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Design and Test of a Concentrated Solar Powered Fluidized Bed Reactor for Ilmenite Reduction

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... on the Moon

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Motivation

- When travelling to space, you have to bring *everything* with you.
- Up-mass is reduced significantly if local resources can be used (*In-Situ Resource Utilization*, ISRU).
- When travelling beyond LEO, more than 50% of the mass is *oxygen*.
- Most abundant element on the Moon is *oxygen*.

=> Oxygen extraction from lunar soil is very attractive.

=> Goal is to build a terrestrial demonstrator.

Lunar Oxygen Production Processes

TABLE III
Qualitative Comparison of Lunar Oxygen Processes

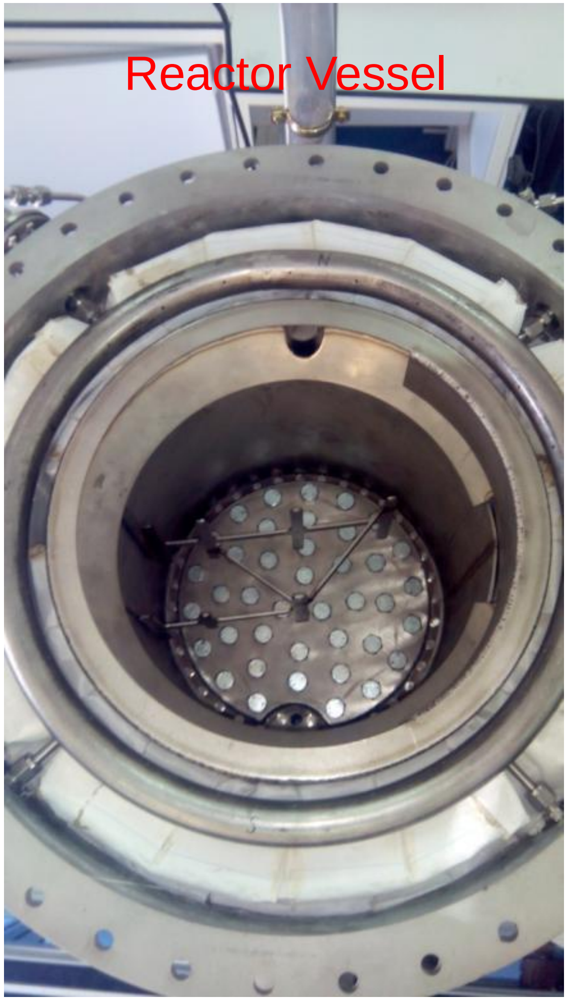
Process	Technology[a]	No. of Steps[b]	Process Conditions[c]	Feed-Stock[d]	Total	Rank
→ Ilmenite red. with H_2	8	9	7	3	27	4
Glass red. with H_2	7	9	7	6	29	2
Molten sil. electrol.	6	8	5	10	29	3
Vapor phase reduction	6	8	6	10	30	1

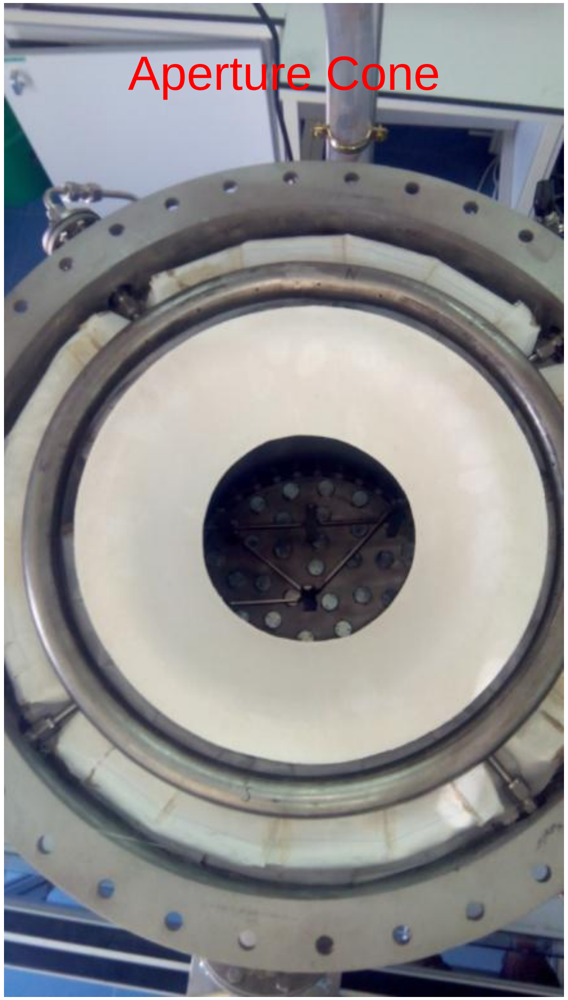
[a] Technology: 1 = major technologic development required; 10 = no major unknowns.
[b] No. of steps: 1 = many (>5); 10 = one step.
[c] Process conditions (temperature, energy, plant mass, corrosion): 1 = severe; 10 = low.
[d] Feedstock requirements: 1 = huge quantities; 2 = mare, beneficiated (ilm); 5 = mare, unbeneficiated; 10 = any feedstock, unbeneficiated.

