Miniaturized metal hydride storage systems for hydrogen maser atomic clocks

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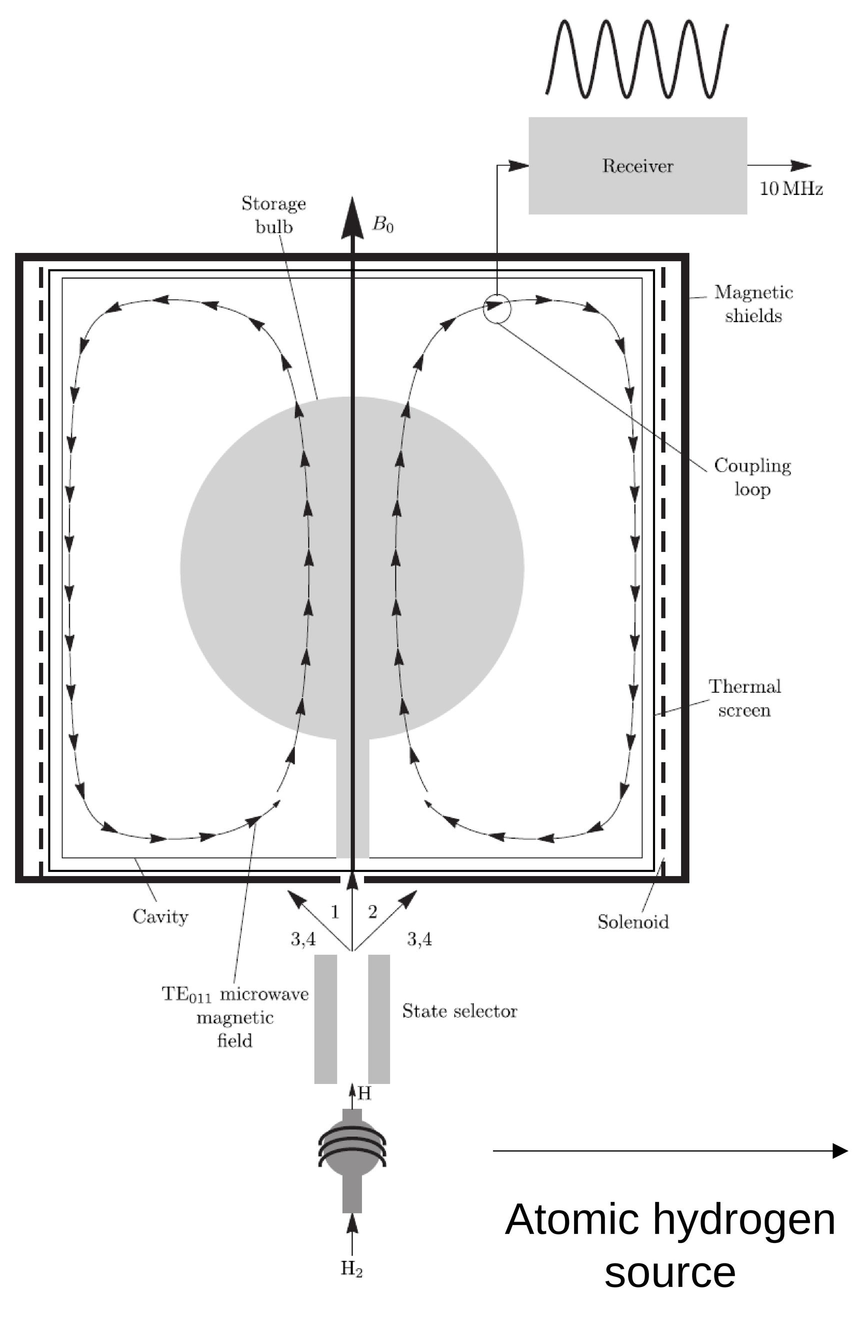
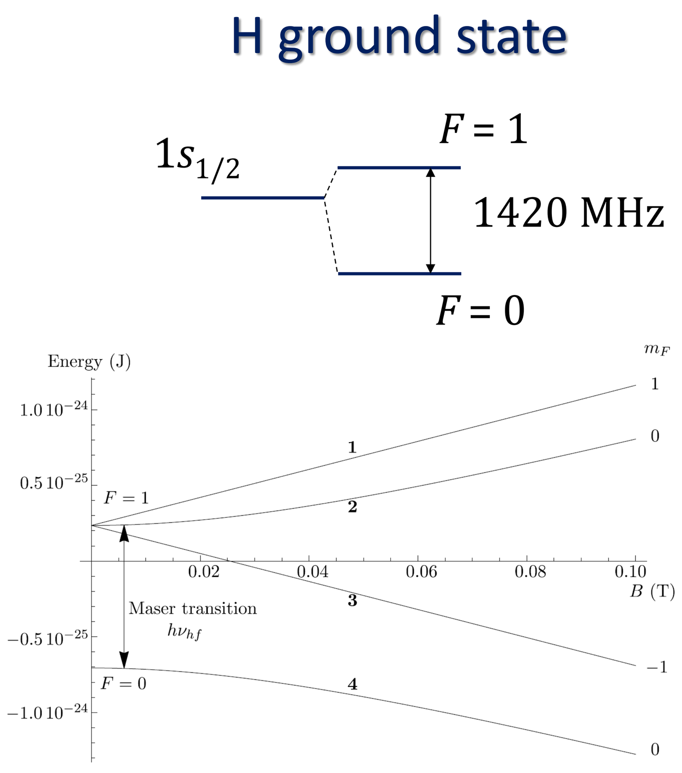
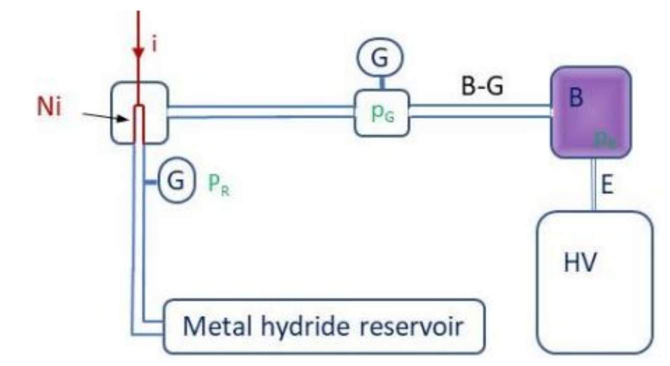
We report an experimental procedure that allows full characterisation of a metal hydride storage system and, using this procedure, demonstrate that the selected storage is suitable for 15 years of compact hydrogen maser operation dedicated to space applications.

