Performance of Hydride Activated Gas Gap Heat Switches in the Planck Sorption Cryocooler

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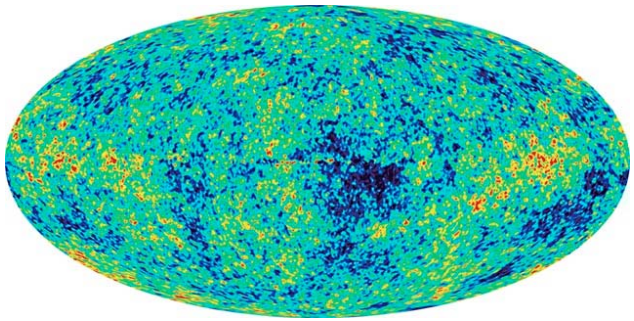
Outline

1. Brief description of the Planck Mission and its objectives
2. What are Planck Sorption Cryocoolers (PSC) & how do they work?
3. Description of Gas Gap Heat Switch (GGHS) technology used in PSC
4. Compressor Element (CE) Configuration & Operation:
   - CE Sorbent Beds for H_2 refrigerant gas (Pressure range: 0.3 bar – 50 bar)
   - Planck GGHS (Pressure range: 1.3 Pa – 1300 Pa)
   - Development stages of GGHS for Planck flight hardware
5. Evaluations of GGHS during PSC development
   - Engineering Bread Board (EBB) Cooler
   - Modifications & validation of flight model GGHS components
   - Performance evaluation of CE/GGHS systems
6. Summary & Conclusions
7. Acknowledgments & References

Planck Mission [1, 2] to Measure Temperature Anisotropy in the Cosmic Microwave Background (CMB)



All-sky CMB map from WMAP space flight mission (2004)

CMB is the Black Body spectrum (T_{peak} = 2.725 K) left from the "Big Bang" creation.

"CMB is the fossil "first light" that allows reconstruction of the Universe as it was ~14 Billion years ago"

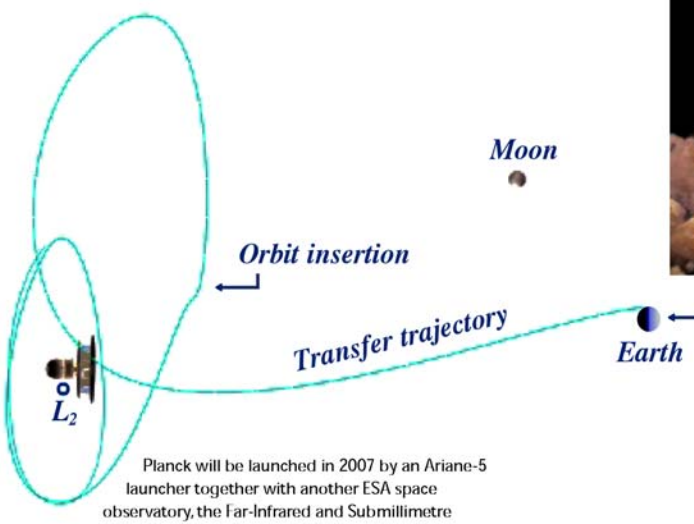
Objectives of the Planck Mission (ESA Project with NASA contributions):

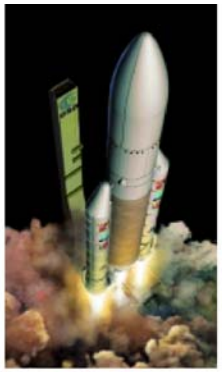
- Mapping of CMB anisotropies with improved sensitivity and angular resolution
- Determination of Hubble constant and other fundamental cosmological parameters
- Testing inflationary models of the early universe
- Measuring amplitude of structures in CMB at resolution of a few μK

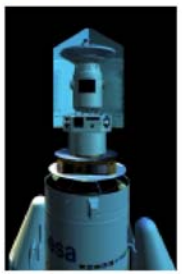
Planck uses two State-of-Art Instruments to gather data

1. LFI - Array of tuned radio receivers (25 - 100 GHz) operating at 20 K.
2. HFI - Array of Far-IR bolometers (90 - 1000 GHz) operating at 0.1 K

Planck Spacecraft to Launch in 2008

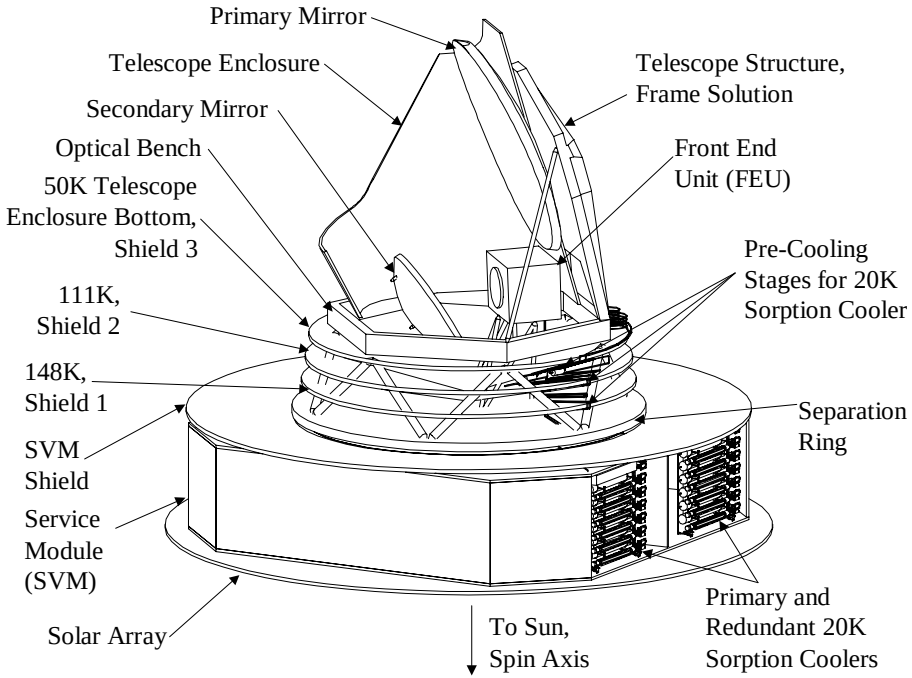






Planck will be launched in 2007 by an Ariane-5 launcher together with another ESA space observatory, the Far-Infrared and Submillimetre Telescope (FIRST). The two satellites will separate shortly after launch and proceed to different orbits. They will be operated independently.

