# Iron alloy smelting behaviour on Mars

D.C. Nababan[1,2], M.I. Pownceby[1], and M.A. Rhamdhani[2]

[1]CSIRO Mineral Resources, Melbourne, VIC 3168; [2]Swinburne University of Technology, Melbourne, VIC 3122

Deddy.Nababan@csiro.au

## 1. Introduction and Concept

*In-situ* resource utilization (**ISRU**), particularly the production of structural metals is crucial for supporting further exploration on Mars.

**Martian regolith**, typically containing plagioclase, pyroxene, olivine, magnetite, and hematite minerals [1] could be utilized as the primary source of key metals.

A previous study [2] has suggested that carbothermal reduction is the most feasible technique to produce metals on Mars considering the accessibility of **$CO_2$ (96%) in the atmosphere** [3] as a carbon source. Nababan *et al.* [1] also provide a flowsheet for iron production as shown in Figure 1.

This current work is to study the smelting behaviour of Martian regolith on Mars.

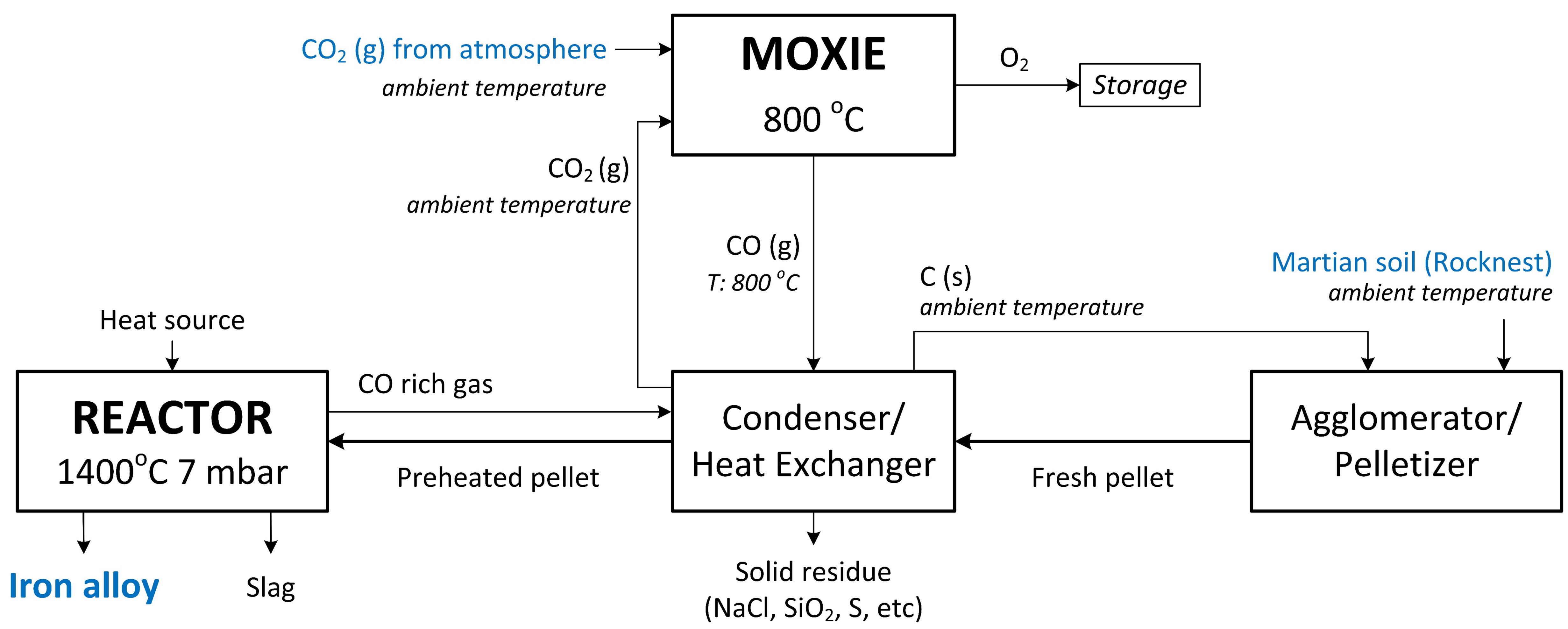



**Figure 1:** Proposed process route for metal (Fe) extraction on Mars through carbothermic reduction from Nababan *et al.* study [1].