Hydrogen maser: scheme of principle

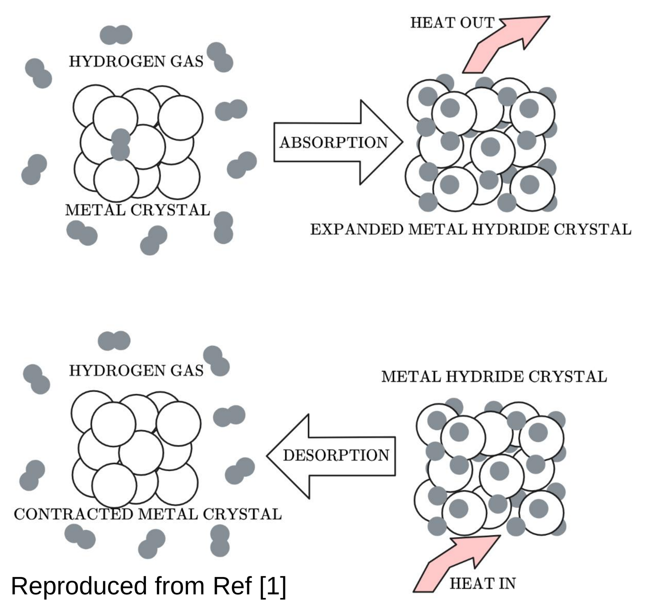






Atomic hydrogen source scheme of principle (Ni: current-controlled (i) Ni tube, G: pressure gauge, B: RFdischarge bulb, pG [pB]: pressure at G [B], B-G: bulb-gauge pipe connection, E: bulb exit channel, HV: high-vacuum atomic clock zone).

