Appendix B

Columbus Thermal Control System On-Orbit Performance

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Abstract

The Columbus laboratory module, a major European contribution to the International Space Station, was launched onboard the Space Shuttle Atlantis on 7 February 2008. The presentation will present some early data on the performance of the Columbus thermal control, both active and passive, after start of on-orbit operations. The data will be compared to a set of analysis results from the Columbus Integrated Overall Thermal Mathematical Model (IOTMM), which have been produced with the observed ISS on-orbit conditions as input.

Columbus Thermal Control System On-Orbit Performance

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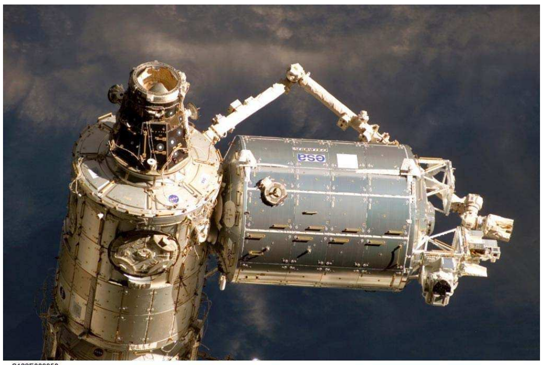
Introduction

- Mission
  - ESA microgravity laboratory for the ISS
  - Launch on STS-122/F1E on 7 February 2008
- Design
  - Cylindrical pressurized compartment, diameter 4.5 m, length 6.4 m
  - Accommodates 10 payload racks internally and 4 attached payloads externally
  - Supports a shirtsleeve environment for 3 crew members



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- Thermal control
  - Combination of passive and active
  - MLI (beta cloth top layer on exposed blankets)
  - Chromic acid anodization on MDPS panels
  - Aluminium shell with external heater foils
  - Internal cooling by water loop, with interface to Condensing Heat Exchanger for cabin temperature and humidity control and heat exchangers for heat rejection to the ISS

Objective

- Due to practical constraints, the Columbus module has never been subjected to a thermal balance test
- The Columbus thermal design has been verified by applying a validated Integrated Overall Thermal Mathematical Model (IOTMM) for the flight predictions. The Columbus System Requirements Document, COL-ESA-RQ-001, specifies

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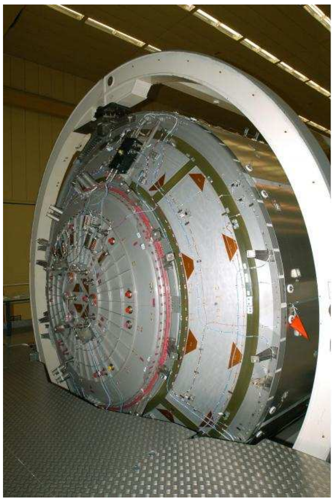
The thermal design of the APM shall be consistent with all specified operational scenarios and derived contingency modes without causing heat soak back, undercooling, condensation or other adverse effects.

Note : (Requirement Clarification): Qualification on FC level is via analysis supported by test on PFM (to validate analysis). Test is performed at system level in the frame of the integrated system test. ATCS is tested at S/S level during the water loop step 4 to validate the TCS TMM. THG is tested at section level to validate the THG TMM. Unit Thermal design is tested at unit level. (THG – Temperature and Humidity Grid)

- The purpose of the current simulation is to gain insight into how well the chosen method of verification has managed to produce an IOTMM which is able to reproduce the observed on-orbit TCS performance

Thermal control overview
1. Shell heater design architecture (1)



- Main and redundant heater chains have 78 heaters each
- Each chain has 6 circuits with 13 heaters
- Main heater chain is powered and controlled by HCU 1
- Redundant heater chain is powered and controlled by HCU 2
- Three redundant thermistors are implemented for the HCU to control each individual circuit
- Heater elements are trapezoid-shaped Kapton foils (1249 +/-3% ohms)
- With 120 VDC, it produces around 146 W per circuit and almost 900W per chain

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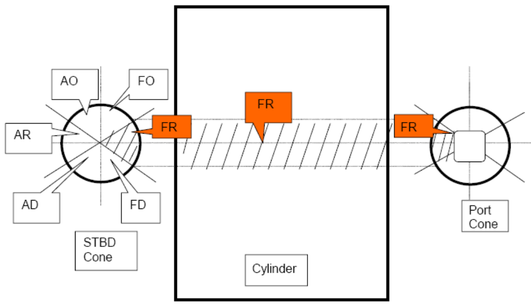
Thermal control overview
1. Shell heater design architecture (2)