## 2. Experimental technique

A synthetic Mars regolith (Mars Global Simulant (MGS-1) prepared by Exolith Lab) was used in the experiments to model iron production on Mars. Its mineralogy is provided in Table 1.

**Table 1:** Mineralogy of MGS-1 obtained by the semi-quantitative XRD analysis.

| Mineral composition (wt.%) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Plagioclase | Olivine | Pyroxene | Magnetite | Anhydrite | Hematite | Quartz | Ilmenite |
| 40.70 | 20.50 | 30.40 | 2.80 | 1.40 | 1.60 | 1.30 | 1.30 |

The experimental sample was made by mixing 94% MGS-1 and 6% graphite and then pelletized. The experiment was conducted for 3 hrs in a furnace equipped with pressure controllers as shown in Figure 2.

The pressure could be controlled from 4 mbar to 10 mbar (~7 mbar is the median) which is similar to the typical pressure on Mars.

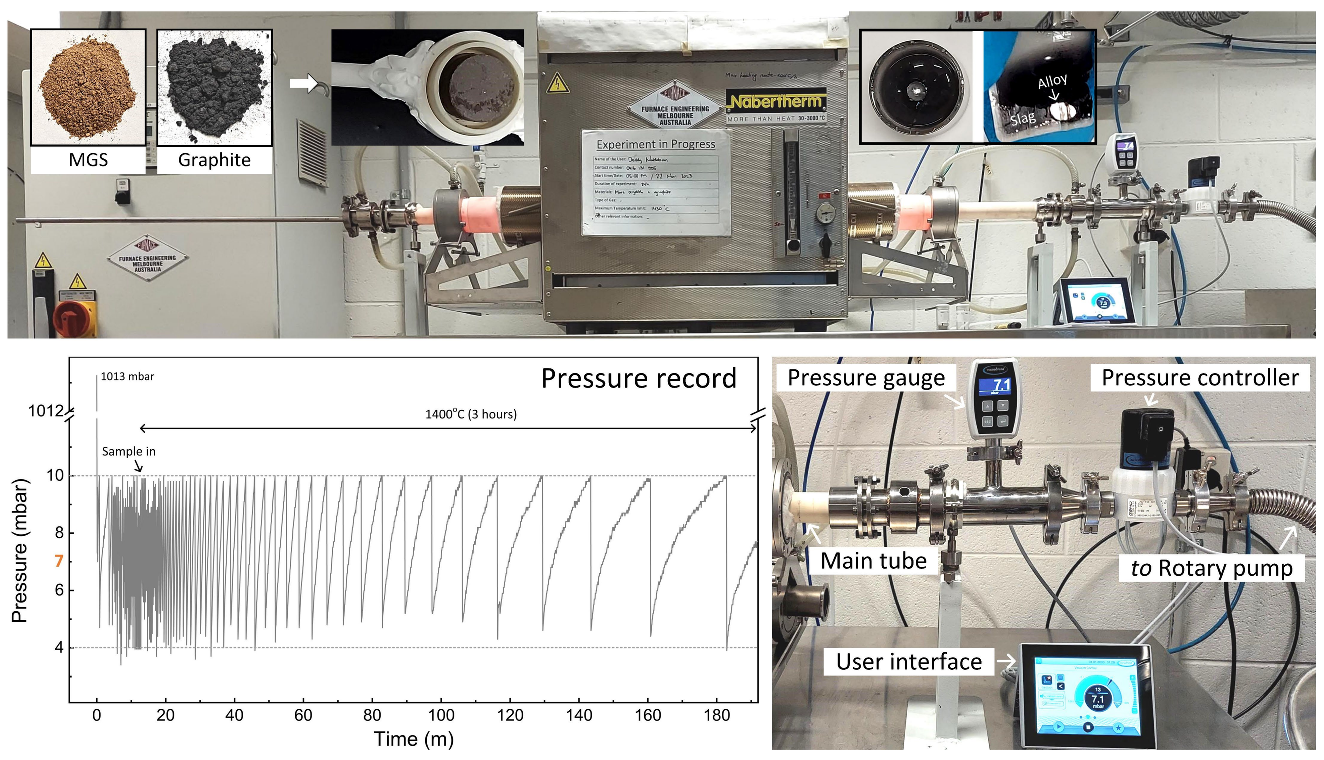
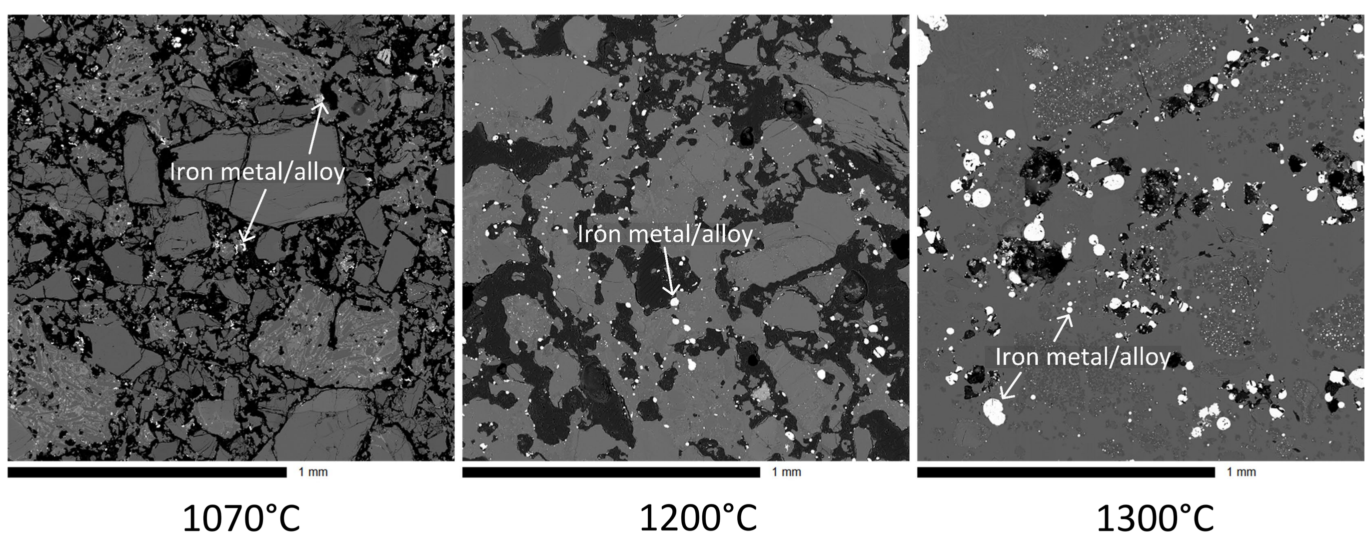



**Figure 2:** Apparatus used for this study with main features: an electric resistance tube furnace, rotary pump, and pressure controller.

## 3.a. Result – various temperatures (7 mbar)



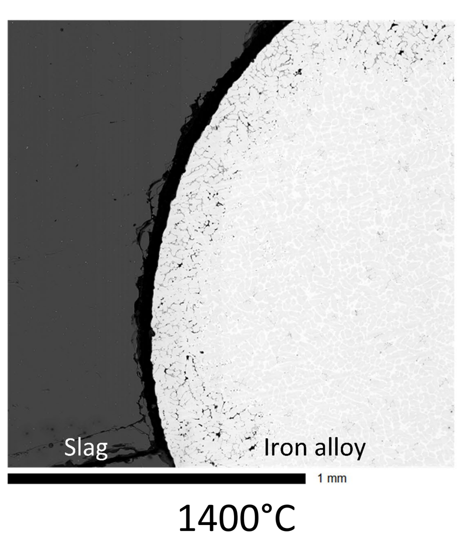




**Figure 3:** Typical microstructure formed during the reduction process of MGS-1 at different temperatures under 7 mbar.