Metal hydrides

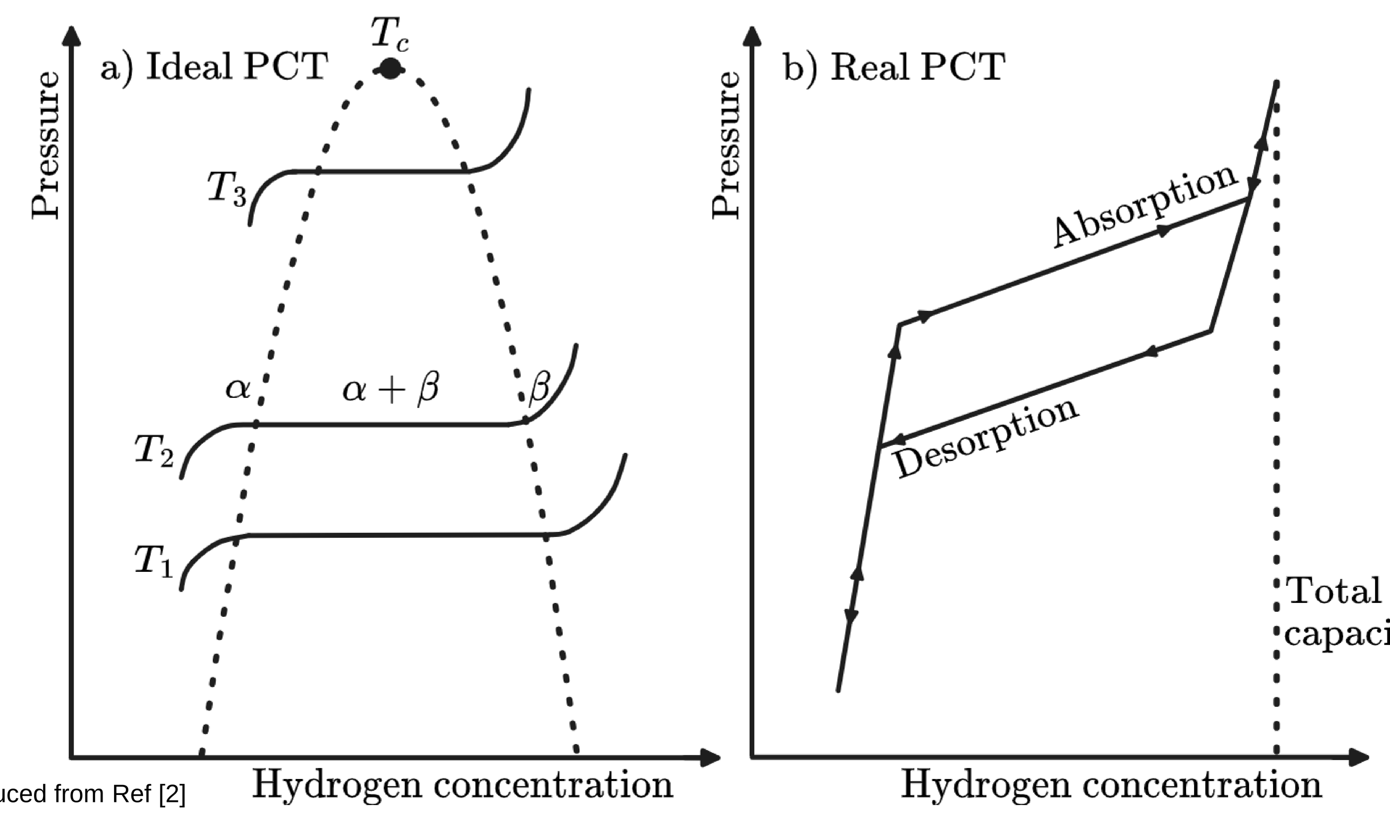


Reproduced from Ref [1]