- The shell, i.e. the Port Cone, the Cylinder and the STBD Cone, is subdivided into 6 zones (AD, AR, AO, FO, FR, FD) in the longitudinal direction, each covered by one main and one redundant heater circuit
- The 3 main and the 3 redundant thermistors are located at the two cones and in the middle ring of the shell
- Each heater circuit is activated when at least one of the three thermistors detects a temperature < = 20 °C and is switched off when all the three thermistors detect a temperature > = 23 °C *(valid for the default temperature setting)**

*) The default control set points have been selected in order to keep a comfortable margin w.r.t. the maximum dewpoint (15.5 °C) permitted in manned modes



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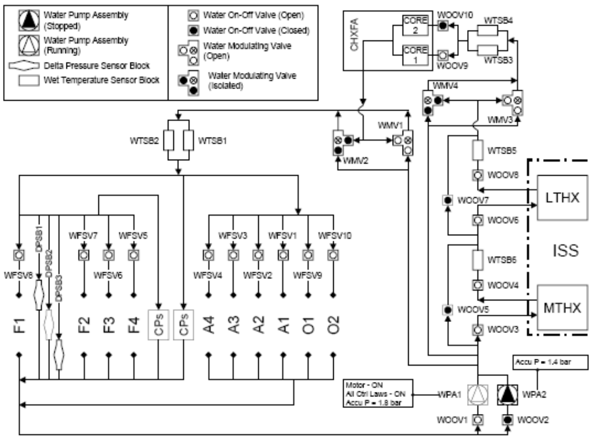
Thermal control overview
2. Water loop design architecture (1)

- Active Thermal Control data
  - Single-loop architecture
    - 22-kW heat rejection capability (14.5 kW from payloads)
  - Service to
    - 10 payload racks
    - 24 cold-plate mounted avionics boxes
    - 1 condensing heat exchanger
  - Components
    - Redundant water pumps
    - Redundant pair of three-way water modulating valves
    - Water on-off valves
    - Payload water flow selection valves
    - Wet temperature sensor blocks
    - Delta pressure sensor blocks
  - Operational boundaries and control set-points
    - Water from ISS in the range 1.1 to 6.1°C
    - CHX inlet temperature control at 5±1°C
    - Plenum inlet temperature control at 17±1°C
    - Plenum delta pressure control in the range 40 to 44 kPa
    - Operating WPA at 1.8±0.15 kPa



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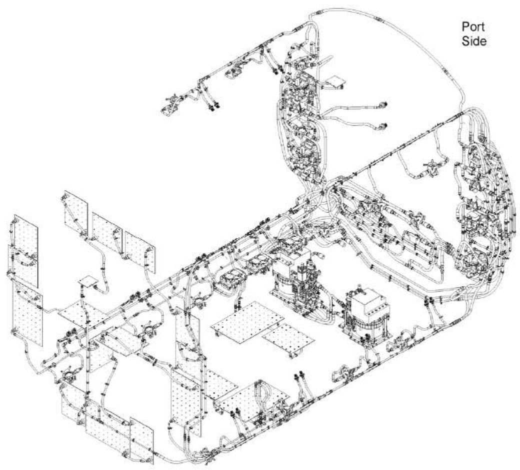
Thermal control overview
2. Water loop design architecture (2)

- Hardware configuration
  - Water lines
    - ¾" titanium hard lines for the main water lines
    - ½" titanium hard lines for the ISPR and cold plate branches
    - wire-braid restrained Teflon flex lines for ATCS equipment and payload rack connections
    - Low temperature section of ATCS, from the ISS to the three-way modulating valve after the CHX, insulated with Armaflex foam insulation to avoid condensation
  - Cold plates
    - 14 1.5 ATR cold plates (Spacelab heritage)
    - 5 Standard cold plates (Spacelab heritage)
    - 2 Allied Signal -4 cold plates
  - Connections
    - Standard hydraulic screw fittings between water lines and between water lines and cold plates
    - Quick Disconnects between water lines and ATCS equipment and payload racks
  - Volume
    - 208 litres with the maximum allowed payload volume of 80 litres
    - The F1E payload configuration has had a total volume of 120.5 litres