The formation of metallic phases started at 1070°C as shown in Figure 3. Higher temperatures produced coarser metallic phases and the sample was partially melted.

At 1400°C, the sample was fully smelted to produce liquid iron alloy and slag.

## 3.b. Result – various pressures (1400°C)

Figure 4 shows that the MGS–graphite sample was partially smelted under the pressures of 1013 mbar (i.e. ambient pressure on earth) and 100 mbar, containing liquid alloy, slag, and various solid phases.

At lower pressures, e.g. 7 mbar (typical pressure on Mars) and 0.1 mbar, the sample was fully smelted. The liquid alloy produced under 7 mbar pressure contained about 80% Fe and 12% Si with Cr and P as minor elements and the slag contained 22% Si, 10% Al, 10% Mg, 6% Ca with a small amount of Na and K.

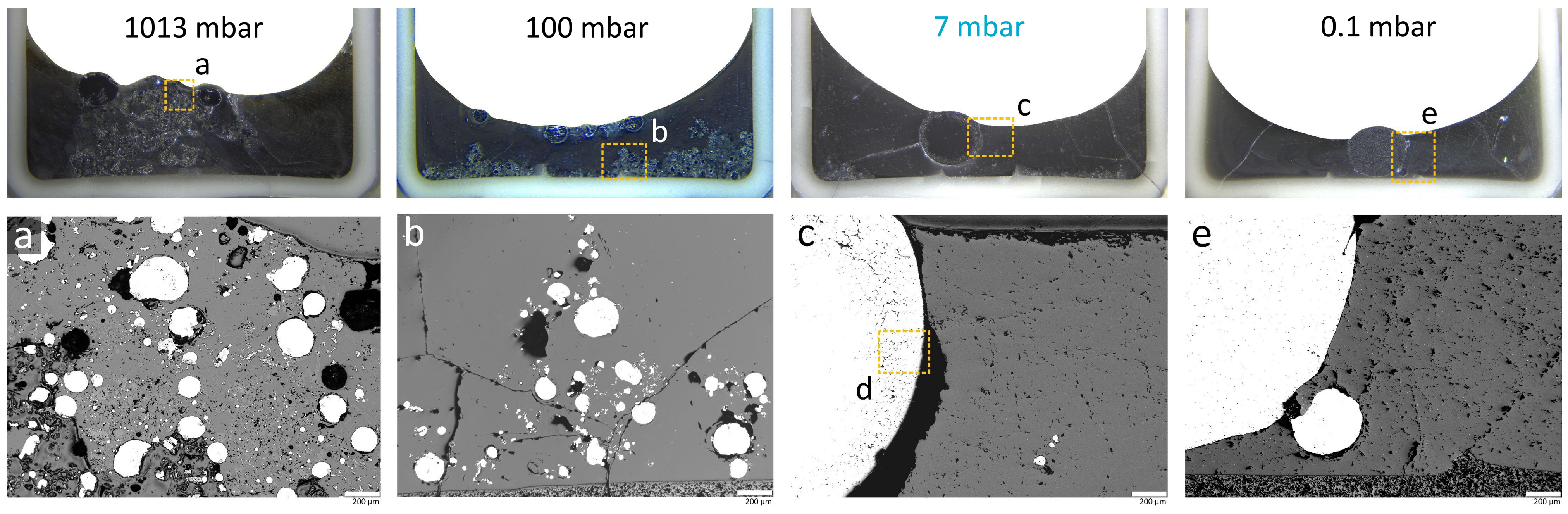



**Figure 4:** Typical cross section MGS-graphite sample during the reduction process at 1400°C under different pressures.

