed.*, 36, 2, 54
[13] Goroshin, S. et al. (1996), *Symposium on Combustion*, 26, 2, 1961–1967
[14] Cohanim, B.E. (2013), M.Sc. Thesis, MIT
[15] Shafirovich, E. et al. (2006), 59, 8, 710–716
[16] Goroshin, S. et al. (1999), 35th Joint Propulsion Conference and Exhibit
[17] O'Neill, G. (2004), University Press of the Pacific
[18] Merstallinger, A. et al. (2009), *ESA Sci. & Tech. Mem.*, 279, 57
[19] Gilbert, A. (2021), *Milken Inst. Rev.*