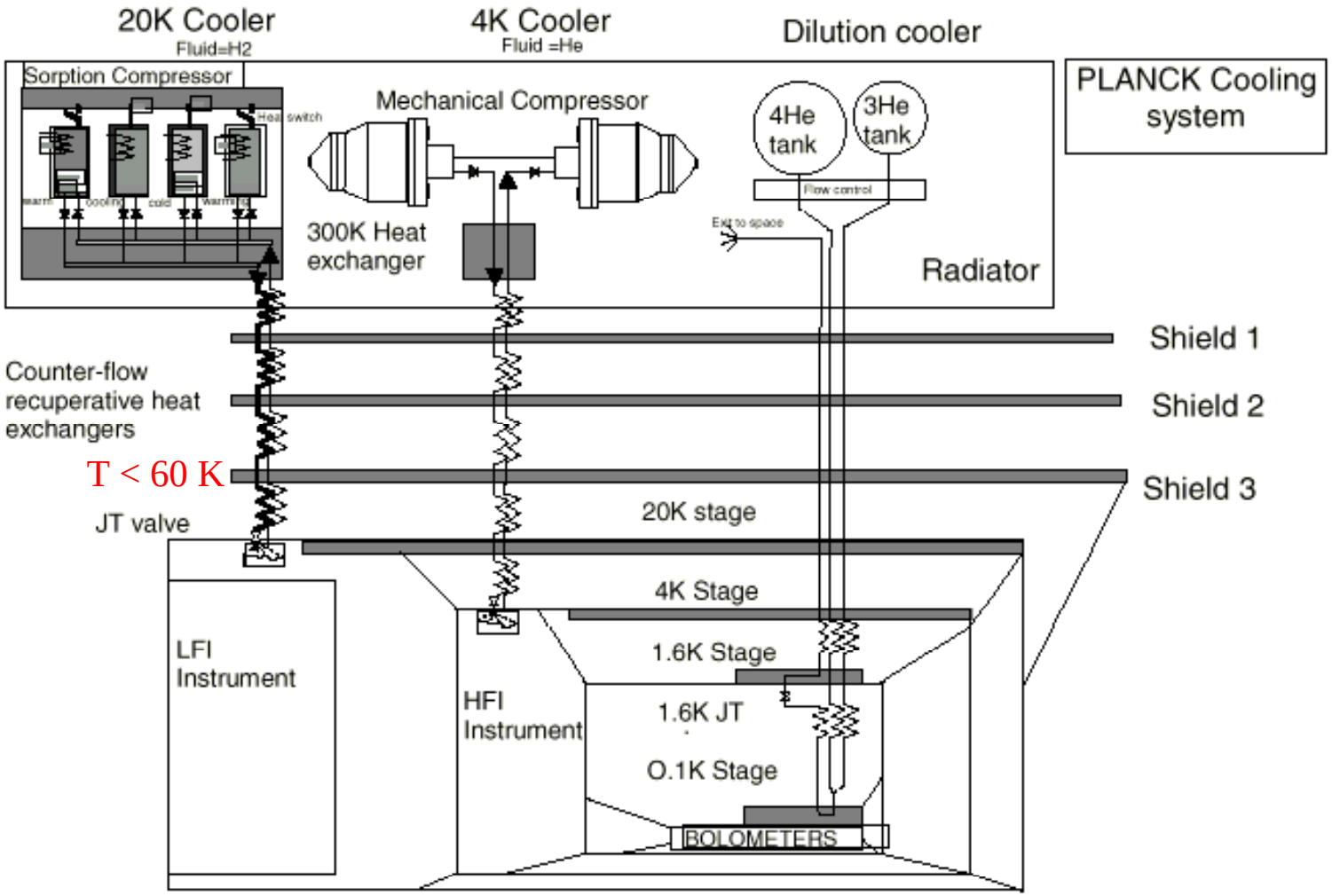
About four months after launch Planck will reach its final destination: a so-called 'Lissajous orbit' around a virtual point in space known as the 2nd Lagrangian point of the Sun-Earth-Moon system(L2). The L2 point is located about 1.5 million kilometres away from the Earth – four times the distance to the Moon. From this position Planck will be able to elude the emission from the Earth, the Moon and the Sun, which would otherwise confuse the signal from the cosmic background.