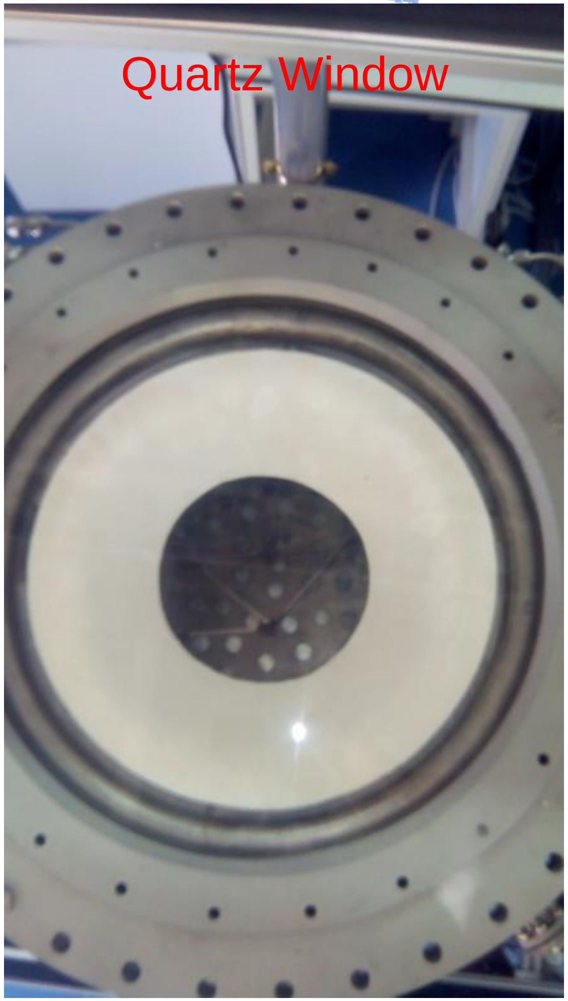
$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O \qquad (1)$$
$$H_2O \rightarrow H_2 + \tfrac{1}{2} O_2 \qquad (2)$$

Source: Taylor, Carrier: *Oxygen Production on the Moon: An Overview and Evaluation.* Univ. of Arizona Press; 1993.

