Session 10 – Metals and Melts

Hydrogen Reduction of Ilmenite for the Production of Oxygen and Metals from Lunar Regolith

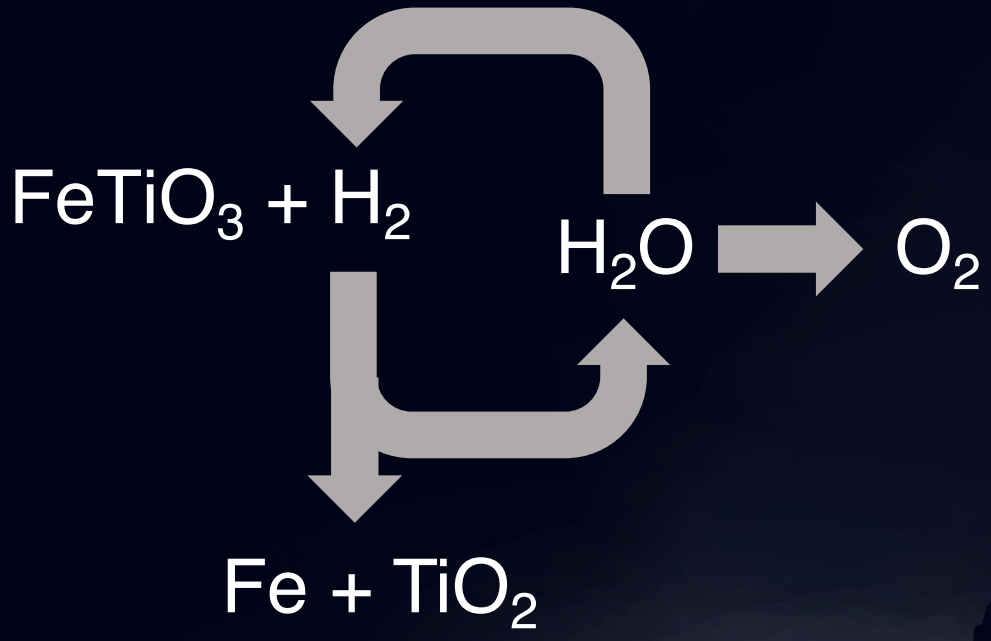
Current research at ESRIC

D. Harries, A. Maulu, E. Scolan, T. Schild, A. Yerzhankyzy, K. Hadler, B. Lamaze, M. Conti

SPACE RESOURCES ROUNDTABLE

esric esa LUXEMBOURG SPACE AGENCY LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

Ilmenite reduction by hydrogen



Advantages

- — Relative simplicity
- ► No aggressive high-T melts (*cf.* MSE, MRE)
- ► Easy intermediate storage of H_2O product
- — Well established*

Disadvantages

- — $BYOH_2$ and H_2 leakage
- ► Requires local H_2 sources
- — Low yield and high waste heat
- ► Requires beneficiation of raw regolith

** Williams et al. 1985, Lunar Bases and Space Activities of the 21st Century*
Denk et al. 2017, SolarPACES 2017. Solar Power & Chemical Energy Systems
Sargeant et al. 2020a,b, Planetary and Space Science 180, 104759, 104751
Sargeant et al. 2021, Planetary and Space Science 205, 105287

esric esa LUXEMBOURG SPACE AGENCY LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

Fluidized-bed hydrogen reduction

ALCHEMIST-ED being commissioned at ESRIC (ESA loan)