Metal hydride storage → Solid state storage

Equilibrium between gas pressure and amount of hydrogen stored in the metal

→ Characterization: Pressure Composition Temperature (PCT) curves



Reproduced from Ref [2]

Total capacity VS Exploitable capacity

Stability requirements:

→ Need of a constant output pressure

→ Heating of the container during desorption
The container cannot withstand temperatures above 50°C

→ **Exploitable capacity < Total capacity**

Metal hydride storage selected based on theoretical and numerical arguments [1]: BL-30 with alloy L from Fuel Cell Store

Objective: Verify that the exploitable capacity of the selected container will suffice to sustain hydrogen maser operation in a satellite (typical duration of 15 years)

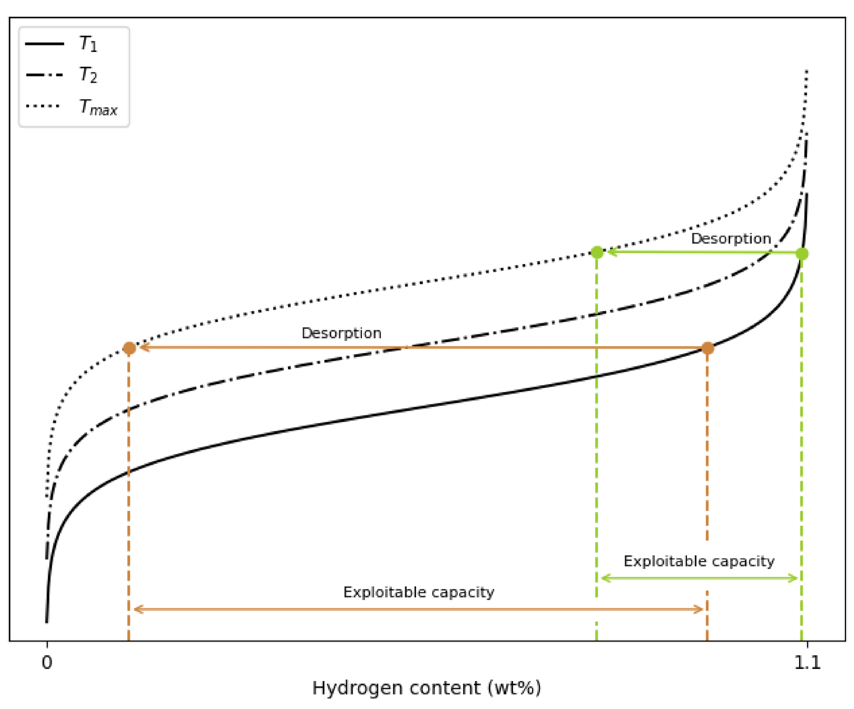
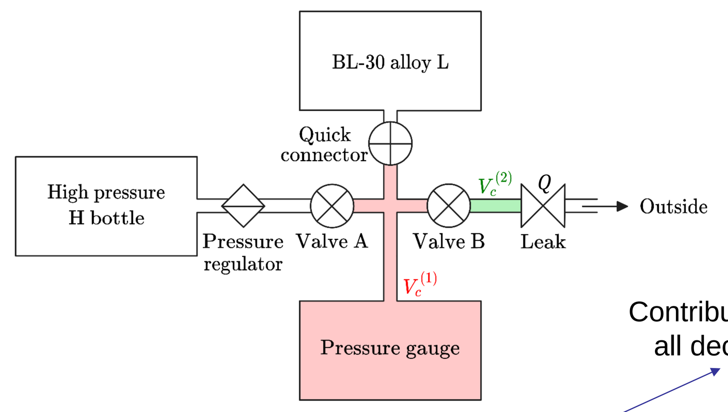