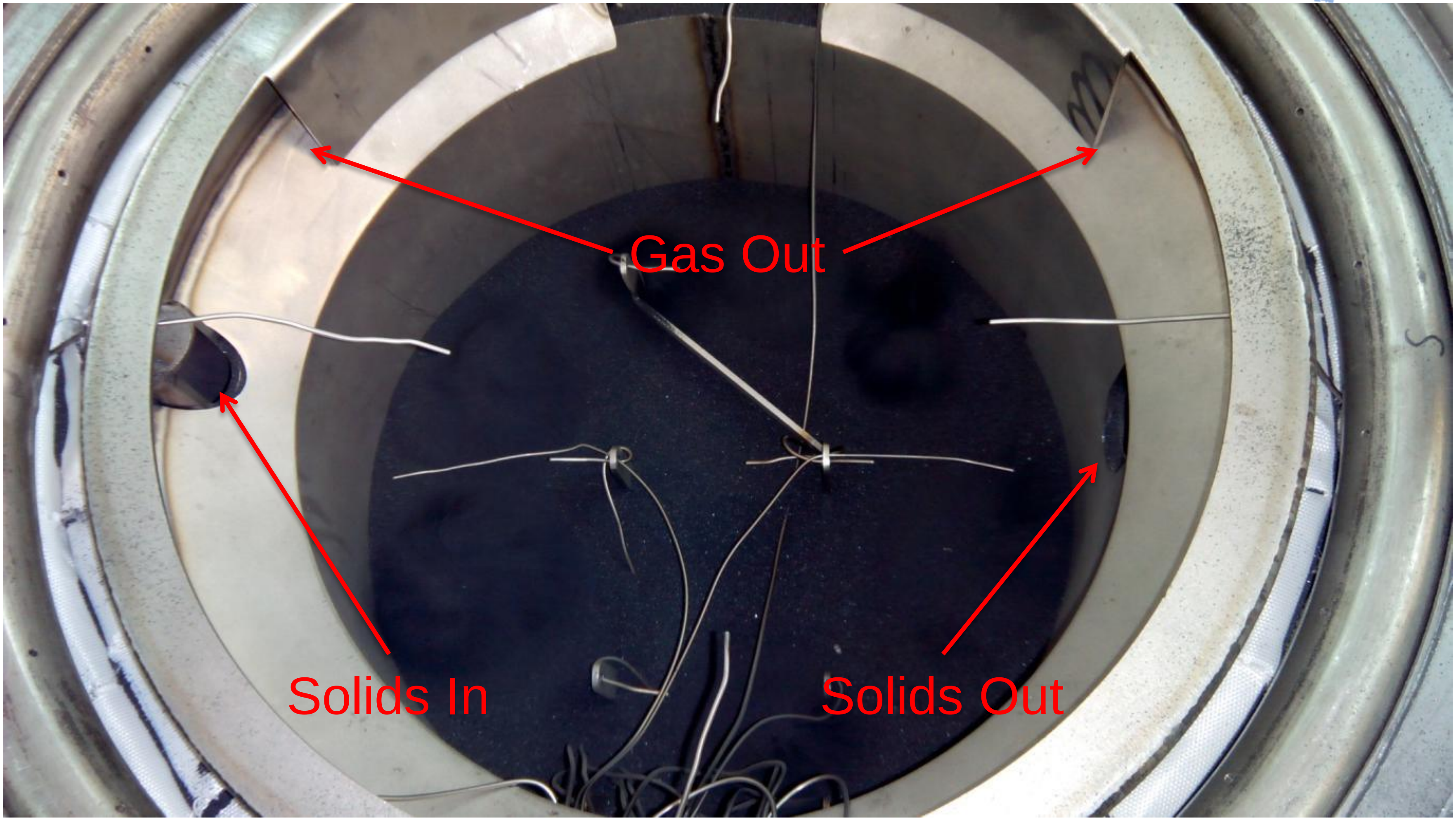
Fluidized Bed Reactor



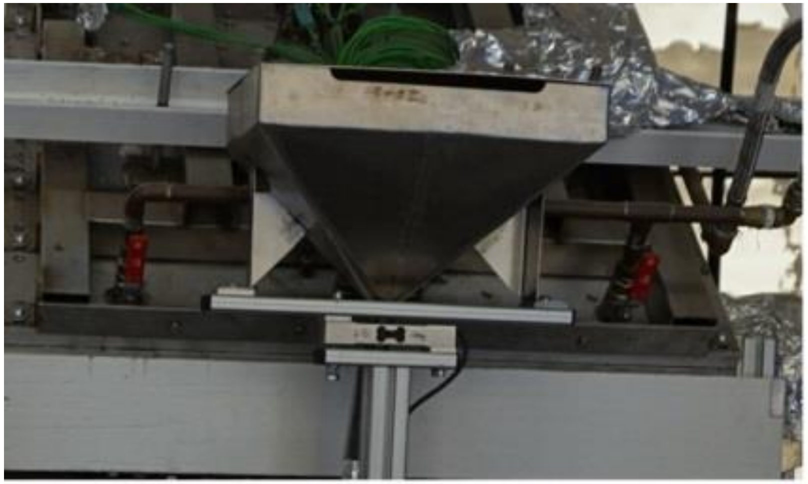


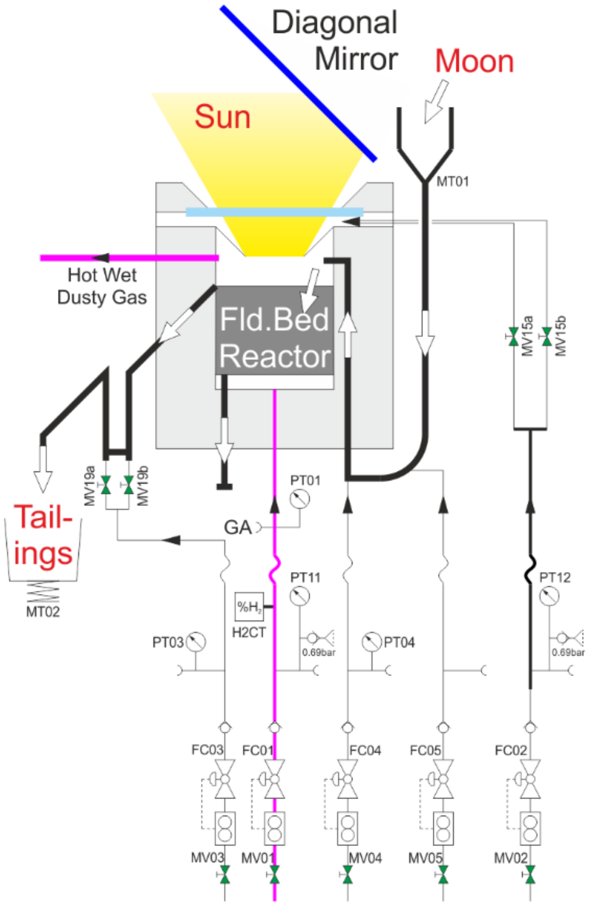


Fluidized Bed Reactor

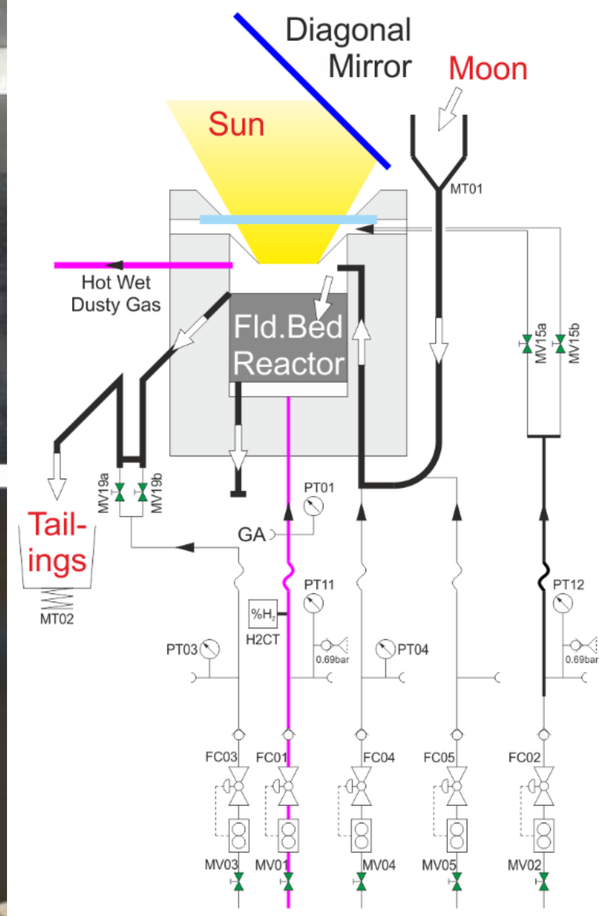


Particles Feed





Particles Removal



Gas Treatment ("Downstream")

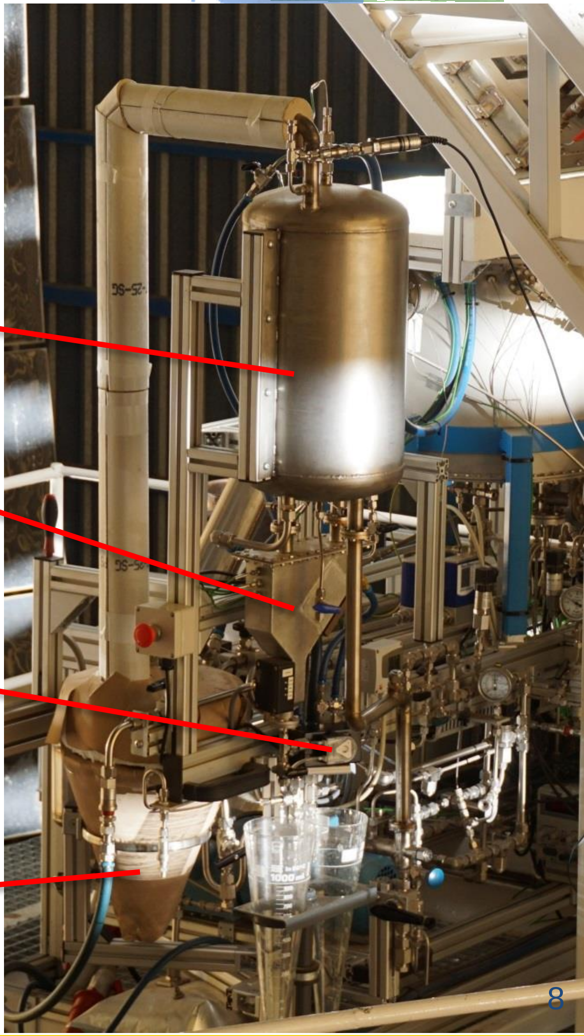
Cooler 1

Cooler 2

Water Separator

Water Extraction Pump

Particles Separator (T>100°C!)



Goals , Particles, Test Phases…

1. Identify the gas flow demand of the main (+auxiliary) fluidized bed(s) in the reactor as a function of the temperature.
2. Demonstrate continuous operation, especially particles feed and removal.
3. Operate the reactor at 800°C – 1000°C solely heated with concentrated solar power.
4. Demonstrate water production from the reaction of the ilmenite with hydrogen.