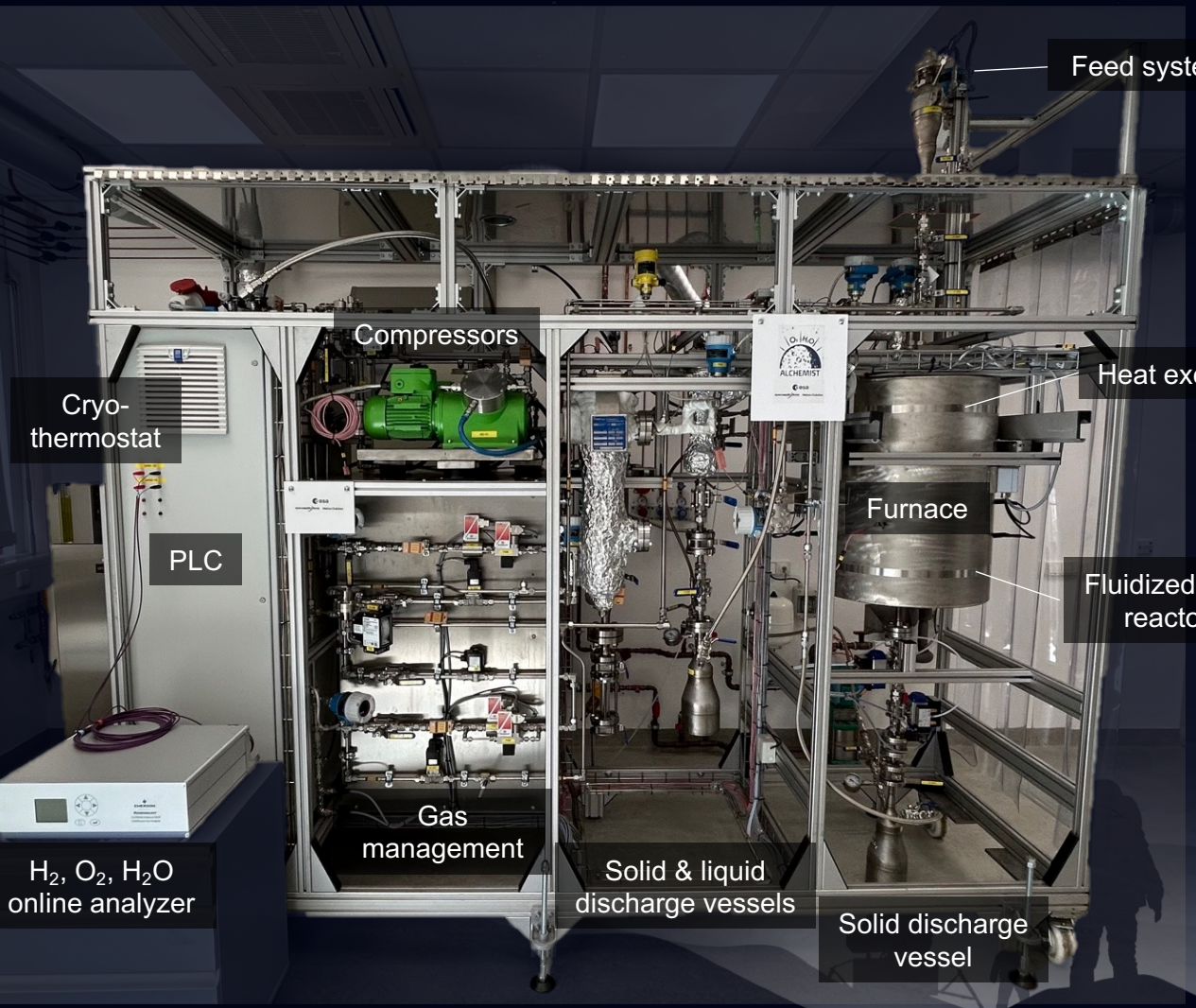
Objectives

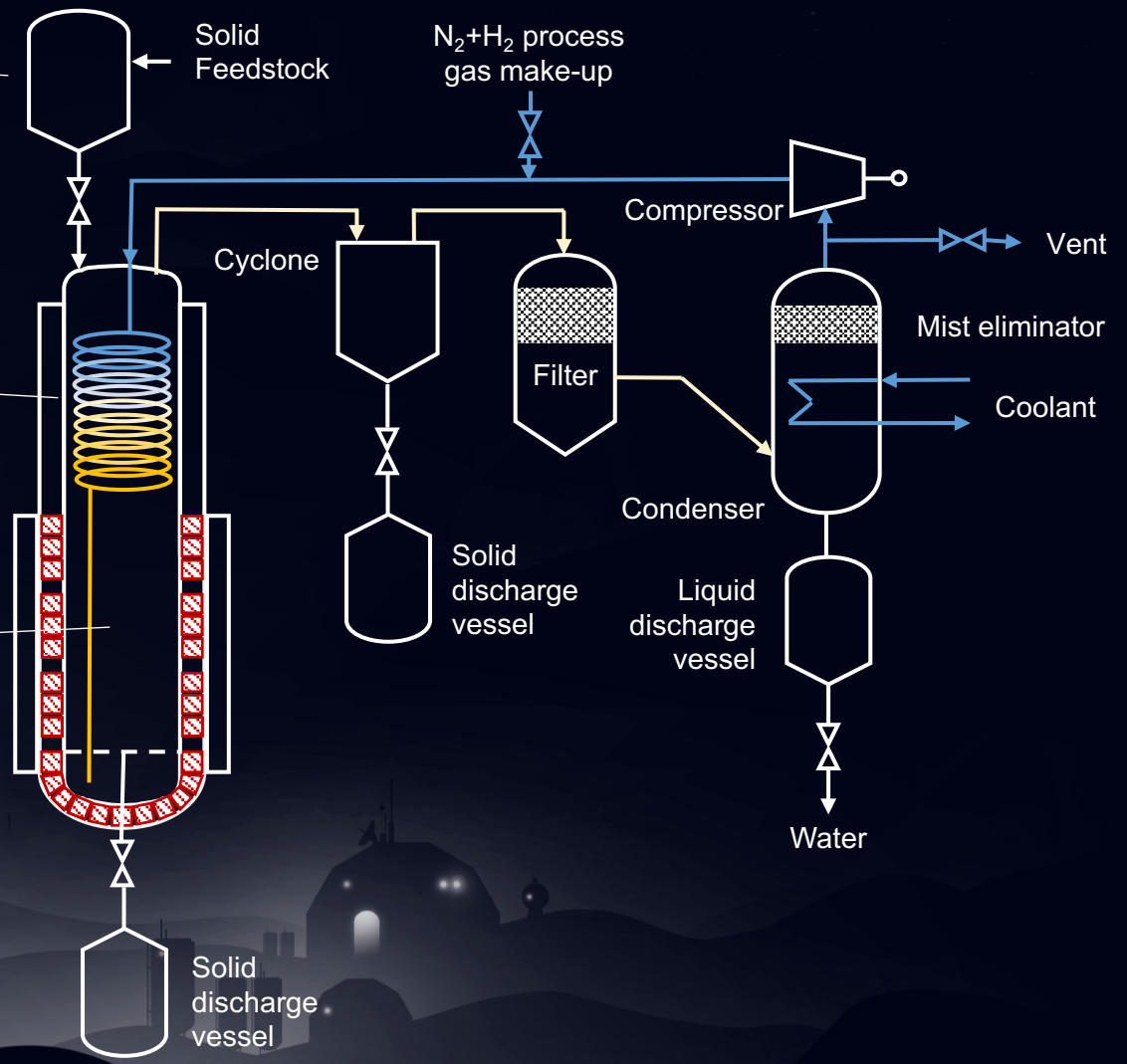
Efficiency baselines and optimization strategies

- Process thermodynamics and competing kinetics
  - Chemical control on reaction rates
  - Transport control on reaction rates

Urbina et al. (2022) 73rd International Astronautical Congress/IAF Space Exploration Symposium, 1-15.

ALCHEMIST-ED





esric esa LUXEMBOURG SPACE AGENCY LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

Urbina et al. (2022) 73rd International Astronautical Congress/IAF Space Exploration Symposium, 1-15.