Illustration of the exploitable capacity for 2 different filling pressures

Experimental procedure to obtain PCT curves

Metal hydrides exhibit low desorption rates

→ Discrete measurements



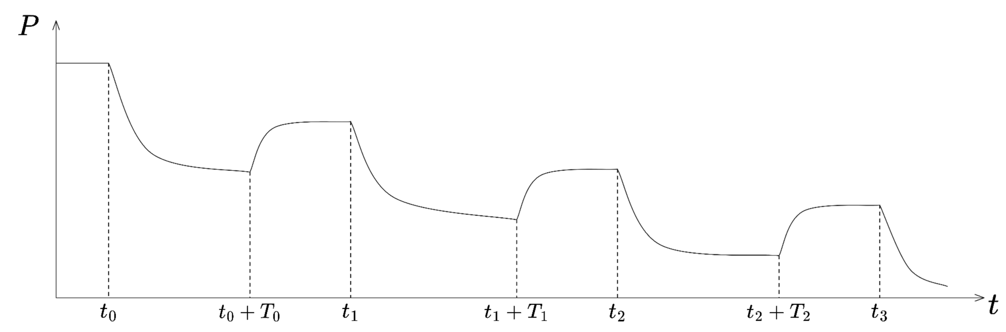


Illustration of the measurement to obtain a PCT curve

$$n(P(t_{i+1})) = n_0 - \sum_{k=1}^{i}\left(\int_{t_k}^{t_k+T_k} Q\big(P(t)\big)dt + \frac{P(t_k+T_k)V_c^{(2)}}{RT}\right) - \frac{P(t_{i+1})V_c^{(1)}}{RT}$$

- Contribution of all decays.
- $n(P(t_{i+1}))$: Amount of stored hydrogen corresponding to the equilibrium pressure $P(t_{i+1})$
- n_0: Initial amount in the apparatus
- $\int Q\,dt$: Amount that has exited the apparatus during the decay
- $\frac{P(t_k+T_k)V_c^{(2)}}{RT}$: Amount present between valve B and the leak that can exit after valve B closing
- $\frac{P(t_{i+1})V_c^{(1)}}{RT}$: Amount in the connecting pipes

Leak rate calibration

The manufacturer-stated accuracy of the leak rate is 20%

→ Need to calibrate the leak

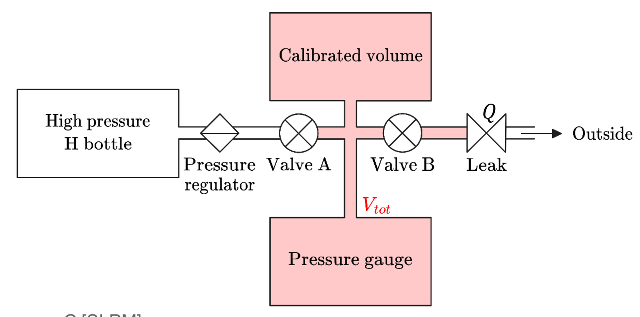
Main issue: connecting pipe volume is unknown

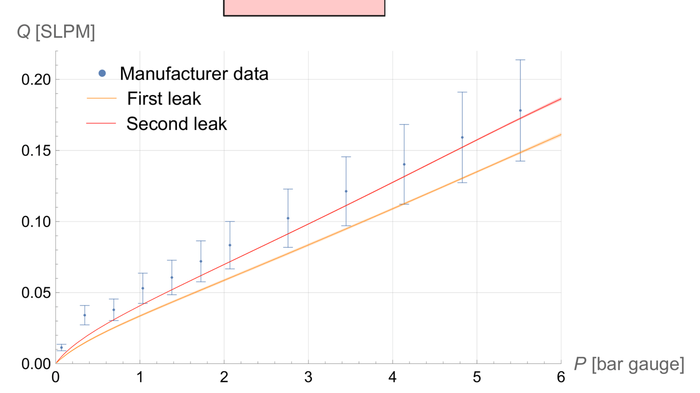
→ Use of different calibrated volumes V_1, V_2 and V_3