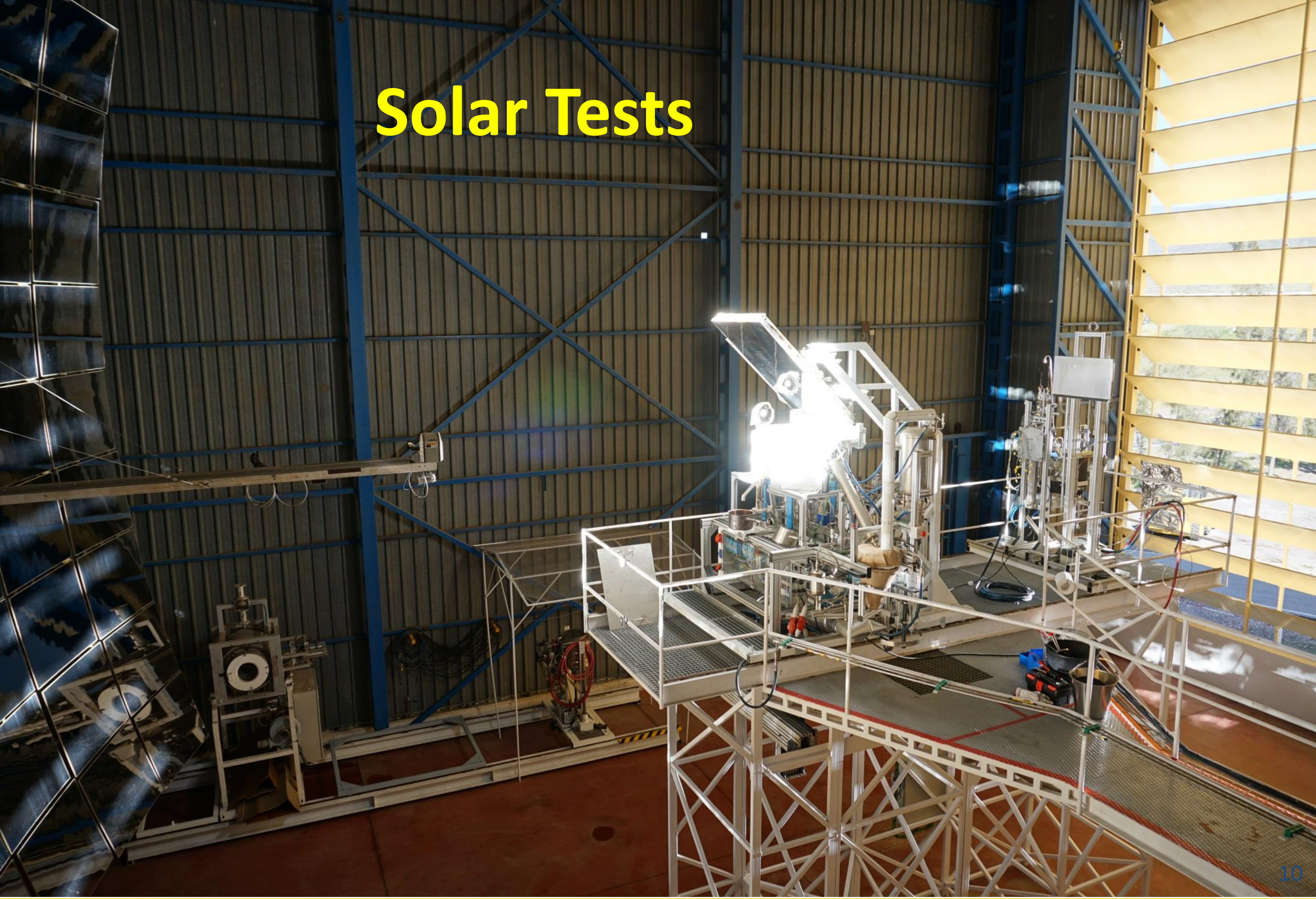
- Particles: Pure Ilmenite, 150µm (sorry, no real Moon rocks yet ☹)
- Gas: Argon, with up to 10% H_2

Phase 1: Air, 400°C (5 tests)

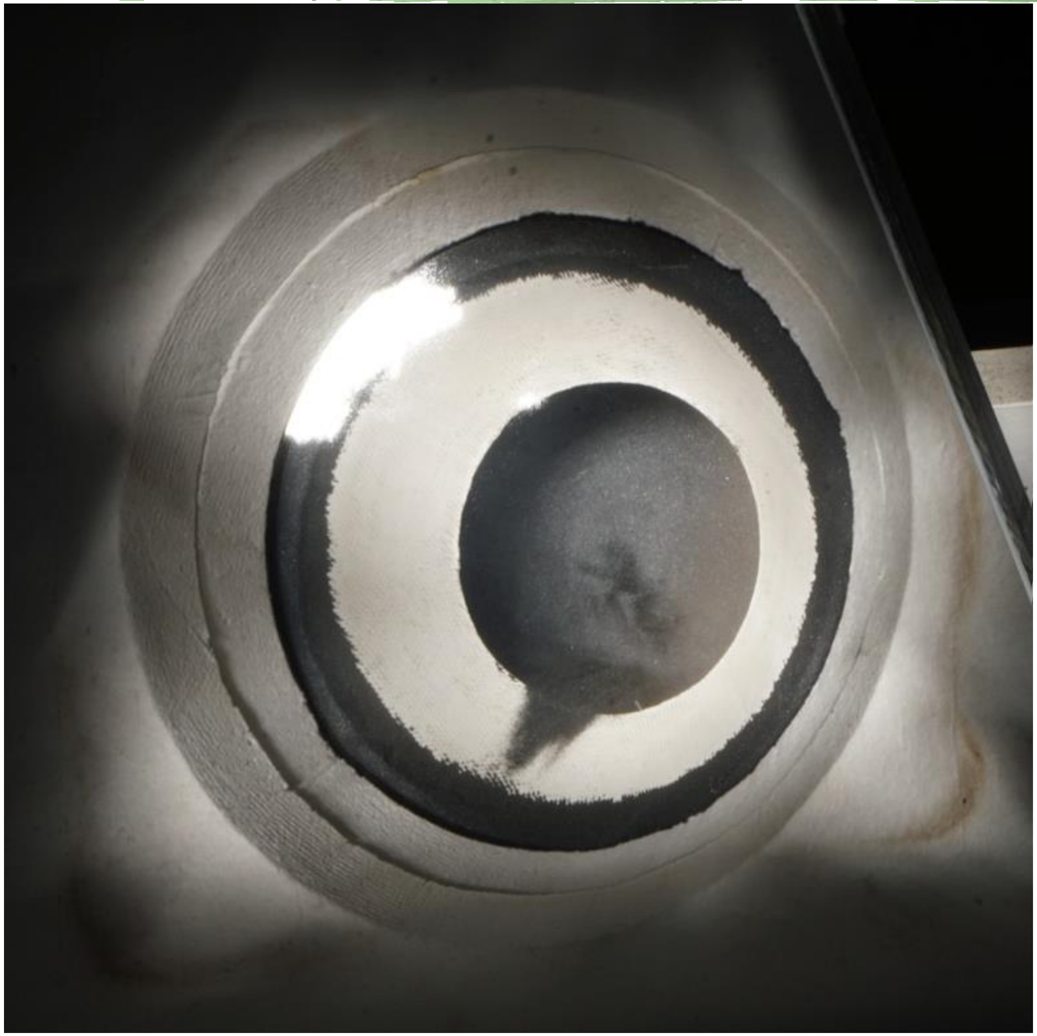
Phase 2: Argon, 800°C (6 tests)