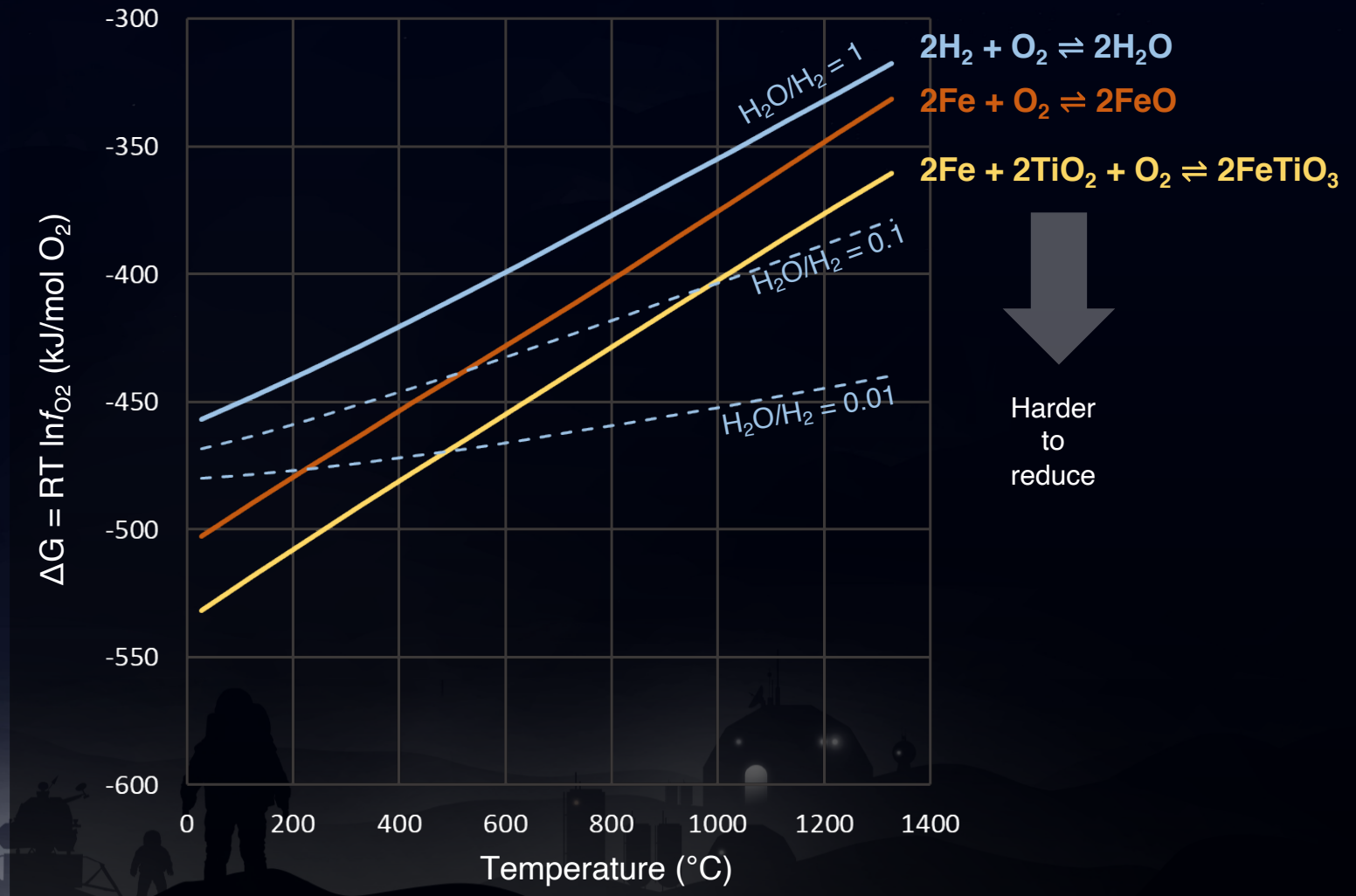
Thermodynamic control on reaction kinetics

$FeTiO_3 + H_2 \rightleftharpoons Fe + TiO_2 + H_2O$

Linear kinetics ► Limits of reaction rates in gas-solid interactions by molecule-surface collision:

$$\frac{d\xi}{dt} \propto \left(p^{eq}_{H_2O} - p_{H_2O}\right)$$

- ► Reaction progress ξ limited by reverse reaction with H_2O
- ► Removal of water to drive the forward reaction
- ► Efficient condenser/adsorber system(s)



esric esa LUXEMBOURG SPACE AGENCY LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