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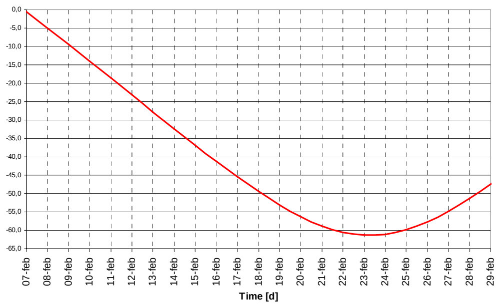
22 and 28 February operational configuration

- Internal configuration
  - No payload in operation except for FSL being activated on 22 February
- External configuration
  - SOLAR and EuTEF external payloads in commissioning phase



Rack Location	Facility	Sub Rack Facilities
A1	Not Used	N/A
A2	Biological Laboratory (BLB)	WAICO
A3	European Physiology Module (EPM)	MEEMM, CARDIOLAB, NASA-Drawer
A4	Not Used	N/A
F1	European Drawer Rack (EDR)	PCDF EU
F2	Not Used	N/A
F3	Not Used	N/A
F4	Not Used	N/A
O1	Fluid Science Laboratory (FSL)	Geoflow
O2	Not used	N/A
O3	Zero-g Stowage Rack	N/A
O4	Zero-g Stowage Rack	N/A
D4	European Transport Carrier (ETC)	N/A

EPF Location	Facility	Sub Facilities
SOZ	Solar Monitoring Observatory (SOLAR)	SOVIM, SOLSPEC, SOLACES
SOX	European Technology Exposure Facility (EuTEF)	DOSTEL,EXPOSE,DEBIE-2 , FIPEX, MEDET, PLEGPAY, TRIBOLAB, EuTEMP, EVC
SDX	Not used	
SDN	Not used	

- Thermal environment
  - ISS flying in +XVV Z-Nadir attitude
  - Beta angle around -60°, representing a hot case, with high starboard solar flux

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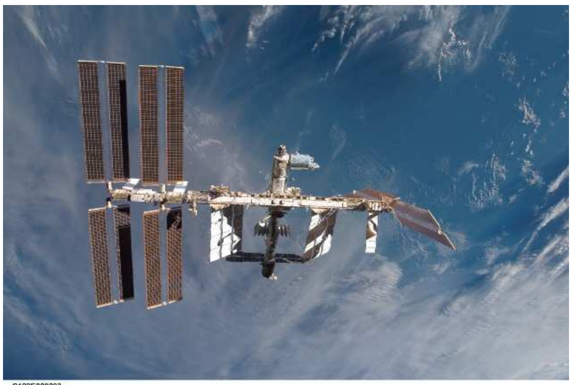
ISS and Columbus sun exposure

- The photo shows the ISS at the time of Space Shuttle Atlantis departure on 18 February 2008
- The ESARAD image shows a sun view of the ISS and the Columbus IOTMM on 22 February 2008



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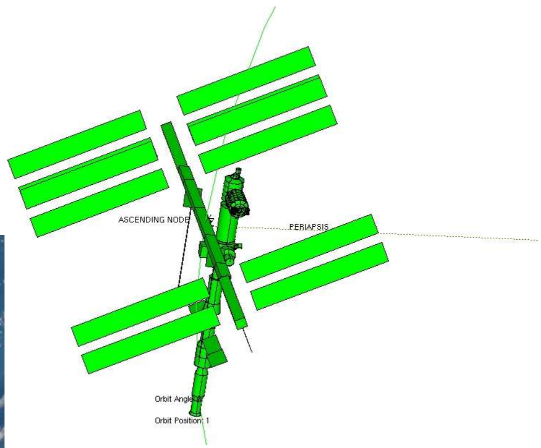