$$\begin{cases}\dot P_{V_1}(P) = \dot n(P)\dfrac{RT}{V_{tot,1}}\\ \dot P_{V_2}(P) = \dot n(P)\dfrac{RT}{V_{tot,2}}\end{cases} \Longrightarrow \dot n(P) = \frac{1}{\frac{1}{\dot P_{V_1}(P)} - \frac{1}{\dot P_{V_2}(P)}}\frac{V_{tot,1}-V_{tot,2}}{RT} = -Q(P)$$

with $V_{tot,1}-V_{tot,2} = V_1 - V_2$

The average of the 3 independent estimations for the pairs (V_1, V_2), (V_2, V_3) and (V_1, V_3) is then taken

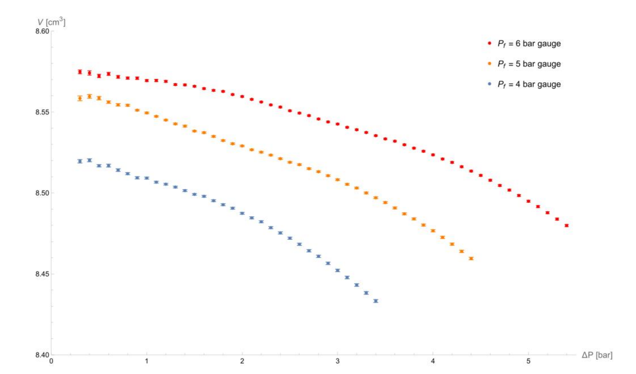




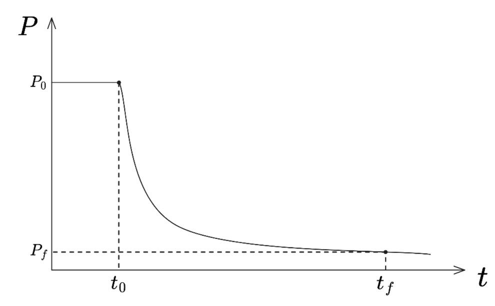
Leak rate calibrations for both leaks used during the experiments

Connecting pipe volumes

$V = V_c^{(1)} + V_c^{(2)} = \frac{\Delta n}{\Delta P}RT$, with $\Delta n = \int_{t_0}^{t_f} Q\big(P(t)\big)dt$, and $\Delta P = P_f - P_0$



Connecting pipe volume estimation as a function of the pressure interval length on which the estimation is performed, for three different starting pressures



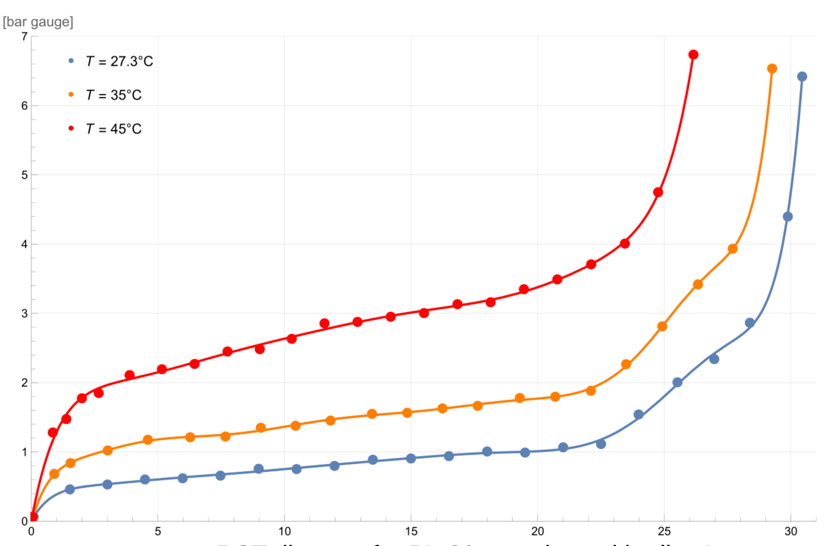
A systematic bias is observed, with an undetermined origin