Schematic of Planck Spacecraft

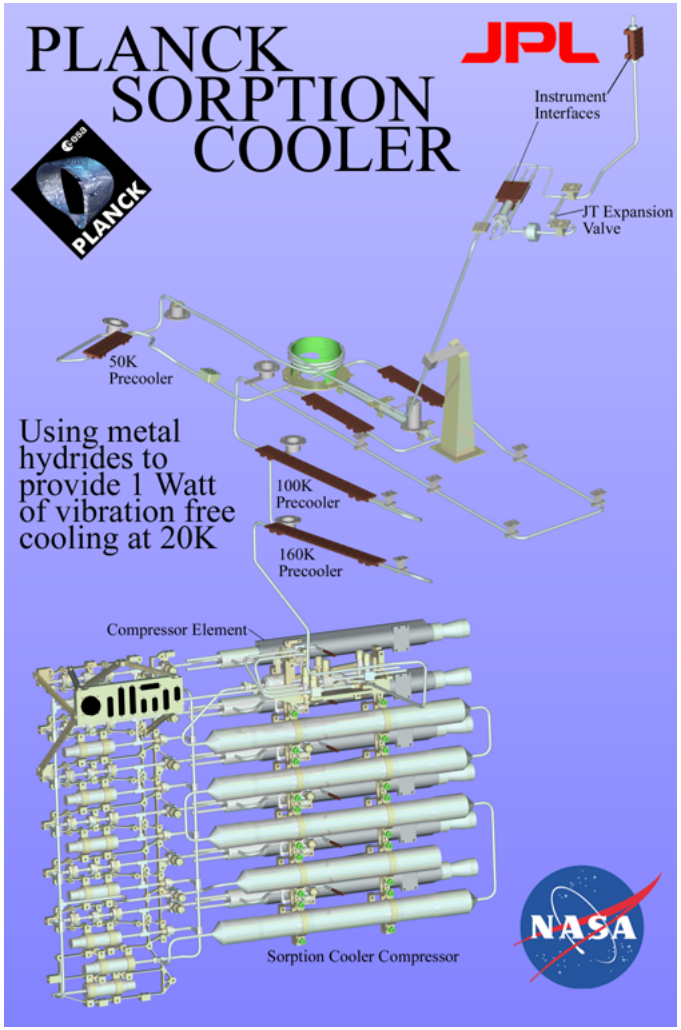
- **Dimensions: ~ 4 m by 4.5 m**
- **Mass: ~1500 kg**
- **Mission Operating Life: >21 months**

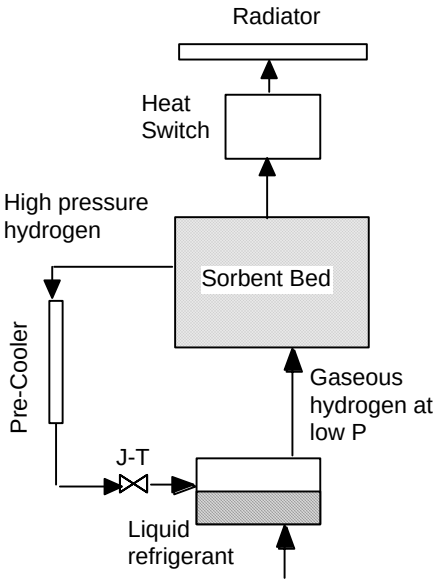
Schematic of Planck Cryogenic Systems [3]

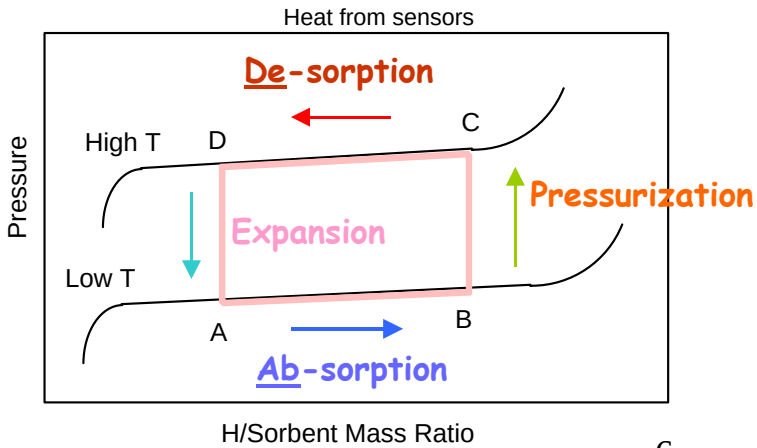


Basic Principles of Planck Sorption Cryocoolers [2,4]

PSC = Closed-Cycle Joule-Thomson (J-T) Device Producing Liquid H_2 @ T < 19 K







Key Performance Requirements for PSC

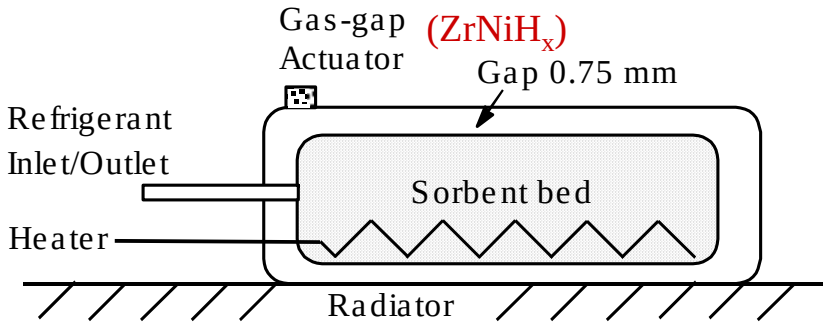
JPL delivers Thermo-Mechanical Unit - TMU (excl. electronics)

- Provide **~ 1W** Total Heat lift at instrument interfaces
  - LFI @ < 22.5 K ***[80% of Total Cooling]***
  - HFI @ < 19 K ***[20% of Total Cooling]***
    - **With ≤ 60 K pre-cooling temperature of coldest V-Groove**
- Temperature stability *(over TMU operating period, ~4000 s):*
  - ≤ 450 mK, max. to min. at HFI Interface
  - ≤ 100 mK, max. to min. at HFI Interface
- **TMU Input Power Consumption < 470 W (End-of-Life)**
- Operational Lifetime: 2 years
  - **18 months flight; 6 months total ground tests (JPL+Europe)**
- Storage Life: 6 years
- Two completely *independent* coolers (TMU+Electronics)
  - provides 100% redundancy
- Mass and Volume (Each Cooler):
  - Total mass ≤ 53.3 kg
  - Total PSC Compressor Volume < 0.18 m^3 (fit with allocated profile)