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Thermal modelling details

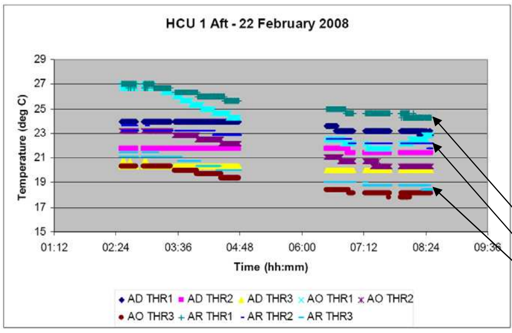
- The TASI ESATAN/FHTS modelling from 2004, which is available at ESTEC, forms the basis for the simulation. However, the ESARAD modeling has been augmented with a 2-D automatic sun orientation for pointing the solar panels to the sun and rotating the radiators out of the sun for each orbit position. The input has been adapted in order to correspond to the operating conditions on 22 February, with, in terms of geometry, two important exceptions
  - The Starboard SARJ is modelled as articulating and not fixed
  - The presence of SOLAR and EuTEF is not modelled
- The utilized thermal software and model sizes are
  - ESARAD 6.2.1 – 1232 basic shells
  - ESATAN 10.2 – 2606 thermal nodes
    - 9 level 1 submodels, 1 level 2 submodel
    - 1628 GL conductors
    - 87350 GR conductors
    - 49 GF conductors

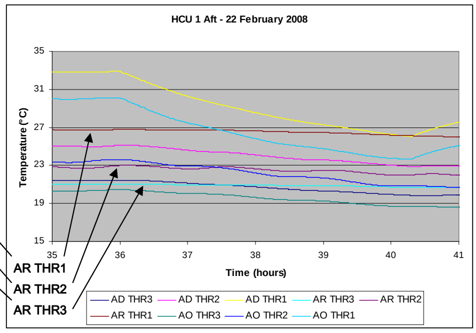
Comparison between shell heater on-orbit and analysis data 22 and 28 February HCU operations

- During the Launch-to-Activation (LTA) phase, with Columbus in the Space Shuttle cargo-bay, it had been noticed that power was drawn predominantly from APCU 1, powering HCU 1, which could be an indication of a problem on HCU 2. While it was found that the difference in part could be attributed to an off-set in the power telemetry, a characterization was still regarded as important.
- On 22 February, HCU 2 was switched off and HCU 1 was operating with a steady current draw of about 5 A. With the measured voltage it corresponds to about 600 W or 4 heater circuits. By shifting the HCU 1 temperature set-points to 18 and 20°C, the heaters were powered off and the Columbus shell started to cool down slowly.
- On 28 February, HCU 1 was switched off and HCU 2 was operating with a steady current draw of about 5 A and, similar to HCU 1 on 22 February, the HCU 2 temperature set-points were shifted to 18 and 20°C.

Comparison between shell heater on-orbit and analysis data 22 February results – Aft shell

- Thermistors with number 1 are on the starboard side, with number 2 are at the centre and with number 3 are on the port side. It is clear that the starboard thermistors are at a higher temperature and there is a rather significant temperature gradient in the axial direction. Considering how the heaters are distributed and the heater switching logic, it leads to heaters on the starboard side being powered together with heaters on the port side, due to the relative cool-down of the Port Cone.
- The simulation starts the power outage with the AR zone heaters switched off
- The on-orbit data indicate that the AD and FD zone heaters, are switched off





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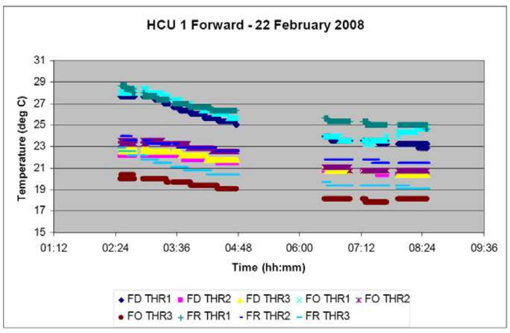
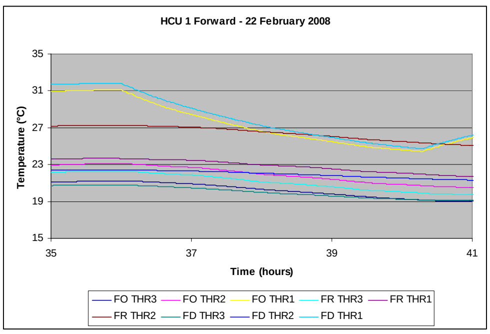
Comparison between shell heater on-orbit and analysis data 22 February results – Forward shell

- Not surprisingly, both aft and forward shell heater zones show the same behaviour and, with some variation, steady-state and transient behaviour is similar both for flight data and simulation results
- The maximum temperatures from the on-orbit data for the starboard cone are lower than for the simulation. The maximum on-orbit temperature gradient from starboard to port sides is 8°C (FO), while the simulation produces a maximum temperature gradient of 13.9°C (AD) on the shell (in steady-state)
- In the circumferential direction, the starboard cone on-orbit data show a maximum temperature gradient of 4.8°C (FR to AD) to be compared to 11.5°C (AD to FR) in the simulation results