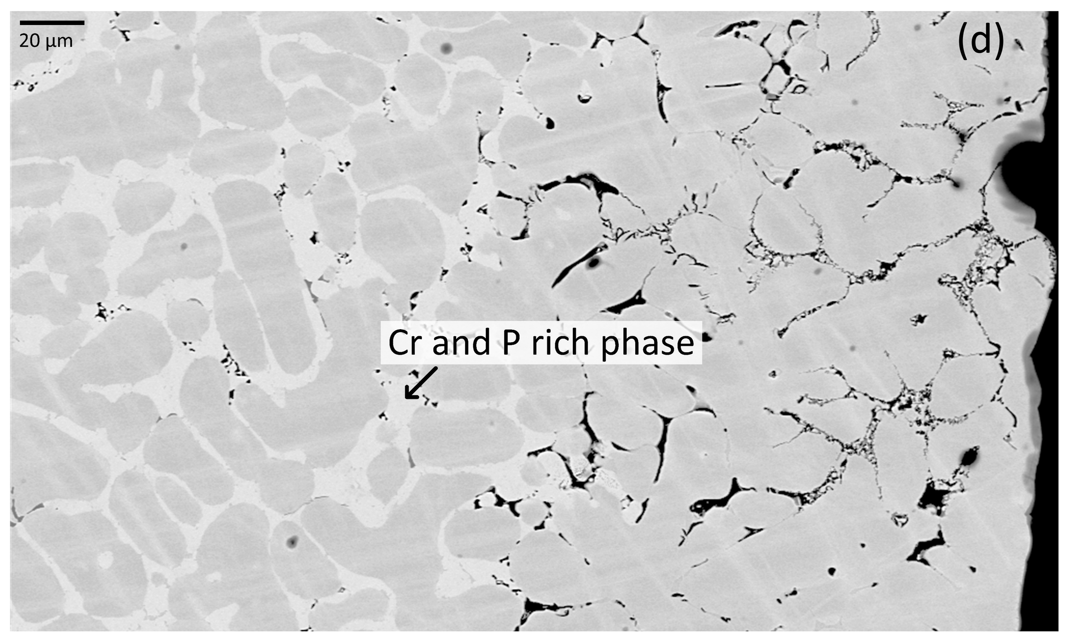



**Figure 5:** Typical microstructure of the alloy formed during the smelting stage of MGS-1 at 1400°C under 7 mbar as labelled "d" in Figure 4.

The typical microstructure of the alloy formed during the smelting stage of MGS-1 at 1400°C under 7 mbar is shown in Figure 5.

It consists of two phases; where the white phase is rich in Cr and P.

## 4. Discussion

The temperature and pressure were crucial parameters in the reduction behaviour of MGS-1 by graphite/carbon. In general, the lower pressure lowers the minimum temperature required to reduce the oxides by carbon [2].

The lower temperature processes (solid-solid reaction) produced metallic iron. However, a certain amount of iron was still left unreduced within the oxide/silicate phases. The high-temperature processes up to the smelting stage would provide a more robust interaction between carbon and MGS sample. Hence, with the same amount of carbon addition, 100% of iron reduction had been achieved.

The produced alloy contained contaminant alloying elements and further processes to refine the metal are required. It is expected that established refining processes used on Earth may also be utilized on Mars. The use of produced slag also needs to be assessed to support the sustainability aspect on Mars.

## 5. Conclusion

- Carbon can be used as a reductant to produce iron alloy from the synthetic Mars regolith.
- The minimum temperature to form $Fe_m$ metallic phase under a pressure of 7 mbar was 1070°C.
- The total pressure had a significant impact on transforming the smelting behaviour of MGS-1.
- This study has provided an analysis of the possible processing routes for metal (iron) extraction from Martian regolith on Mars.

### 6. References

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2. D. Nababan, M. Shaw, M. Humbert, R. Mukhlis, M. Rhamdhani, Metals extraction on Mars through carbothermic reduction, Acta Astronautica (2022).
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