Performance of the Gravity Probe B Cryogenic Sub-System

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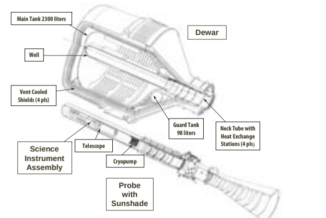
Key Cryogenic Requirements

- Cryogen: < 1.85 K superfluid He
- Instrument temperature: <= 3.0 K at interfaces
- Bath temperature regulation: < 30 mK
  - Controlled by Attitude and Translation Control (ATC) subsystem which uses vent gas for thrusting
  - Porous Plug flow rate range: 4 - 16 mg/s at 1.8 K
- Main tank ground hold (< 1.9 K): > 90 days [108 days achieved]
- Flight lifetime: 16.5 months or more [17.3 months achieved]
- Calorimetric liquid He mass measurement to within 5% [calculated end of life prediction - 6%]
- Steady state field / gyro trapped flux < 9 μG [0.2 to 3.0 μG uniform field equivalent trapped field]
- Superconducting Pb-foil shield < 6.5 K to end of mission [~< 6.5 K maintained over critical region]
- External ac magnetic field attenuation factor <=2×10^{-12} [~2.5×10^{-12}]
- Ability to perform flux flush (heat Nb components of the science instrument above T_c) and low temperature bakeout to achieve pressure < 2×10^{-10} torr in probe [< 10^{-14} torr]

Unique Aspect of GP-B Cryogenic System

The requirement of an ultra-low magnetic field region for the science instrument is satisfied by means of an expanded superconducting Pb-foil shield lining the interior of the dewar well. Once installed, it must be maintained in a superconducting state until the end of the science mission. This requirement must be satisfied even during the insertion and cooling of the room-temperature cryostat probe with its 38 kg science instrument.

Features of Cryogenic System

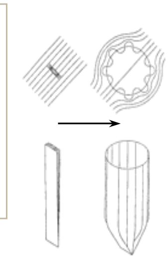


- GP-B dewar is the largest superfluid He flight dewar, containing 337 kg (2320 l) of 1.8 K helium at launch (95% full)
- Dimensions: 2.15 m diameter x 3.03 m height
- Lightest flight helium dewar for its capacity: dry weight: 800 kg (2.4:1)

Ultra-Low Magnetic Field Shield Installation

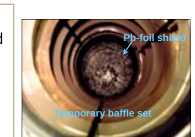
Basic Field Reduction Concept

- 63 μm thick Pb foil (T_c = 7.2 K) is cut, folded, and welded as shown
- Shield is cooled < T_c in ambient field and expanded, reducing the internal field
- Process can be iterated as needed
- See poster L1.00023 for details



Flight Shield Results

- The flight shield had an internal field < 5 ptesla (0.05 μgauss) in the gyro region. Installation of the retainer increased the maximum field to 0.17 nT (1.7 μG).
- Lead bag retainer mechanically protects and thermally isolates shield from probe and sinks shield to liquid He in main tank.
- On-orbit ac shielding factor was 2.5×10^{-12}. (Includes the additional shielding of the science instrument)

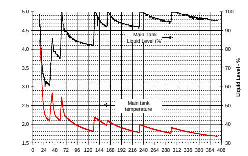


Probe Insertion

- Warm probe cooled by insertion into dewar well
- Well maintained with liquid He by internal transfer from main tank
- Purged airlock used to avoid air contamination of dewar well
- Cool-down rate limited to reduce thermal stress and improve efficiency (~15 hr duration)
- Exchange gas used to cool 38-kg science instrument

Launch Preparations at Vandenberg AFB

- Final preparations performed in NASA's hazardous processing facility (HPF)
  - Condition main tank
  - Install solar arrays



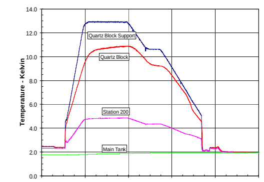
Conditioning the Main Tank

- Main tank conditioned to 1.65 K at 95% full (337 kg He)
  - Pumped on He bath continuously
  - Performed 6 refills with atmospheric liquid He
  - Process took 16 days
- Guard tank maintained with normal boiling point liquid
  - Guard tank heater used to maintain > 1 atm