Phase 3: Argon + Hydrogen, 950°C (11+4 tests)

Solar Tests

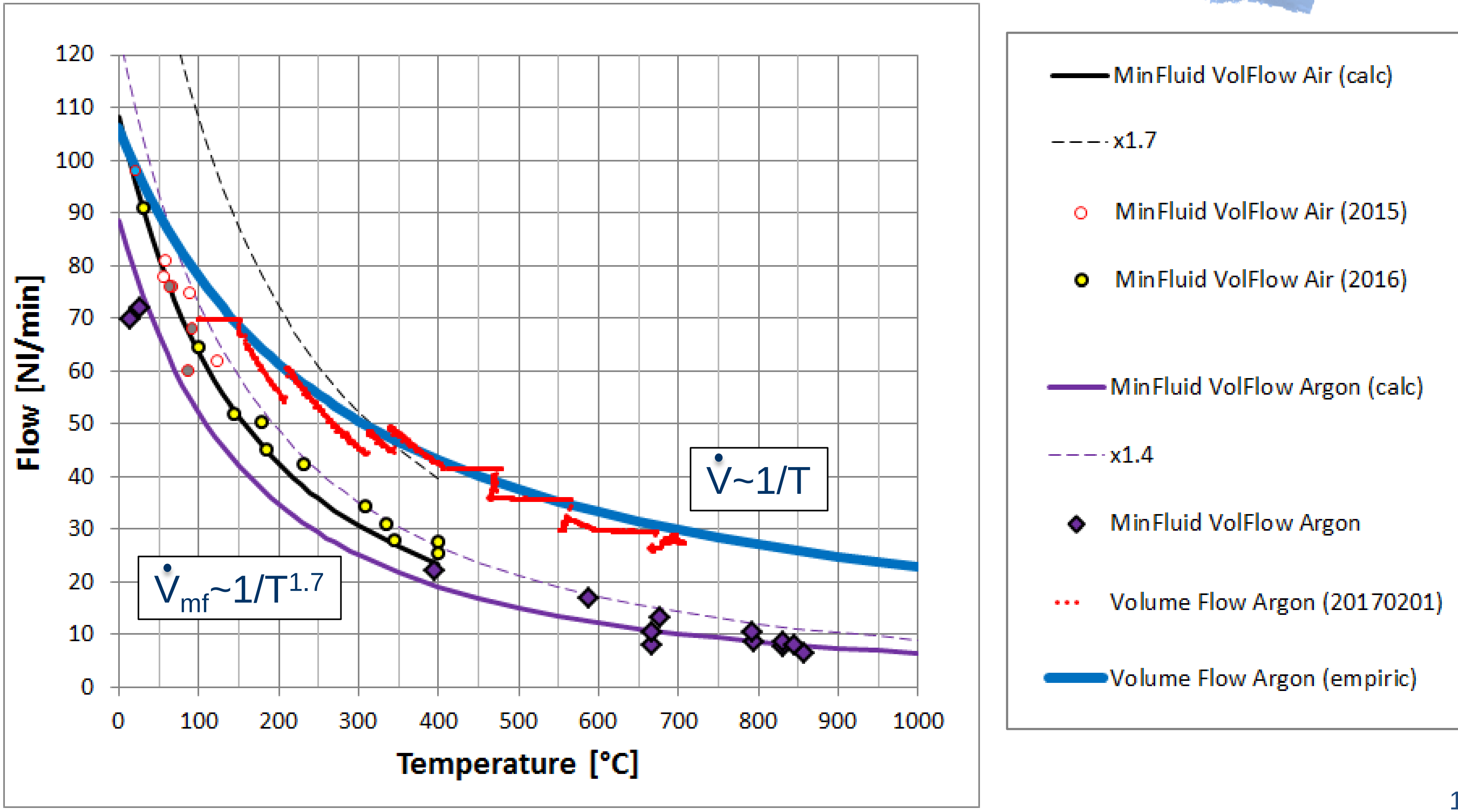


Oresol – Solar Tests

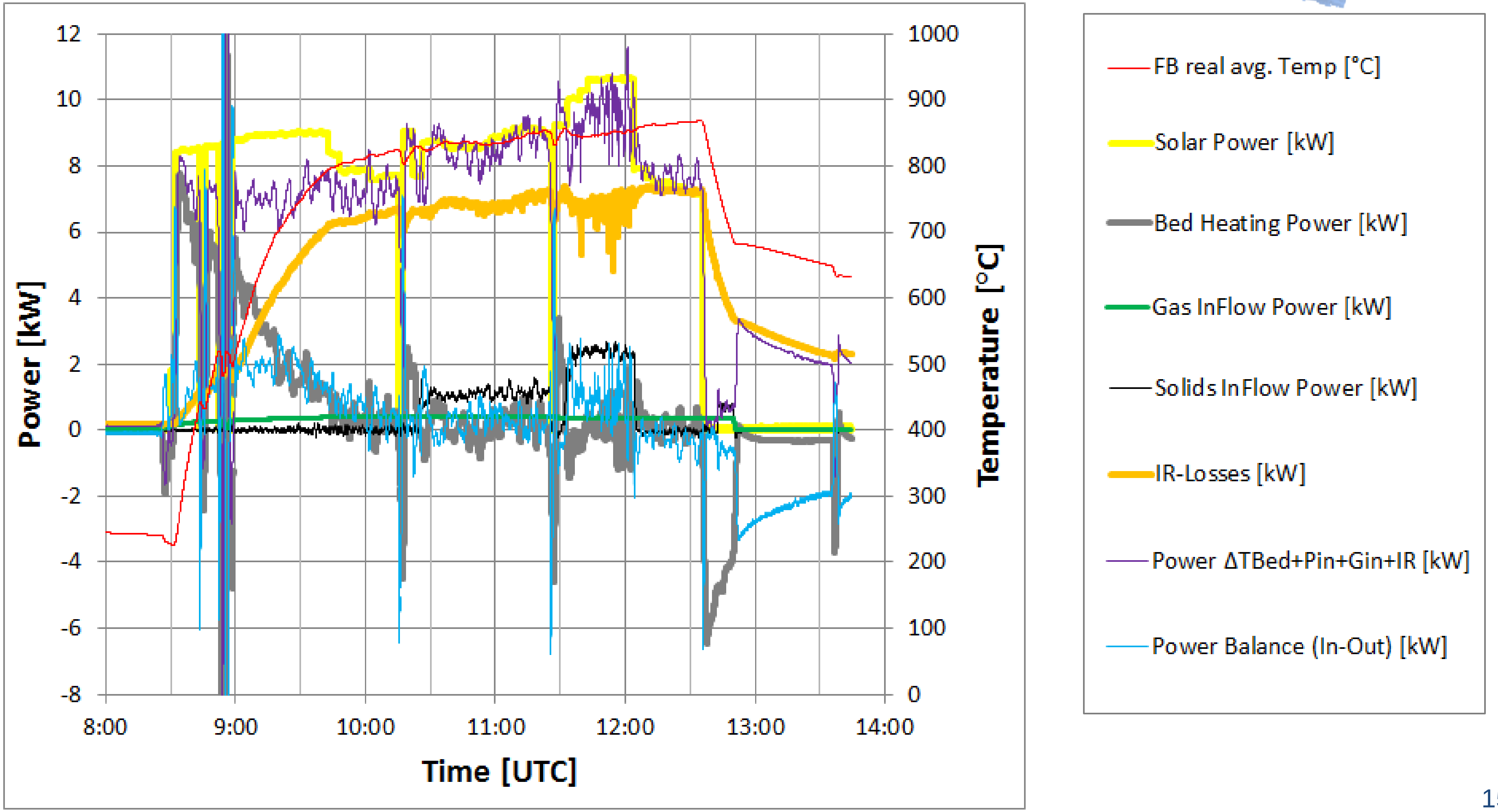


Oresol – Solar Tests

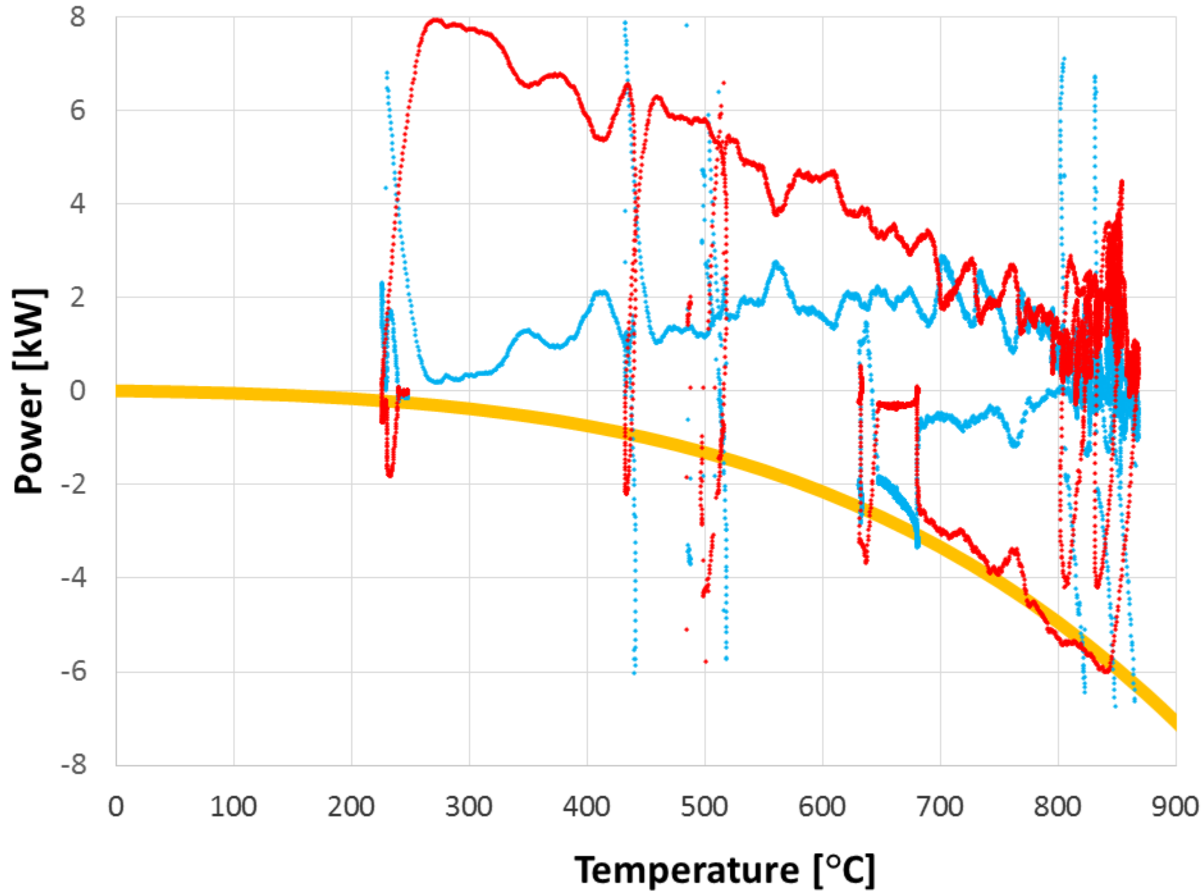
Fluidization Gas Demand



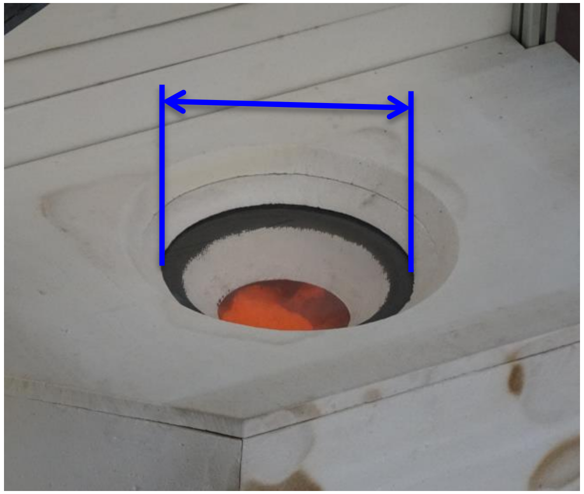
Power Balance



Power Balance



$$P_{IR} = \varepsilon A \sigma T^4$$

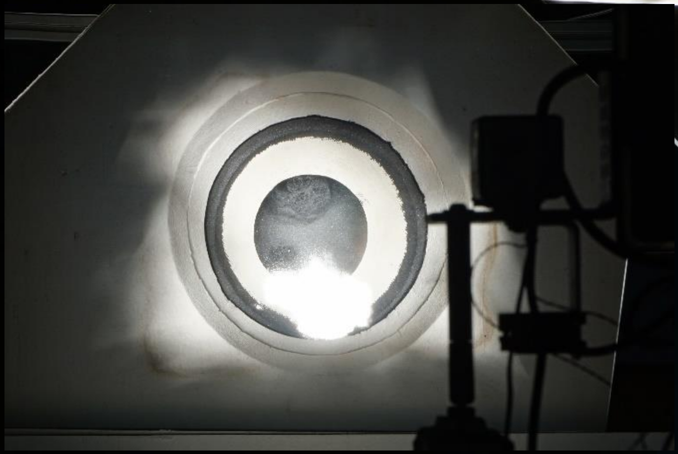


Water Production

- Water came out ☺
- Water separator worked well
- Low quantity (due to low H_2 feed)
- H_2-conv. > 50%
- Water very acidic (pH=3) and contaminated (NH_4^+, Cl^-, …)
- More investigation required

Summary and Outlook

- Solar Thermal Fluidized Bed Reactor for Continuous Operation including Auxiliary Components (especially Off-Gas Treatment) Designed and Built.
- Initial Goals achieved:
  - Automatic Main Gas Flow Control Parameters Identified
  - Continuous Operation incl. Particles Feed and Removal Demonstrated
  - >950°C in the Bed
  - H_2O Production Demonstrated
- Work ahead:
  - Increase Hydrogen Quantity / Percentage / Conversion
  - Use more "Moon-like" Particles (Mix JSC-1A + 10-20% Ilmenite)
  - Testing with 100% Hydrogen
  - Demonstrate Water Production of 0.7kg/h
- Develop Lightweight Solar Concentrator
- Adaption to Real Lunar Conditions (Vacuum, Low Gravity, Regolith…)
- Other Use? (Lunar Poles, Mars. On Earth?)



THANK YOU!

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Solar Concentrator ("Mussel")