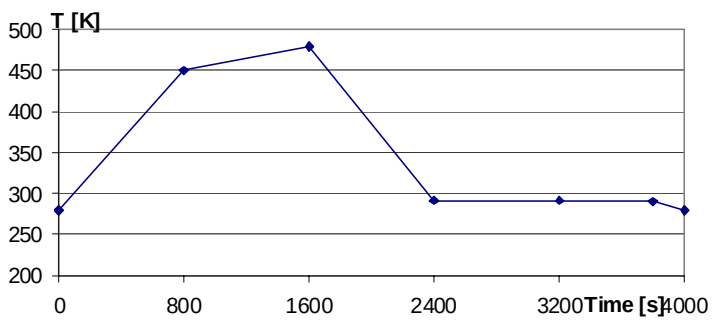
Hydrogen GGHS using Metal Hydride Actuators [5-7]

Hydrogen has largest Heat Conductivity (λ)

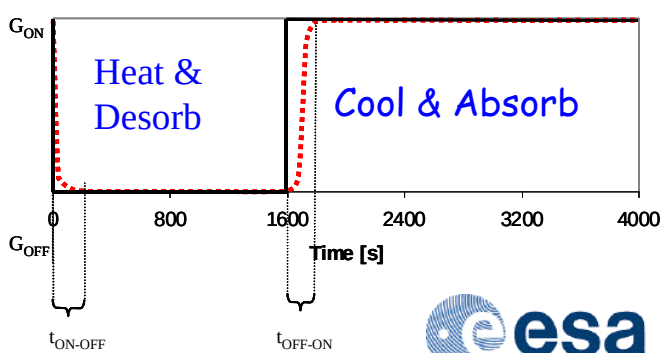
Gas	Continuum λo [10^4 W/cm-K]
Hydrogen	17.3
Helium	14.4
Air	2.4
Argon	1.6

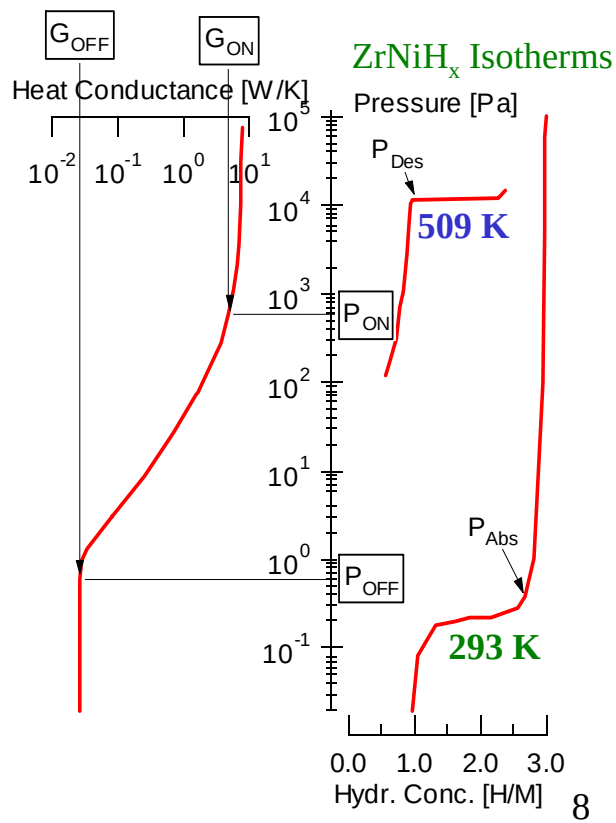


Temperature of compressor sorbent bed



Gap Heat Conductance switches between OFF and ON



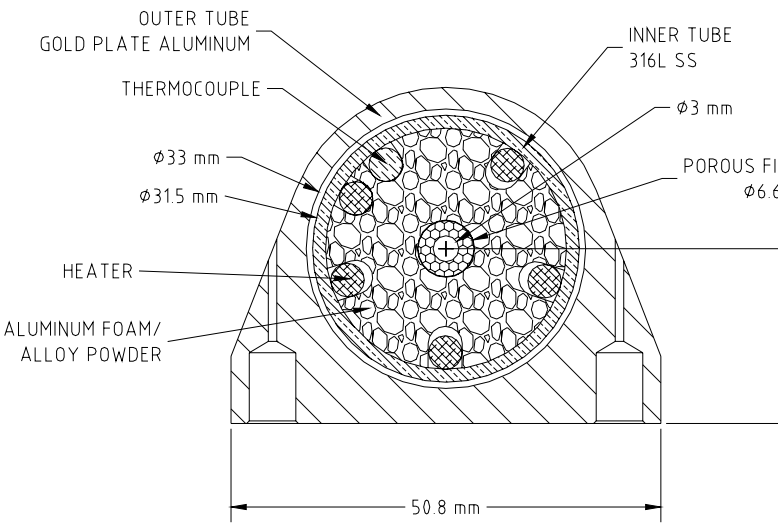


Planck CE-GGA Heat Switch Functional Requirements

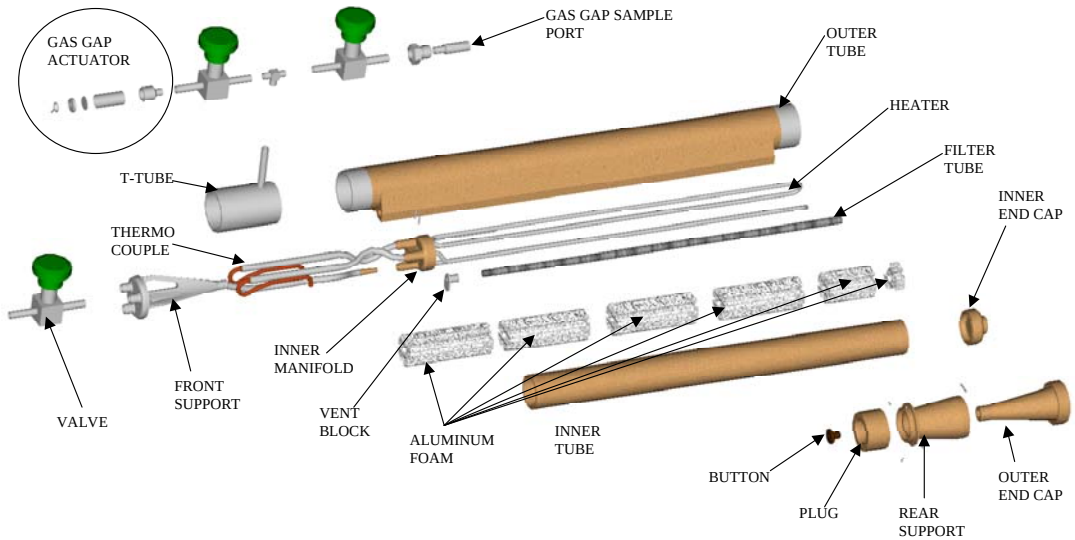
Requirement	Detail	Origin
Power	< 8.5 W @ 12 V	Power budget
Mass	< 300g	Mass budget
Functional: Thermal Conductance	G_{ON} > 5 W/K ± 2% G_{OFF} < 0.05 W/K	Cool the compressor during "on" state and reduce parasitic heat losses during "off" state
Functional: transient	t_{OFF-ON} < 200 s t_{ON-OFF} < 400 s	Cold-end temperature requirements
Operational lifetime	20,000 cycles	Mission life
Shelf lifetime	6 y	Cooler shelf life