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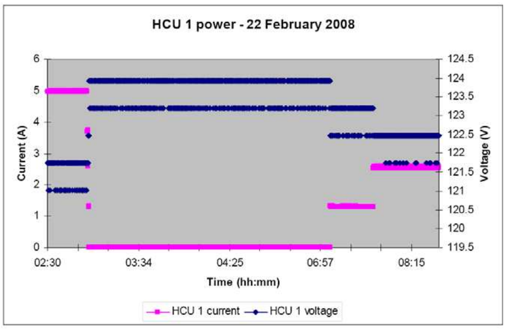
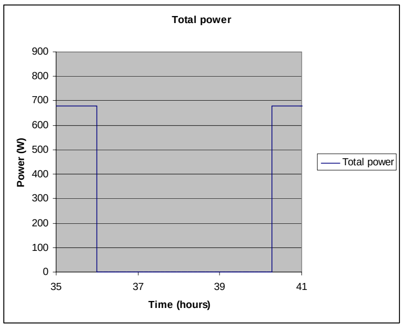
Comparison between shell heater on-orbit and analysis data
22 February results – Heater power consumption

- The simulation was performed completely cutting the power to the heaters, while the on-orbit operation was based on changing the temperature set-point. Consequently the on-orbit power data show a gradual increase in current draw from HCU 1, which also explains the difference in the transient temperature profiles in the two previous viewgraphs
- It has to be noted that the simulation is based on a fixed voltage of 116 VDC from the HCU 1 and the maximum resistance per heater. It translates to 136 W per circuit, to be compared to about 150 W per circuit with the measured values. The on-orbit data present voltage and current to the HCU 1 and the data are not corrected for internal losses





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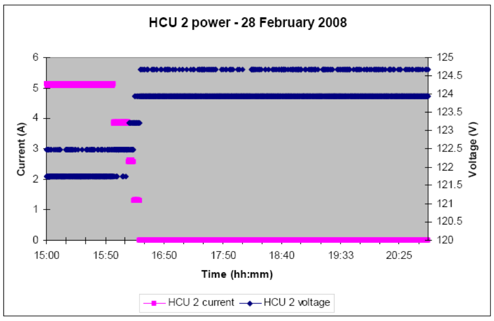
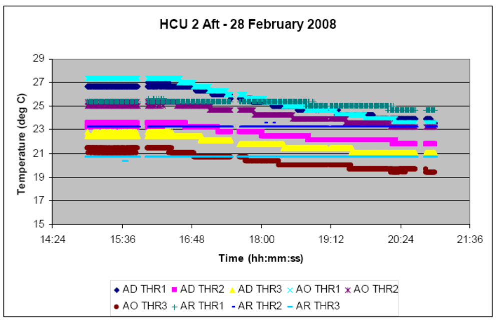
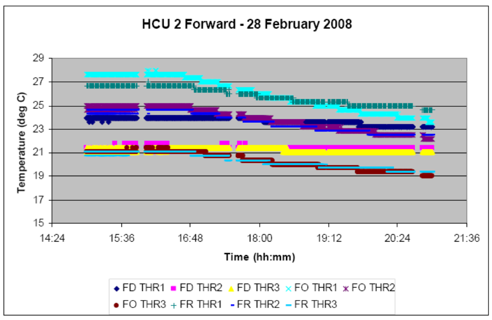
Comparison between shell heater on-orbit and analysis data
22 February versus 28 February results

- The results for HCU 2 on 28 February resemble very strongly the results for HCU 1 on 22 February. None of the thermistors reach the lower threshold of 18°C in the observed period
- The on-orbit data indicate that the AR and FD zone heaters, are switched off at the start of the cool-down transient
- FD THR2 and THR3 readings are very close
- Maximum gradients are 6.3°C (FO) in axial direction and 3.7°C in the circumferential direction (FO to FD)