→ $V = V_c^{(1)} + V_c^{(2)} = 8.50(7)\ \mathrm{cm}^3$

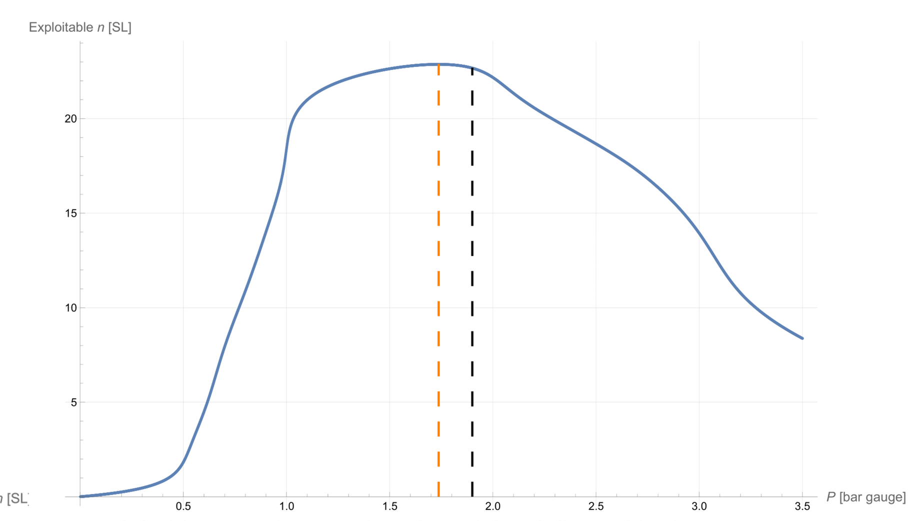
$V_c^{(2)}$ is geometrically determined: $V_c^{(2)} = 1.28\ \mathrm{cm}^3$

$\Rightarrow V_c^{(1)} = 7.22\ \mathrm{cm}^3$

PCT diagram and exploitable capacity



PCT diagram for BL-30 container with alloy L



Exploitable capacity as a function of the delivered hydrogen pressure

Maximum exploitable capacity: 22.9 SL at 2.7 bar absolute

Ideal delivered pressure of 3 bar absolute

→ Need a compromise between maximising the exploitable capacity and reaching a output pressure as close as possible to 3 bar absolute

→ Chosen working pressure of 2.9 bar absolute corresponding to an exploitable capacity of 22.7 SL

The minimum capacity required to sustain onboard maser operation is 19.44 SL [1] → BL-30 with alloy L is suited

Conclusions

We have presented an experimental procedure that allows to completely characterize a metal hydride storage. Using this procedure, the exploitable capacity of the container as a function of the output pressure has been extracted. Regarding the compromise between maximising the exploitable capacity and obtaining a delivered pressure as close as possible to 3 bar, the working pressure has been chosen to 2.9 bar, corresponding to an exploitable capacity of 22.7 SL, thereby demonstrating that the selected container is able to provide molecular hydrogen to a compact spaceborne hydrogen maser for the entire duration of a space mission (~15 years).

→ *The metal hydride storage BL-30 with alloy L from Fuel Cell Store is suited for a spaceborne hydrogen maser*

References

[1] E. Van der Beken, "Numerical Modelling of Hydrogen Maser Physics in the Context of Space Applications", PhD thesis (University of Liège, Liège, Belgique, 2021).

[2] N. Klopčič, I. Grimmer, F. Winkler, et al., "A Review on Metal Hydride Materials for Hydrogen Storage", Journal of Energy Storage **72**, 108456 (2023).