Hydride Compressor Element (CE) for Engineering Bread Board (EBB) Cooler [8]

Compressor Elements Desorb H_2 at Outlet Pressure of 50 atm and Flow of 6.5 mg/s (4.3 slpm) and Absorb at P < 0.6 atm @ 2.2 mg/s (1.4 slpm)



Cross sectional view of EBB-CE showing the gas gap spacing of 0.75 mm



Exploded View of EBB-CE Components

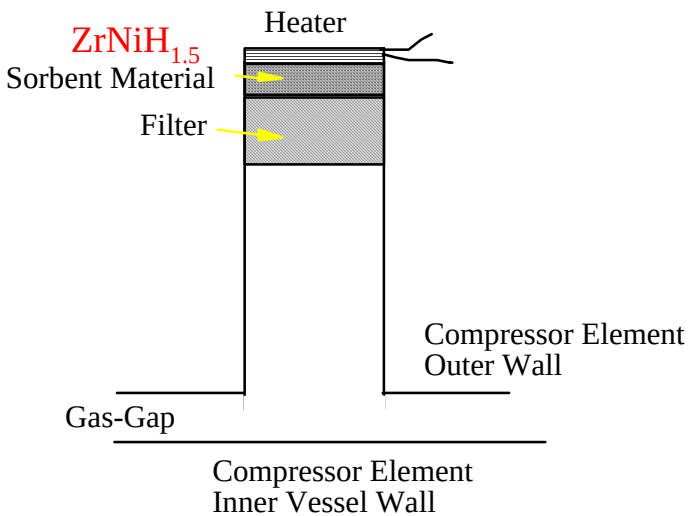
Complete EBB Unit with GGA

Gold Plated Inner Bed Assemblies for EBB-CE

$ZrNiH_x$ in Actuators for Gas Gap Heat Switches

Hydride Gas Gap Actuator (GGA) developed for EBB Compressor Elements

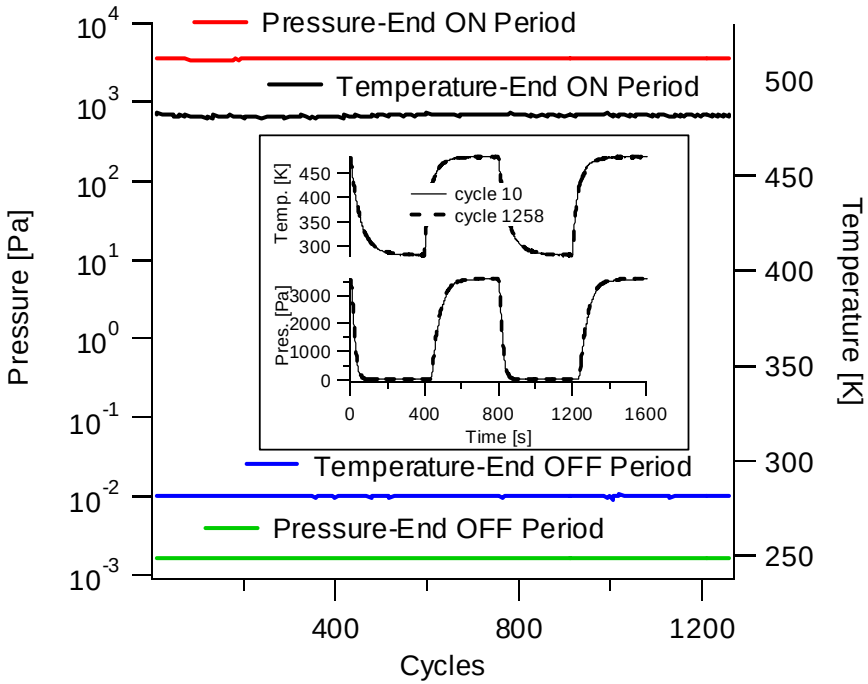
- Heat Conducting ON State: P_{GG} > 10 Torr (1300 Pa)
- Insulating OFF State: P_{GG} < 10 mTorr (1.3 Pa)
- GGA Input Power ~3W



Heater brazed to ring on actuator cap

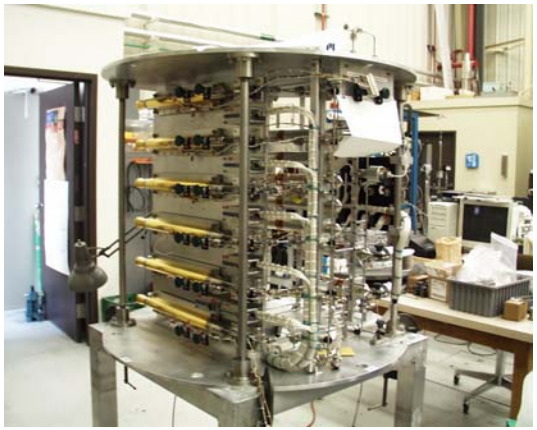
EBB-GGA Properties:

Alloy mass = 0.28 grams
Total H2 = 31.3 scc
Δx = 3.2 %
ΔH_2 cycle ~ 1.0 scc

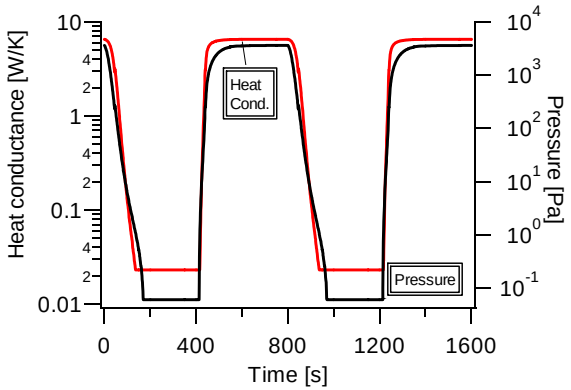


Initial tests of +1000 cycles before integration in the EBB-CE

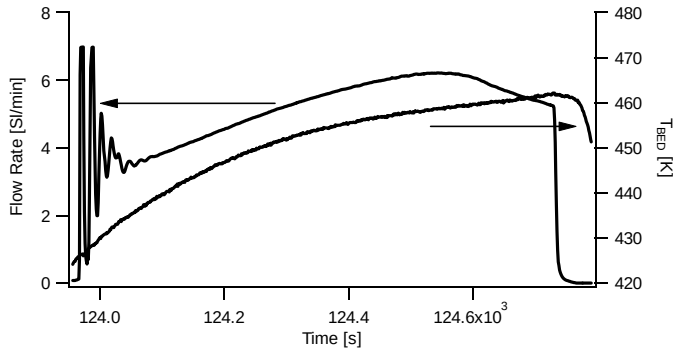
Individual EBB-GGA Cycling Performed Prior to Installation into EBB Compressor Verified GGHS [8]



EBB Compressor Assembly

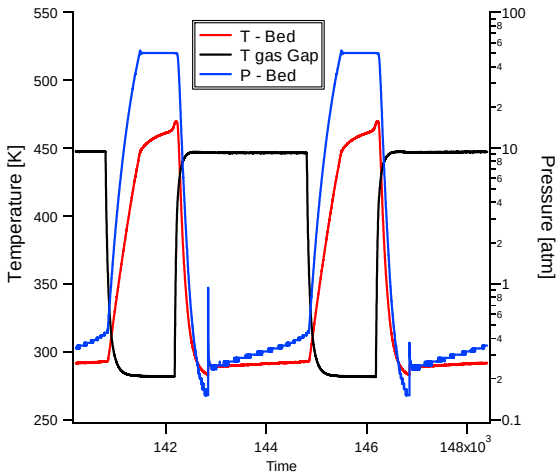


GGHS Pressure Cycles

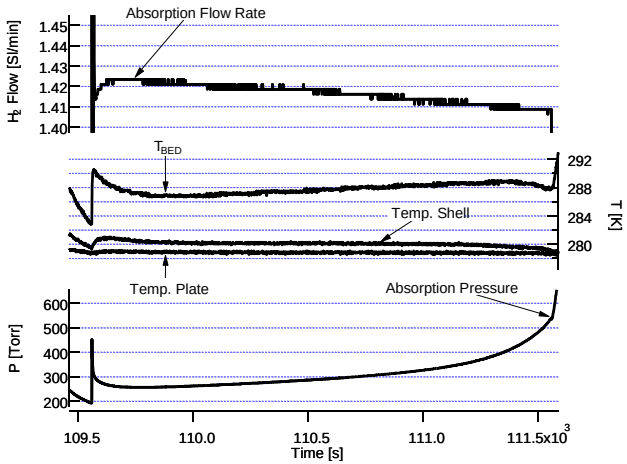


CE Desorption Phase Parameters

EBB-CE-GGA installed in vacuum test chamber



CE/GGHS P & T Parameters



CE Absorption Phase Parameters

EBB Cooler Met Most BOL Performance Parameters & Model Predictions

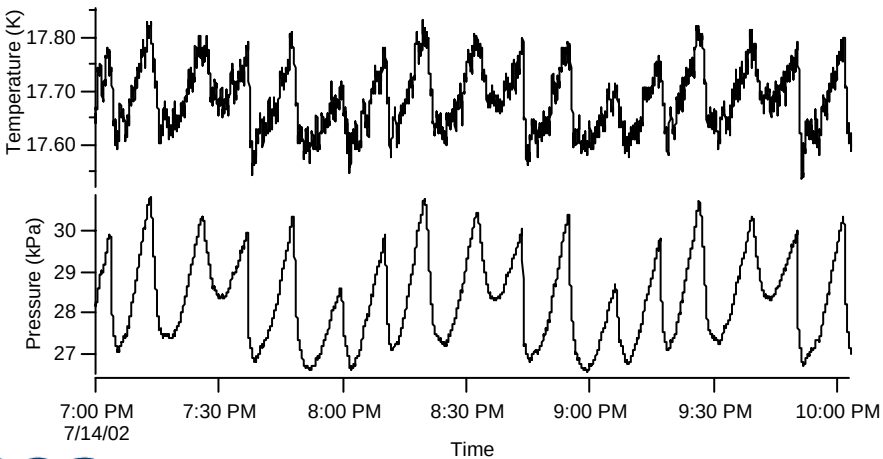
EBB Compressor operated for 4000 cycles during laboratory testing in 2002/2003