Transport control on reaction kinetics

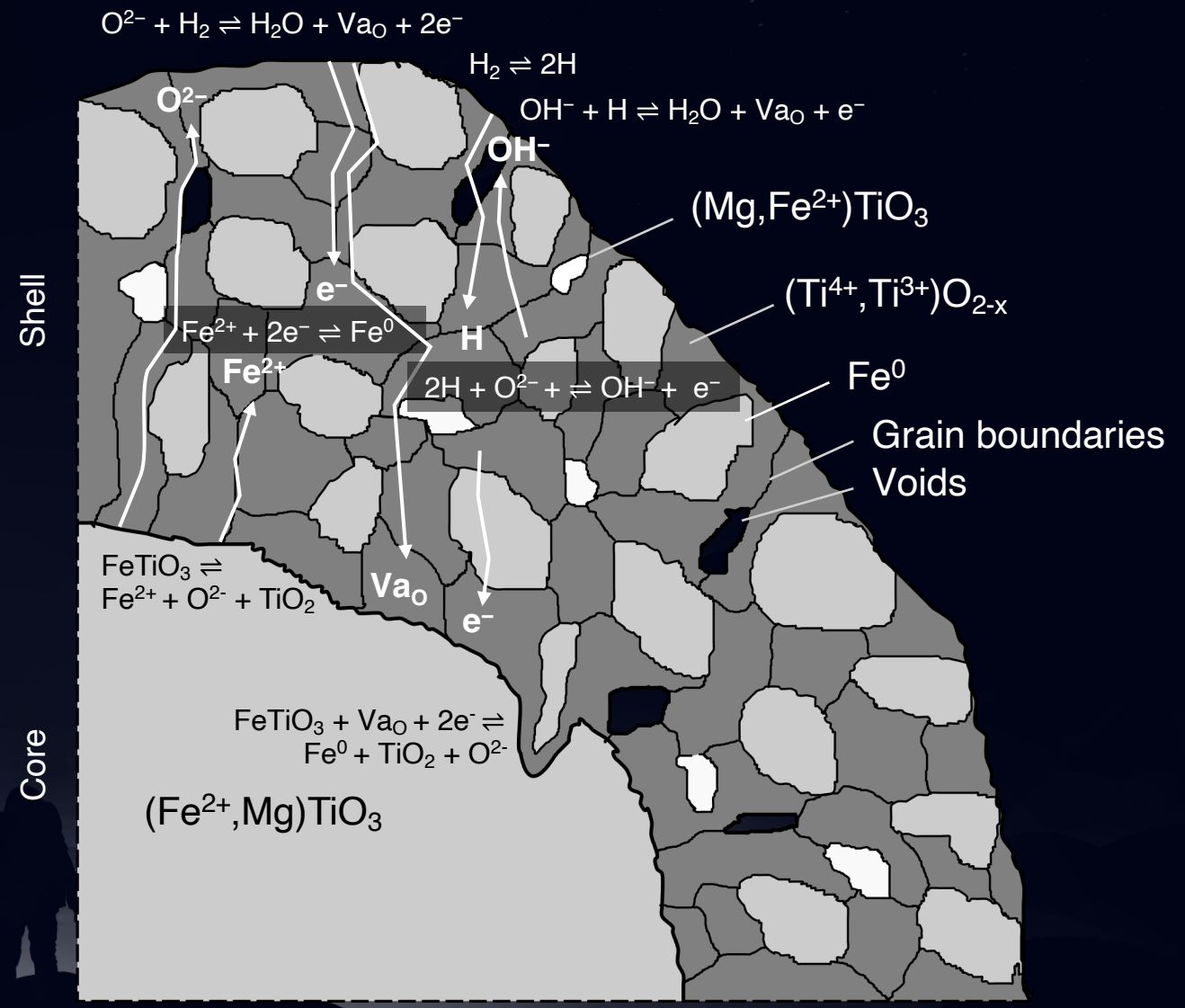
$FeTiO_3 + H_2 \rightleftharpoons Fe + TiO_2 + H_2O$

Core-shell model (Dang et al. 2015)

Parabolic diffusion kinetics ► Rate-limiting bottleneck

$$\frac{d\xi}{dt} \propto \frac{1}{\sqrt{t}}$$

- ► Large set of mobile species (Fe^{2+}, O^{2-}, e^-, vacancies, H species) and reactions
- ► Fast anomalous diffusion along voids, and grain boundaries
- ► Texture evolution controls transport and reaction rate



Dang et al. 2015, Journal of Alloys and Compounds 619, 443-451 (core-shell)
Harries 2019, ACS Earth and Space Chemistry 3, 2207-2224 ($Fe-Fe_3O_4$)