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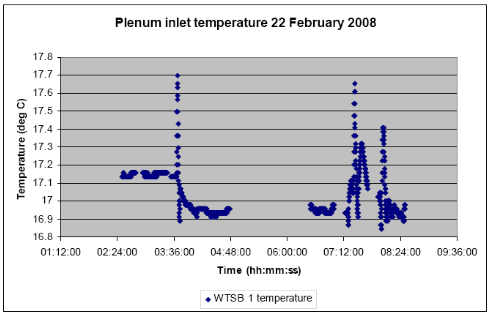
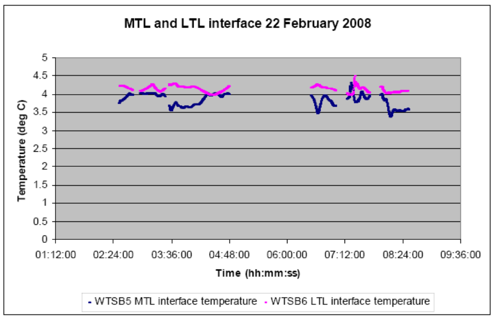
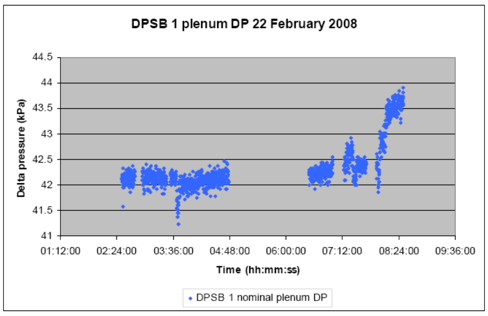
Comparison between water loop on-orbit and analysis data 22 February – ATCS performance

- The measured LTL interface temperature of 4°C has been used as input for the simulation
- The effect of the TCV kick operation is clearly shown in the on-orbit data for the DPSB 1 and WTSB 1. The TCV kick operation, every 1 ¼ hour, has to prevent condensate carry-over in the CHXFA. For high by-pass ratio, it moves the TCV to achieve 70% air flow through the active core
- The resulting higher water temperature produces a brief upset of the plenum inlet temperature







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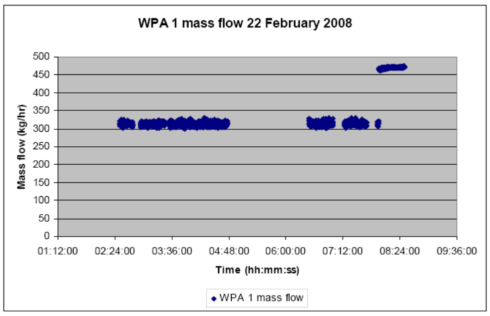
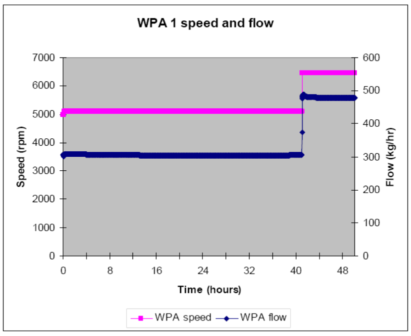
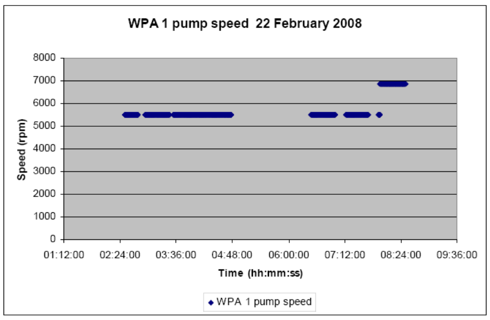
Comparison between water loop on-orbit and analysis data 22 February – Pump flow rate and speed

- The increase in flow rate and speed on 22 February is caused by the activation of FSL in ISPR location O1. FSL is calibrated for a flow rate of 170 kg/hr at 40 kPa
- From a comparison between the plot below and the plots to the right, it is obvious that the IOTMM is able to reproduce, with good fidelity, the on-orbit data
- The simulated pump speed is somewhat lower than the measured one, but that is fully in line with the finding during the IOTMM correlation







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Conclusions

- Generally the IOTMM results correlate well with the on-orbit data
- A significant longitudinal temperature gradient is created on the Columbus shell for negative beta angles due to the heater implementation
- Most likely the heater power consumption could be reduced by optimization of the heater control algorithm, e.g. by lowering the upper threshold to below 23°C or by using a scheme based on the average shell temperature to control the heaters. Further investigation would be needed, but there is limited overwrite capability of the HCU EPROM on-orbit
- The simulated water loop behaviour corresponds closely to what is observed during flight

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