EBB Cooler & Compress Assembly in JPL PSC Test Facility

Performance issue with GGHS found during EBB cooler testing

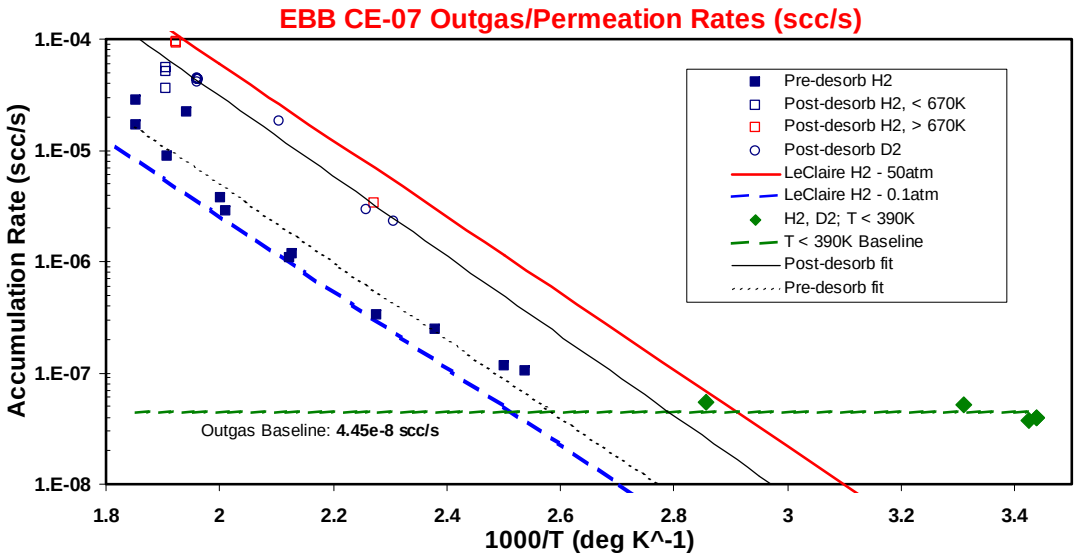
- **Increased input power to CE sorbent beds needed with cycling – hydrogen pressure build up in Gas Gap Heat Switches of Compressor Elements**

Initial T & P data for EBB Cryostat



Observed Pressure Increase from H_2 in GGHS

P_{GGHS} > 10 mTorr in gas gap volumes lead to increase parasitic heat loss in OFF state (i.e., More power needed by cooler)



Rate (scc/s) = $P_m(T) \cdot A_s\{P_H^{1/2} - P_L^{1/2}\} / d$

LeClaire's (1983) empirical equation for H_2 Permeation parameter $P_m(T)$ for austenitic stainless steels (i.e., 316L)

$P_m(T) = \{2.33 \times 10^{-2}\}\exp[-15.7(\text{kcal/mol})/RT]$

Data points measured at JPL using a EBB-CE unit [8,9]

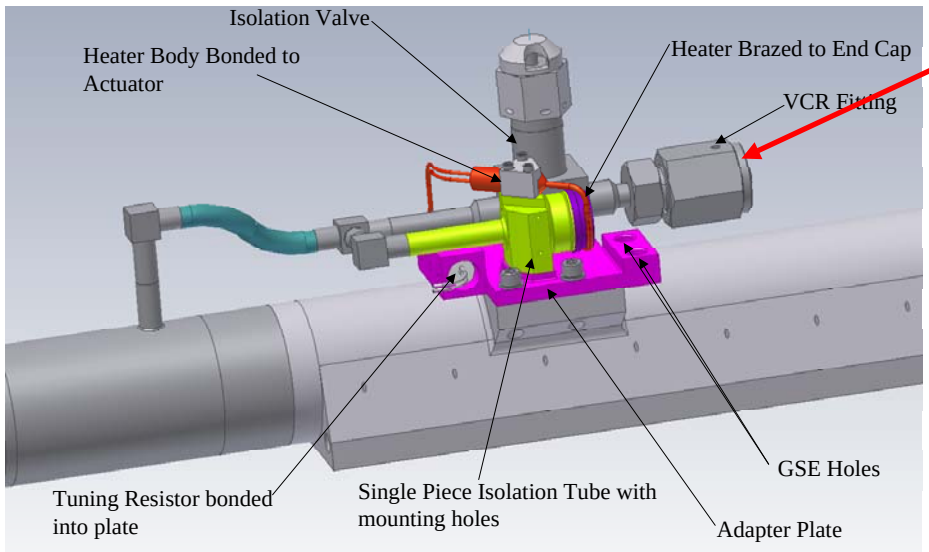
Sources [9] of hydrogen in the gas gap volume are:

- Electroplated gold/nickel layers on GGHS surfaces of EBB compressor elements
- Outgassing from 316L SS and Al walls
- Permeation through inner bed wall (d = 0.12 cm thick) from sorbent bed gas during desorption phase (P = 50 atm and 450 K < T < 500 K)

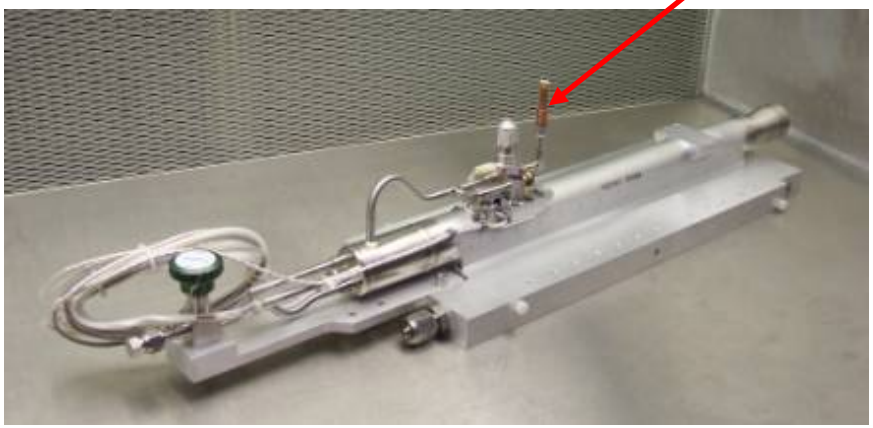
Configuration of the Flight Model CE/GGHS Units

Modifications made to flight GGA addressed H_2 permeation/outgassing and other issues relating to thermal performance and mechanical robustness