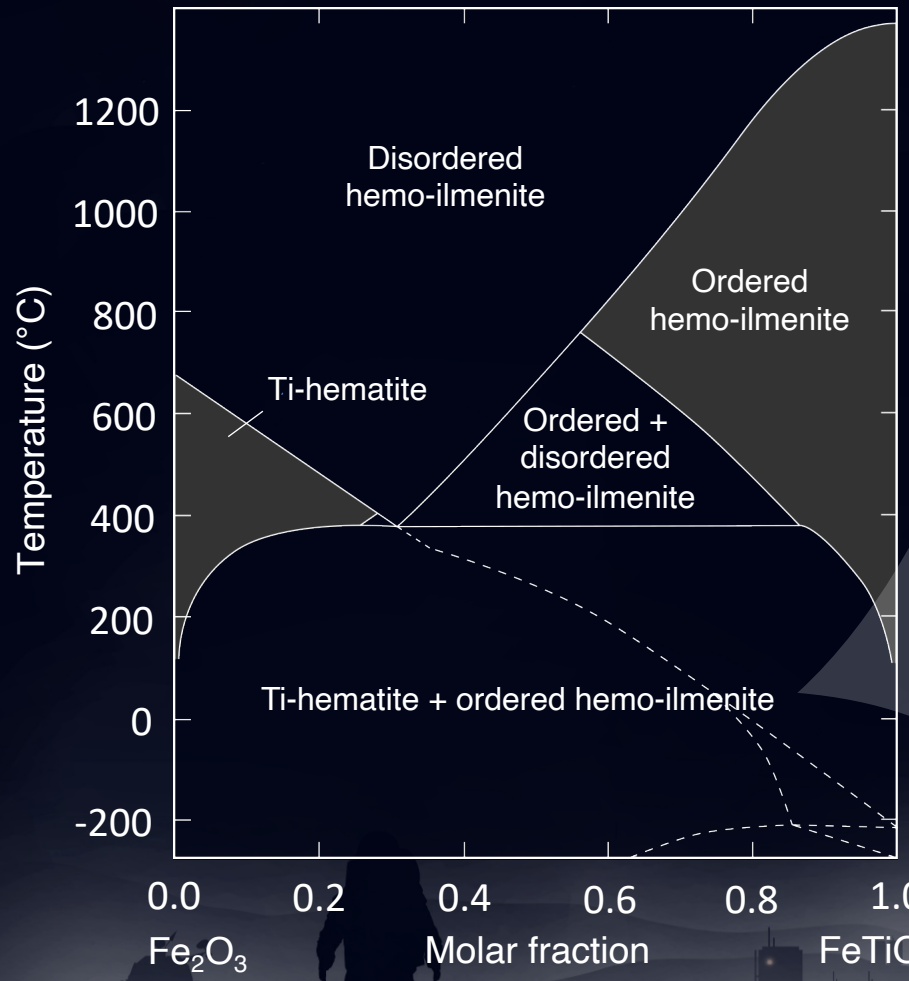
Fidelity of terrestrial ilmenite analogues

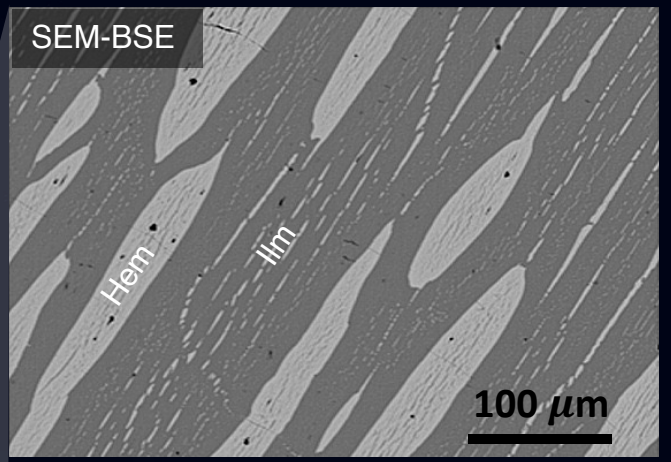
$(Fe^{2+},Fe^{3+},Mg)TiO_3$

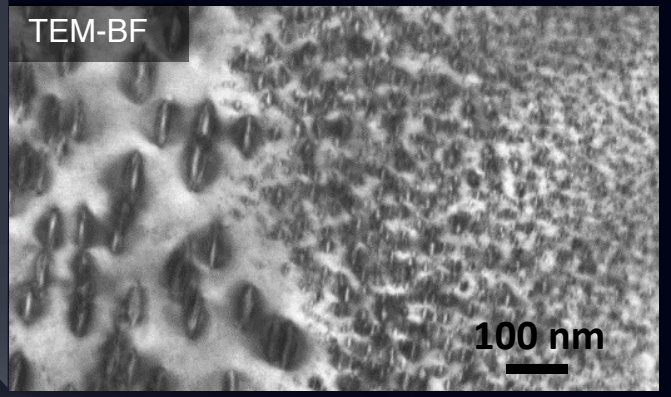
Terrestrial ilmenite commonly contains Fe^{3+} and exsolved (nano-scale) hematite lamellae