Pre-launch Hold Times

- Guard tank hold time
  - 5 days (100 -> 20%) in order to leave sufficient liquid for precooling to initiate refill
  - Refill done every 3 days for margin
- Main tank hold time (1.65 -> 1.9 K)
  - 108 days (90 days required)
  - 56 days actually used
  - 32 mW average heat rate

Flight Thermal Operations: Flux Flush

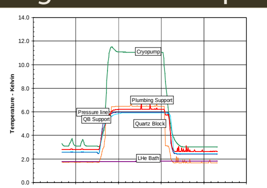


- A thermal cycle performed to expel magnetic flux trapped in superconducting Nb components (e.g., gyro rotors) due to launch vibration
- Thermal contact with suspended rotors maintained during thermal cycle by flowing He gas into vented probe at a rate sufficient to yield a pressure of ~7 mPa

Results of Flux Flush

- Uniform field equivalent of flux trapped in gyro rotors as measured by readout SQUIDs after thermal cycle:
  - Gyro 1: 0.30 nT
  - Gyro 2: 0.13 nT
  - Gyro 3: 0.08 nT
  - Gyro 4: 0.02 nT
- Requirement: uniform field equivalent of rotor trapped flux < 0.9 nT (9 μG)

Flight Thermal Ops.: Low Temp. Bakeout



- Residual He gas remaining in the probe after gyro spin-up would produce excessive damping torques. A modest bakeout of cold surfaces in the probe while the probe is vented to space will greatly reduce the amount of weakly bound adsorbed gas.
- Effectiveness of the bakeout is substantially improved by the addition of a sintered Ti cryopump (located forward of the telescope) that adds 230 m² of bakeable area.

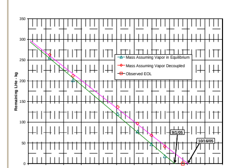
Results of Bakeout

- Ideally, gas pressure can be deduced from gyro damping time constant :
  - Gyro 1: 15,800 yr
  - Gyro 2: 14,700 yr
  - Gyro 3: 7,000 yr
  - Gyro 4: 25,600 yr
- Lack of consistency and other evidence indicate that damping times are not gas-limited. Best evidence indicates damping dominated by a patch effect mechanism.
- Upper limit on gas pressure: ~10^{-12} Pa (~10^{-14} torr). Requirement: <2×10^{-10} torr

End of Life Prediction

- **EOL prediction needed to determine when to switch to calibration phase without prematurely terminating Science**
- **Calorimetric method: Heat Pulse Meter (HPM)**
  - Determine liquid mass by measuring temperature rise as a result of a known heat input under the condition of a constant vent rate
    - Heat input chosen to achieve ~10 mK rise
  - EOL prediction independent of scale factor error
  - Used only 6 times because of risk and system disturbance
- **Integration of vent flow rate measurements**
  - Useful for daily trending
  - EOL prediction sensitive to scale factor error
  - ATC flow rate estimated from thruster nozzle pressures

- Predicted EOL on 9/1/05 based on last HPM measurement (7/29) for a lifetime of 16.3 mo.
- Actual EOL: 9/29/05 for a lifetime of 17.3 months
  - Lifetime corresponds to 7.4 mg/s or 172 mW average heat rate
- Major source of error in EOL prediction is uncertainty in modeling response of vapor
  - Assuming vapor in equilibrium with the liquid under-predicts lifetime
  - Ignoring vapor over-predicts



Conclusions

- **All key cryogenic requirements met**
- **Dewar and its superconducting shield kept cold > 8 years**
  - Required removing guard tank vent line frozen air blockages on several occasions without warming shield
  - Utilized computer-triggered commercial alarm system and surveillance of data fed to web site
    - Alarms tripped by out-of-limit data or by watchdog timer in case of computer malfunction
  - In case of critical operations, 24/7 on-site monitoring was maintained
- Guard tank (GT) a valuable asset in the pre-launch environment where it provides a long main tank hold time, eliminating the need to service a sub-atmospheric main tank on the Mobile Service Tower
  - GT vent line built-in isolation valve could have prevented vent line blockages
  - GT heater should be sized to reach >50 K to clear line blockages if necessary (GP-B dewar had this ability)
- Dewar vacuum hold time was excellent: indefinite with the well evacuated and ~ 3 months with He in the well
- Lifetime prediction
  - Although a superfluid He vessel is an ideal system for calorimetric mass gauging, accuracy is limited by uncertainty in the response of the vapor phase

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