- 10-times larger ZrNi hydride sorbent bed in GGA to give a predicted 24-month GHHS operating life
- Removed all gold plating from GGHS surfaces
- Closed manual isolation valve with external, evacuated volume sealed with a copper pinch-off tube.
- Fixed thermal isolation mounting
- 8.5 Watt heater with tuning resistor



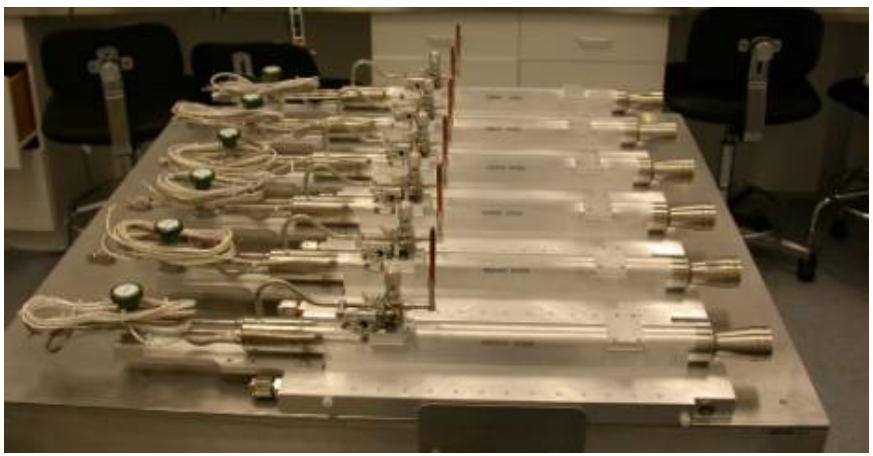
Replaced with copper pinch-off tube



GGHS Functional Criteria for PSC Flight Hardware

- OFF-state pressure < 0.020 torr [2.7 Pa]
- ON-state pressure > 4.36 torr [581 Pa]
- Switching time ON < 200 sec to reach 4.36 torr [581 Pa]
- Switching time OFF < 400 sec to reach 0.020 torr [2.7 Pa]
- Leak Rate (external or thru-the-valve using helium) < 10^{-9} atm-cc/s
- Pass/Fail criteria are for a simulated radiator temperature of 262 – 282 K and a GGA heater input power of < 8.5 W.

FM1 CE (S/N-03) in Vacuum Test Chamber

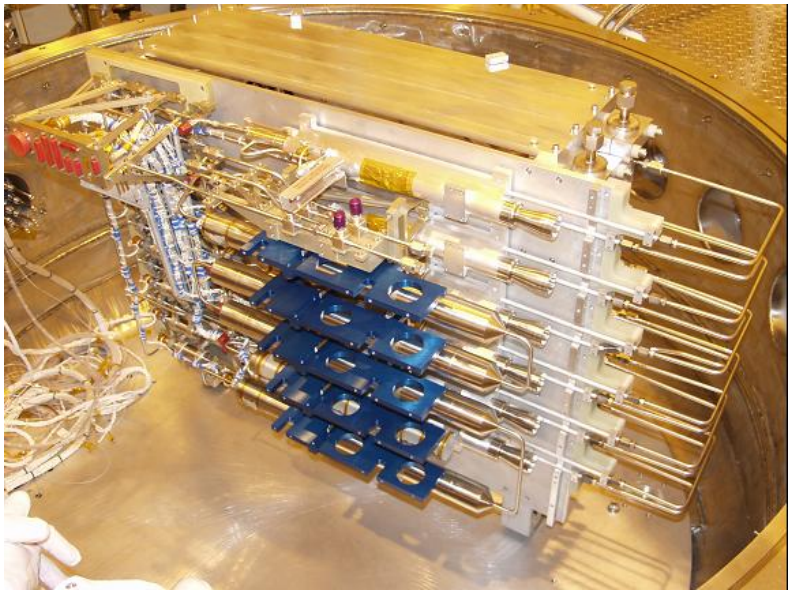


Six Flight CE units for delivery to FM1 cooler

SUMMARY OF Planck GGHS

Summary of GGHS Development for PSC

- **GGA Development – $ZrNiH_x$ best sorbent**
  - Met all Pressure range & kinetics goals
  - 25,000 cycles w/o degradation
- **EBB CE demonstrated GGA works @ BOL**
  - Brazed GGA heater stable to ~24,000 cycles
  - No performance degradation during 1000+ cycles
  - First detected H_2 outgassing during EBB cooler tests
  - Characterized H_2 release rates 290K – 550K
- **Prototype 10X-GGA for Flight CEs**
  - Developed better attachment of new GGA heater
  - Met all cycling parameters with an EBB-CE bed
  - Validated EOL hydride performance
- **Pathfinder CE with Flight-like GGA**
  - Built w/o hydride or Au plating
  - Estimated H_2 outgassing/permeation rates to verify 10X-GGA should work to EOL
- **Fabrication & Testing of Flight CE/GGHS completed**
  - Delivered 12 flight units for two TMU coolers in 2003 & 2004



PSC Flight compressor as being installed into vacuum test chamber.

CONCLUSIONS

GGHS lets the PSC-CE meet its performance requirements with only ~22% of power needed compared to mounting sorbent bed directly to radiators – **without GGHS this cryocooler <u>cannot operate</u> on available power from Planck spacecraft!**

General Attributes of Hydride GGHS for Future Systems:

- Long life potential (~5+ years)
- Closed Cycle operation (i.e., does not require separate H_2 bottle to supply vented gas with an open-cycle switch)
- Low power requirements (< 10 W per switch)
- High TRL level (based on Planck EBB/flight coolers and development tests)
- Large ON/OFF conductance switching ratios (>200)
- Low mass/volume
- Simple operation (turn ON or OFF by throwing an electrical switch)
- No moving parts
- No hysteresis
- Simplicity of implementation

ACKNOWLEGMENTS & REFERENCES

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