- Absent in lunar ilmenite

- May enhance reduction rates and yields
- May affect texture evolution
- Magnetic properties (lamellar magnetism)





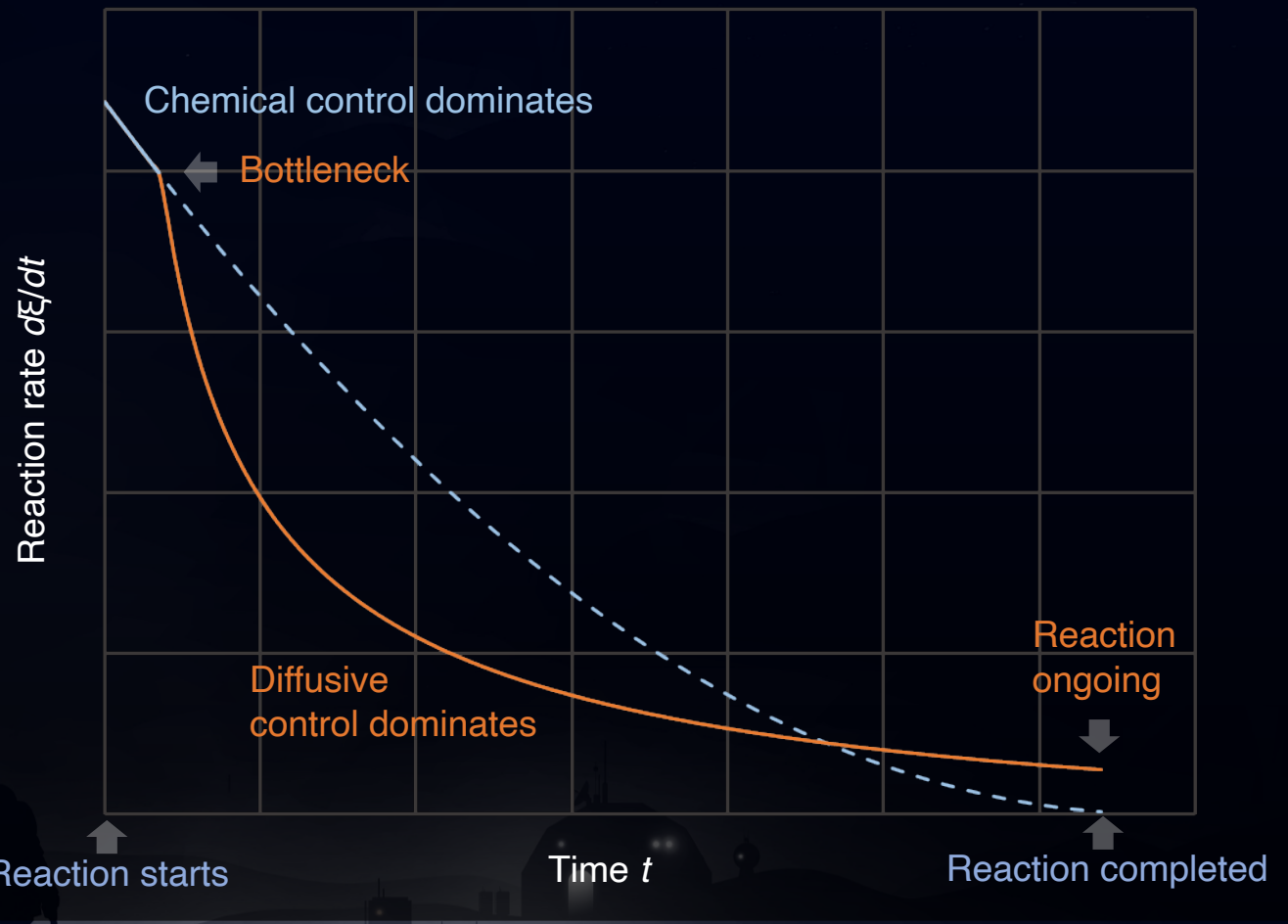


McEnroe et al. 2002, Geophysical Journal International 151, 890-912
Robinson et al. 2002, Nature 418, 517-520
McEnroe et al. 2007, Journal of Geophysical Research 112, B10103

Summary

Power and energy optimization

- Which factors determine the switchover to diffusion control?
- How can linear, chemical control be promoted
- When to cut off the reaction before completion?



esric esa LUXEMBOURG SPACE AGENCY LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST