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Abstract. The soft x-ray spectrometer (SXS) was a cryogenic high-resolution x-ray spectrometer onboard the Hitomi (ASTRO-H) satellite that achieved energy resolution of 5 eV at 6 keV, by operating the detector array at 50 mK using an adiabatic demagnetization refrigerator (ADR). The cooling chain from room temperature to the ADR heat sink was composed of two-stage Stirling cryocoolers, a ^{4}He Joule–Thomson cryocooler, and super-fluid liquid helium and was installed in a dewar. It was designed to achieve a helium lifetime of more than 3 years with a minimum of 30 L. The satellite was launched on February 17, 2016, and the SXS worked perfectly in orbit, until March 26 when the satellite lost its function. It was demonstrated that the heat load on the helium tank was about 0.7 mW, which would have satisfied the lifetime requirement. This paper describes the design, results of ground performance tests, prelaunch operations, and initial operation and performance in orbit of the flight dewar and the cryocoolers. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JATIS.4.1.011208]

Keywords: Hitomi; x-ray microcalorimeter; space cryogenics; superfluid liquid helium; Joule–Thomson cryocooler; Stirling cryocooler.

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1 Introduction

Hitomi, formerly known as ASTRO-H, was the sixth Japanese x-ray astronomy satellite and was developed under extensive international collaboration between Japan and the United States with European and Canadian participation.[1] The soft x-ray spectrometer (SXS)[2,3] was a cryogenic high-resolution x-ray spectrometer onboard Hitomi, utilizing an x-ray microcalorimeter array.[4] Operated at 50 mK, it was designed to achieve a resolving power of 1000 or larger at 6 keV. The detector array was cooled to 50 mK using a three-stage adiabatic demagnetization refrigerator (ADR).[5] The detector assembly (DA)[6] and the ADR composed a modular unit called a calorimeter spectrometer insert (CSI). The cooling chain from room temperature to the ADR heat sink consisted of two-stage Stirling-cycle (2ST) cryocoolers,[7] a ^{4}He Joule–Thomson (JT) cryocooler,[7] and superfluid liquid helium (LHe). The lifetime requirement for nominal operation was 3 years (when launched with a minimum of 30 L of LHe), and at least for 9 months in the case of failure of a single cryocooler. It was also designed to operate even when the LHe was depleted.[5,8] The CSI, the aperture assembly with optical/infrared blocking filters,[9] and control electronics for the ADR and the filter heaters were developed by NASA and the University of Wisconsin, and JAXA was responsible for the cooling system from room temperature to the ADR heat sink and cryocooler drive electronics, which were manufactured by Sumitomo Heavy Industries, Ltd. (SHI), with contribution by ESA.

Hitomi was launched on February 17, 2016. Although it became inoperative due to attitude control problems and subsequent loss of communication on March 26, the SXS cooling chain worked perfectly, the detector was cooled to 50 mK, and it achieved the energy resolution better than 5 eV at 5.9 keV (resolving power of about 1200) in orbit.[10,11] In this paper, we describe the design, pre- and postlaunch operations, and in-orbit performance of the cooling system from room temperature to the ADR heat sink.

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2 Design

In this section, the design of the SXS cooling system from room temperature to the ADR heat sink, which reflected many improvements resulting from the failure of the Suzaku x-ray spectrometer (XRS)[12] and lessons learned from it, is described. Details are described elsewhere.[13–15]

The requirements for the cooling chain from room temperature to the ADR heat sink were to provide a thermal bath below 1.3 K for the CSI with a lifetime over 3 years in the nominal case, and 9 months in a contingency case (failure of one cryocooler case). It was designed to satisfy these requirements utilizing ≥30 L LHe and minimizing a heat load on the helium tank (He tank) to <1 mW.[13] It adopted mechanical cryocoolers and a suspended structure to suppress parasitic heat loads on the He tank as well as to survive the launch load. A schematic thermal diagram and a cross sectional view of the dewar are shown in Fig. 1. The volume of the He tank was 39.5 L. The He tank was enclosed by four layers of vapor-cooled shields (VCS), the JT shield (JTS), the inner VCS (IVCS), the middle VCS (MVCS), and the outer VCS (OVCS). The OVCS, MVCS, and IVCS were enshrouded by 50 layers, 30 layers, and 20 layers of multilayer insulation films, respectively. The JTS was cooled by a ^{4}He JT cryocooler that used two 2ST cryocooler units as precoolers (PC-A and PC-B), whereas the IVCS and the OVCS were cooled by two 2ST cryocooler units called shield coolers (SC-A and SC-B). The JT cryocooler was equipped with two compressor units in series, that were called JT-CMP-L and JT-CMP-H. Therefore, there were six compressor units in total. And all of them were mounted on the vacuum vessel called the dewar main-shell (DMS). Note that microvibration due to the cryocoolers had been a concern from the detector

point of view, and it had turned out that the 2ST compressors degraded the detector performance during tests of the engineering model (EM) dewar. Therefore, the flight dewar was equipped with vibration isolators under the four 2ST compressors.[16] The 2ST cold head (displacer) is equipped with a balancer to reduce vibration of the displacer at the drive frequency, but it did not change the detector noise, and hence, it was decided not to use the capability. The He tank was suspended from the IVCS using 12 straps made of carbon fiber reinforced plastics while the IVCS was suspended from the DMS using 12 straps made of glass FRP. Including a reflecting enclosure around the DMS and a contamination baffle on top it, it was 1.8 m tall and 1.4 m wide at the maximum, and the total mass was 299 kg including LHe. Note that this number does not include the mass of the cryocooler drive electronics (46 kg in total). The shield cooler driver (SCD) was 16.5 kg, the precooler driver (PCD) was 15.0 kg, and the JT cooler driver (JTD) was 14.5 kg.

The He tank was connected to the outside of the dewar through a He fill line and a He vent line. To confine superfluid LHe in orbit, a porous plug phase separator was installed at the vent port of the He tank, and a film-flow suppression system was also introduced to minimize the effect of film-flow loss.[17] One aspect of satisfying the lifetime requirement was to ensure that the total accumulation of He gas in the dewar's guard vacuum would not exceed 16 μg over the lifetime.[13,14] To ensure that He gas venting from the He tank could not re-enter the guard vacuum, the SXS dewar was equipped with a dedicated He vent pipe that ducted the gas outside the spacecraft (S/C). The DMS had a vent valve to connect the guard vacuum to space, but there was no plan to open it in orbit unless there was evidence of
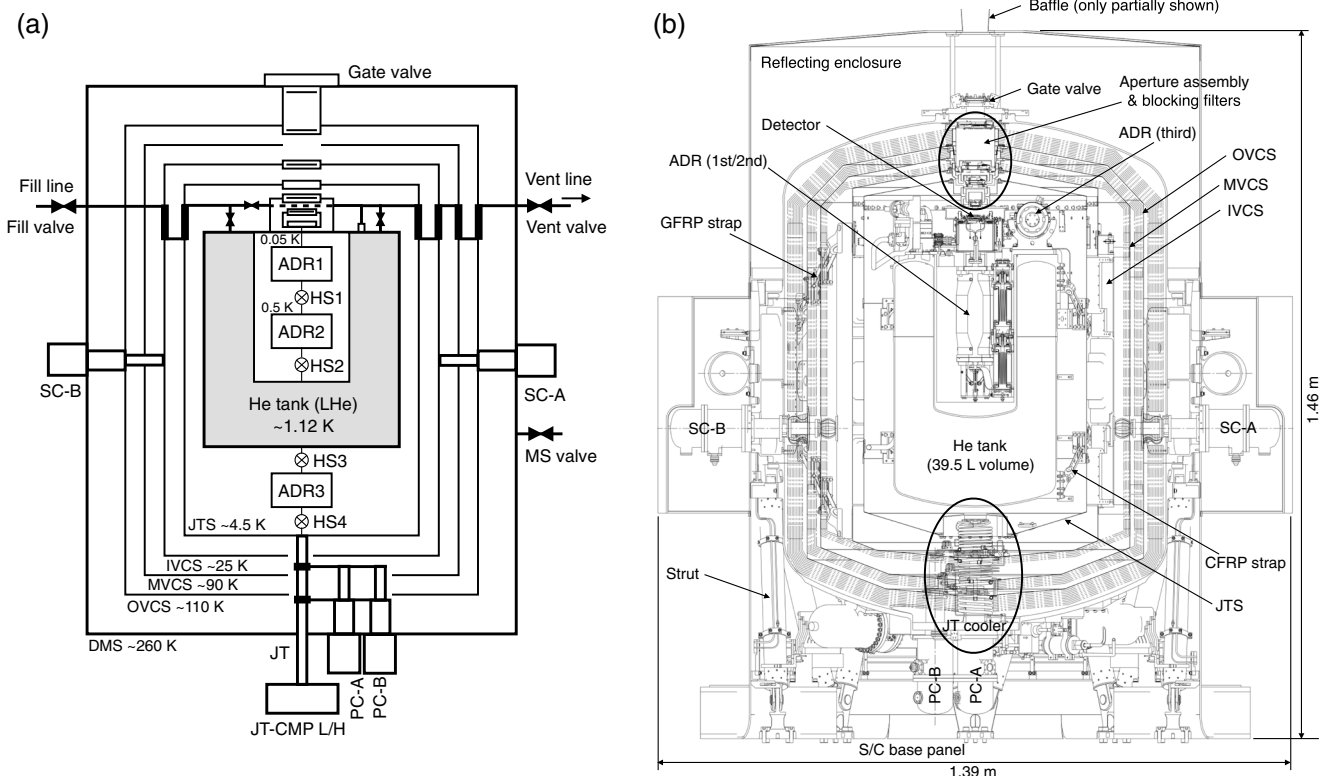

Fig. 1 (a) Conceptual diagram of the SXS cooling system. (b) Cross sectional view of the SXS dewar.

helium contamination affecting components (e.g., the detectors or ADR) in the vacuum space. In such case, the main-shell vent pipe would prevent He backflow even when the DMS vent valve was opened. There was also a charcoal getter in the guard vacuum that could maintain extremely low pressure even if some helium gas was introduced.

At the top of the dewar was a gate valve that provided a vacuum seal to the DMS on the ground, which would be opened on orbit to provide an unobstructed path between the detectors and the x-ray telescope. It was equipped with a beryllium window for ground tests. The gate valve was planned to be opened ≥40 days after the deployment of the extensible optical bench, to make contamination on the DMS filter ≤9 μg cm^{-2} over 5 years. Note that the temperature of the DMS filter was to be controlled at 320 K when and after the gate valve was open. Even after the aperture gate valve was opened, the dewar would be still sealed at the outermost filter (DMS filter). A miniature solenoid valve was installed between the guard vacuum and the space between the gate valve and the DMS filter, to avoid pressure difference over the thin filter when the gate valve was closed.

The internal thermal design assumed that the average external dewar surface temperature was ≤290 K as a boundary condition. On the other hand, the nominal heat dissipation at the cryocoolers was 300 W, which breaks down into 51 W at SC-A, SC-B, PC-A, and PC-B, respectively, and 96 W at JT. Corresponding power consumption at the cryocooler driver units is about 484 W (SCD 163 W, PCD 175 W, and JTD 146 W), not including the ADR controller power consumption at the cryocooler. All the compressors needed to be operated below 40°C. Since they were mounted on the DMS, heat rejection from the cryocoolers was critical. To exhaust heat, the DMS surface was used as a radiator. In addition, the spacecraft system provided two dedicated radiator panels (3 m × 1 m × 2) with two heat sinks on the base panel. To use the DMS surface as a radiator efficiently, the dewar had a reflecting enclosure around it, with one side open to space. The PC-B compressor and one of the two JT compressors (JT-CMP-L) had a direct conduction path to the system heat sinks, since they were located close to them. The PC-A compressor and the other JT compressor (JT-CMP-H) were relatively well exposed to space, hence they only had a conduction path to the DMS. On the other hand, SC-A and SC-B were not well exposed and were located far from the system heat sinks. Therefore, four loop heat pipes (LHPs) were adopted, which were provided by ESA.

3 Performance Verification on Ground

Assembly of the flight dewar was completed in September 2014. The dewar was tested in an SHI's facility in Niihama in October and November 2014. Then, it was shipped to JAXA's Tsukuba Space Center (TKSC) and was tested there from December 2014 to March 2015. This included the dewar-level vibration tests. It was mounted on the spacecraft on April 1, 2015. The system integration and test continued until November 2015. After the test was completed, the spacecraft was shipped to JAXA's Tanegashima Space Center (TNSC) in December 2015.

The heat load on the He tank was measured during the dewar-level test in October 2014, in both the nominal cryocooler case and failed cases. With nominal cryocooler operation and without ADR operation, the measured heat load to the He tank was 0.62 mW, and the thermal calculation predicted

0.64 mW.[15] Discrepancies of the shield temperatures were 10% or less, and it was concluded that the dewar thermal performance was verified. The predicted heat load in orbit including the expected contribution from ADR cycling was 0.75 mW with the beginning-of-life performance of the cryocoolers, and 1.00 mW with the end-of-life performance of the cryocoolers. Assuming 30 L as the initial amount of LHe, the predicted lifetime of LHe in orbit was 3.0 to 3.9 years, which would meet the requirement.

The external thermal design was verified during the system thermal-vacuum test held in June to July 2015.[18] The dewar and the cryocoolers satisfied the temperature requirements in the four tested cases. The thermal mathematical model was correlated with the test results, where the temperatures were consistent within 5°C. The thermal conductance of the thermal links was consistent with the component test results. It was demonstrated that the PC-A compressor temperature could be decreased by changing the operating power of PC-A/B from 50 W/50 W to 40 W/60 W, whereas the cooling performance was unchanged, which provided some flexibility in operating the precoolers. The flight thermal analysis was performed using the correlated thermal mathematical model, and it was verified that the temperature requirements were satisfied.

Note that the ADR operation and the detector operation were verified both in cryogen[19] and cryogen-free operating modes.[8,19] Using the EM dewar, it was also demonstrated that the He tank could be cooled down from room temperature to 4.5 K only with the cryocoolers and without using LHe.[20] It took about 40 days, confirming that even if the cryocoolers needed to be shut down after depletion of the LHe on orbit, it is possible to restart the cryocoolers and resume detector operation.

4 Prelaunch Operation

Since SXS utilized LHe, the prelaunch operations in the vehicle assembly building (VAB) and the launch pad (LP) of TNSC involved a final cooldown, a top-off, and conditioning to ensure it remained below a certain temperature at the time of launch.

To make the porous plug phase separator work properly in orbit, the LHe temperature needed to be kept below the lambda point (2.17 K) in orbit. To achieve this, the He tank temperature was required to be 1.7 K or lower when the vent valve was opened, considering uncertainty of the transient thermal analysis of the LHe temperature after the launch.[21] The final judgment needed to be done when the temperature monitoring was stopped 40 min before the launch, and the temperature limit was set at 1.68 K at that time. Since the countdown sequence is very critical, we set the initial condition to start the countdown sequence as the He tank temperature ≤1.35 K, the JTS temperature ≤5 K, the IVCS temperature <31 K, and the amount of LHe ≥33 L, considering the requirement (30 L at ≤1.3 K in orbit) and the results of the ground test.[15] There were several go/no go decision points related with the countdown sequence operations, and we also defined the upper-limit temperatures at these points considering the expected temperature rise when we followed the nominal sequence, so we can immediately detect anomalies of the dewar. During the conditioning phase, on the other hand, there were rocket activities that required occasionally powering off the cryocoolers, pumps, and other ground support equipment (GSE), for safety reasons. In addition, unexpected events such as lightning could also require powering off the cryocoolers, making it very important to have a detailed
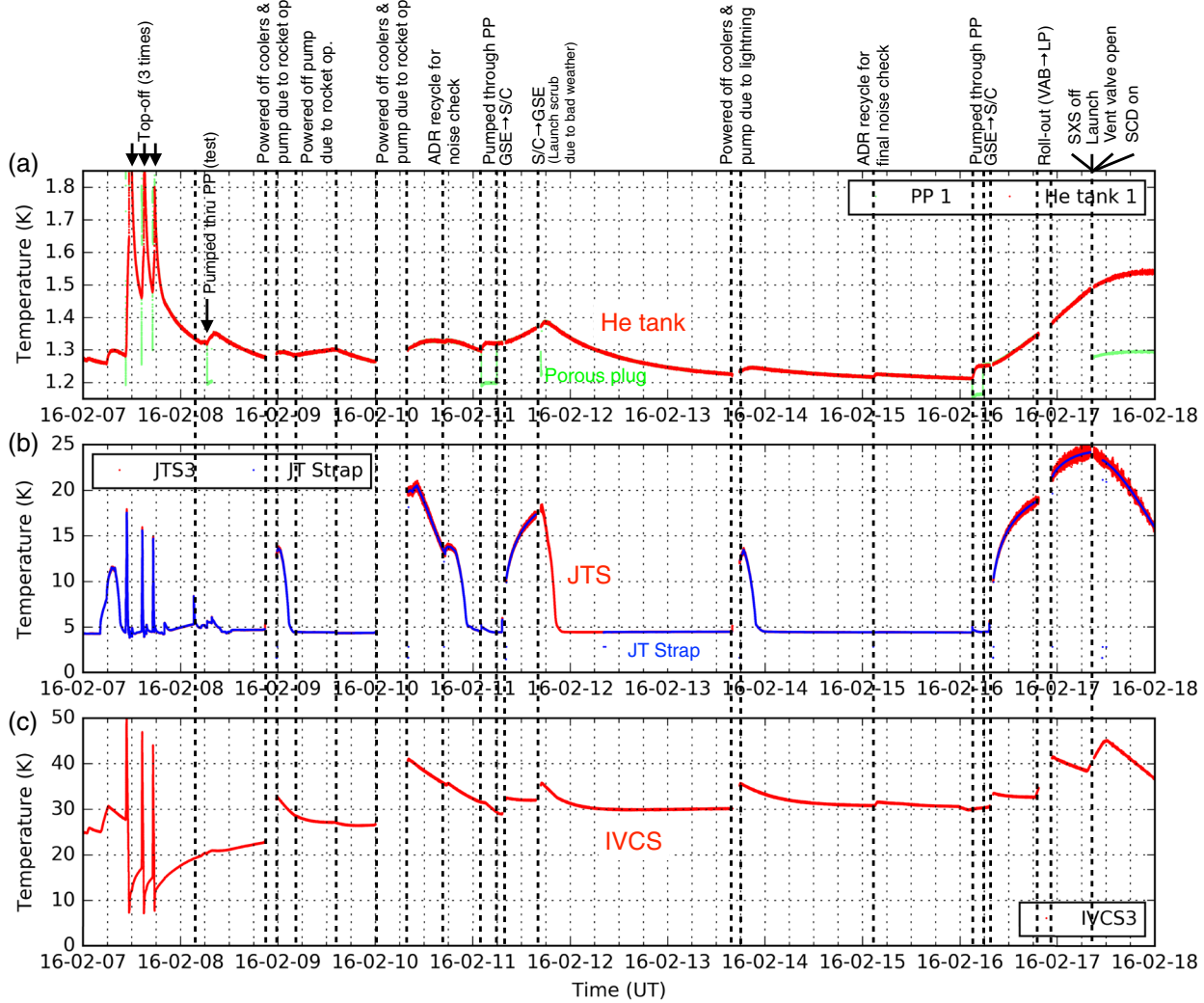
Fig. 2 Temperature profiles during the operation at VAB and LP. (a) He tank and porous plug (PP). (b) JTS, which was cooled by the JT cryocooler. (c) IVCS, which was cooled by the 2ST shield coolers.

operation plan of the SXS at VAB and LP that was coordinated with facility staff and to conduct full simulations of the prelaunch operations. These and many partial tests were performed in October 2014[15] and during the system test phase at TKSC.

The spacecraft covered with a fairing was installed on top of the H2A rocket No. 30 on January 30, 2016, at the VAB. On February 4 to 6, we conducted the final cool down. It was started from room temperature so any contamination previously accumulated on the filters inside the dewar could be evacuated before cooling. The temperature history starting from February 7 is shown in Fig. 2. On February 7 and 8, we conducted the low-temperature helium top-off, which involved three successive transfers to fill the He tank with liquid just above the lambda point (2.17 K) and then cool by pumping. After the third transfer, the liquid temperature was 1.8 K.

After the top-off operation, we continued pumping to cool down the LHe temperature. During the pumping, there were two critical rocket operations that required us to turn off the pump and the cryocoolers, once for about 3 h on February 9, and once for about 6 h on February 10. As shown in Fig. 2, the shield temperatures increased in these periods, as expected

from the simulation of the prelaunch operations. On February 11, the countdown operation was started, which caused another temperature rise of the He tank and the shields. However, the launch was scrubbed due to bad weather. After that we continued pumping, waiting for good weather, until February 16. We once had to turn off all the cryocoolers and GSE for about 1 h due to lightning, but except for that, the operation was smooth, and the He tank temperature was reduced to 1.25 K, when the countdown sequence was restarted on February 16.

Figure 3 shows the profile of the He tank temperature during the countdown sequence, as well as the hard-limit on the He tank temperature to hold the launch. As described in the previous paragraph, the He tank temperature was low enough when we started the countdown sequence on February 16, and the amount of liquid when we closed the vent valve, determined using the liquid level detector and gas flow meter measurements, was 35.6 to 37.6 L, depending on which data were used. There were almost no unexpected events during the countdown sequence. The He tank temperature (He tank 1) was 1.487 K when we turned off the SXS components and stopped temperature monitoring, 40 min before the life-off.
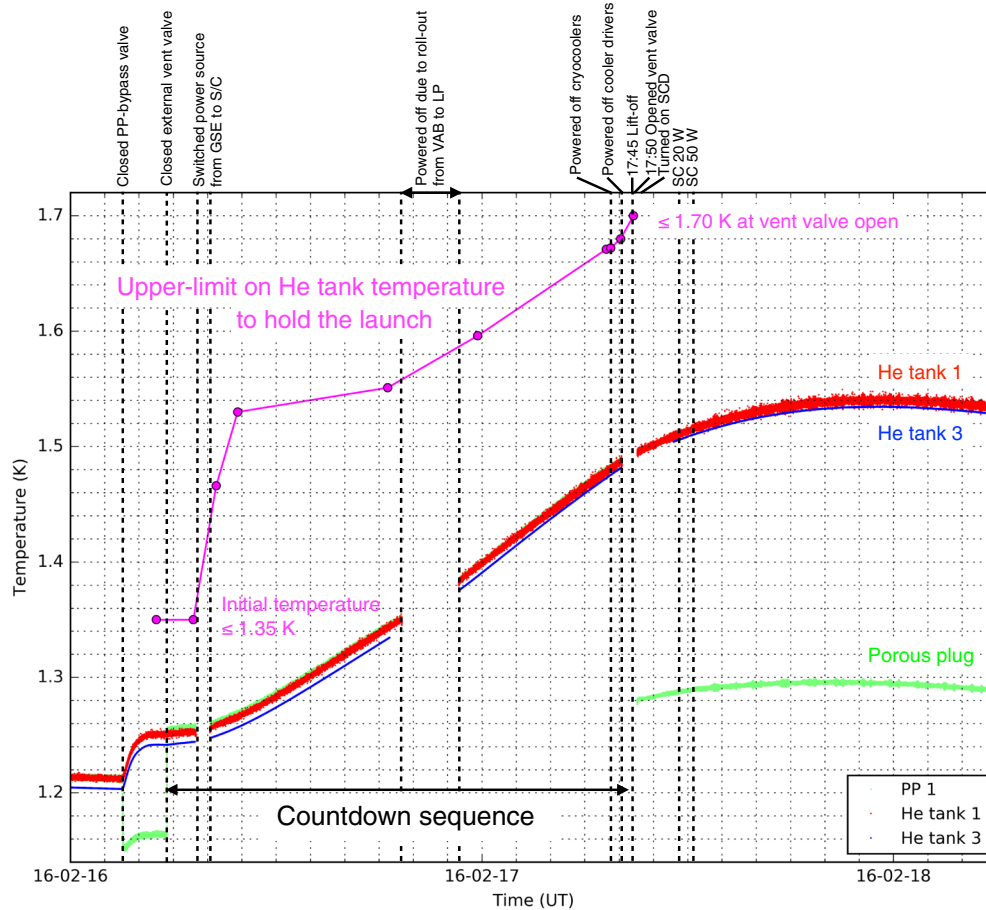
Fig. 3 Temperature profile of the He tank and the porous plug, during the countdown sequence and just after the lift-off. The upper limit on the He tank temperature to hold the launch is also shown.

5 In-Orbit Operation and Performance

Figure 4 shows the internal and external temperatures of the dewar during the initial 5 days. Hitomi was launched on February 17, 2016, 8:45 (UT). At 8:50, when the rocket was still accelerating, the He vent valve was opened, to start He venting through the porous plug. At 9:04, the SCD was turned on to start temperature monitoring, and the He fill valve was opened to vent the He fill line. The temperature of the He tank was 1.495 K, and the porous plug temperature was 1.281 K. It was verified that there was about 0.21 K temperature drop at the porous plug, which indicated the porous plug was operating properly and He was venting. Note that no significant temperature jump was seen during the launch, which indicated that any effect of sloshing was very small. The 1σ upper limit of the temperature jump was ~0.4 mK and the corresponding upper limit of the heat input was ~2 J, by filtering and linearly extrapolating the He tank temperature of the last 10 min before the launch and the initial 10 min after the launch.

At 10:30, during the contact at JAXA's Uchinoura station, the PCD and the JTD were turned on. At 11:17, during the contact at Santiago, we started operations of SC and PC at low voltages. At 12:15, during the second Uchinoura contact, the SC power was set at the nominal number (50 W × 2). The LHPs were also started, and temperature of the SC compressors started decreasing. Note that the LHPs for the SC cold heads stopped automatically because of small heat loads. This was expected, when they were operated with the nominal power. On February

18, the PCs were set at the nominal power, and the operation of the JT started. After the PCs were turned on, the PC-A and PC-B compressor temperatures increased to ~300 and ~282 K, respectively. The difference was due to the difference of the thermal paths from these compressors, as shown in Sec. 2. The DMS temperature also increased slightly, and the final temperature was ~260 K. The voltage of the JT cryocooler was increased gradually, and the JTS temperature reached 4.5 K on February 21. Note that oscillations seen in the DMS and compressor temperatures were caused by orbital motion of the spacecraft.

Figure 5 shows the internal and external temperatures of the dewar until the last telemetry on March 26. The ADR checkout was conducted on February 20, and the first recycle was carried out on February 21. After that, ADR recycles were performed periodically to keep the detector temperature at 50 mK. The He tank temperature was slowly decreasing and reached ~1.12 K at the end. On March 14, the PC-A power was decreased to about 40 W. As a result, PC-A compressor temperature decreased to 294 K. On March 15 and 24, the JT powers were slightly increased to keep the JTS temperature unchanged. As of March 25, heat dissipation of the cryocoolers was 203 W (46.4 W at SC-A, 48.7 W at SC-B, 42.3 W at PC-A, 50.7 W at PC-B, and 15.3 W at JT). The total power consumption at the cooler drivers was 359 W (SCD 157 W, PCD 158 W, and JTD 44 W).

Thermal analysis was conducted using the DMS temperature of 260.8 K and the He tank temperature of 1.12 K as boundary
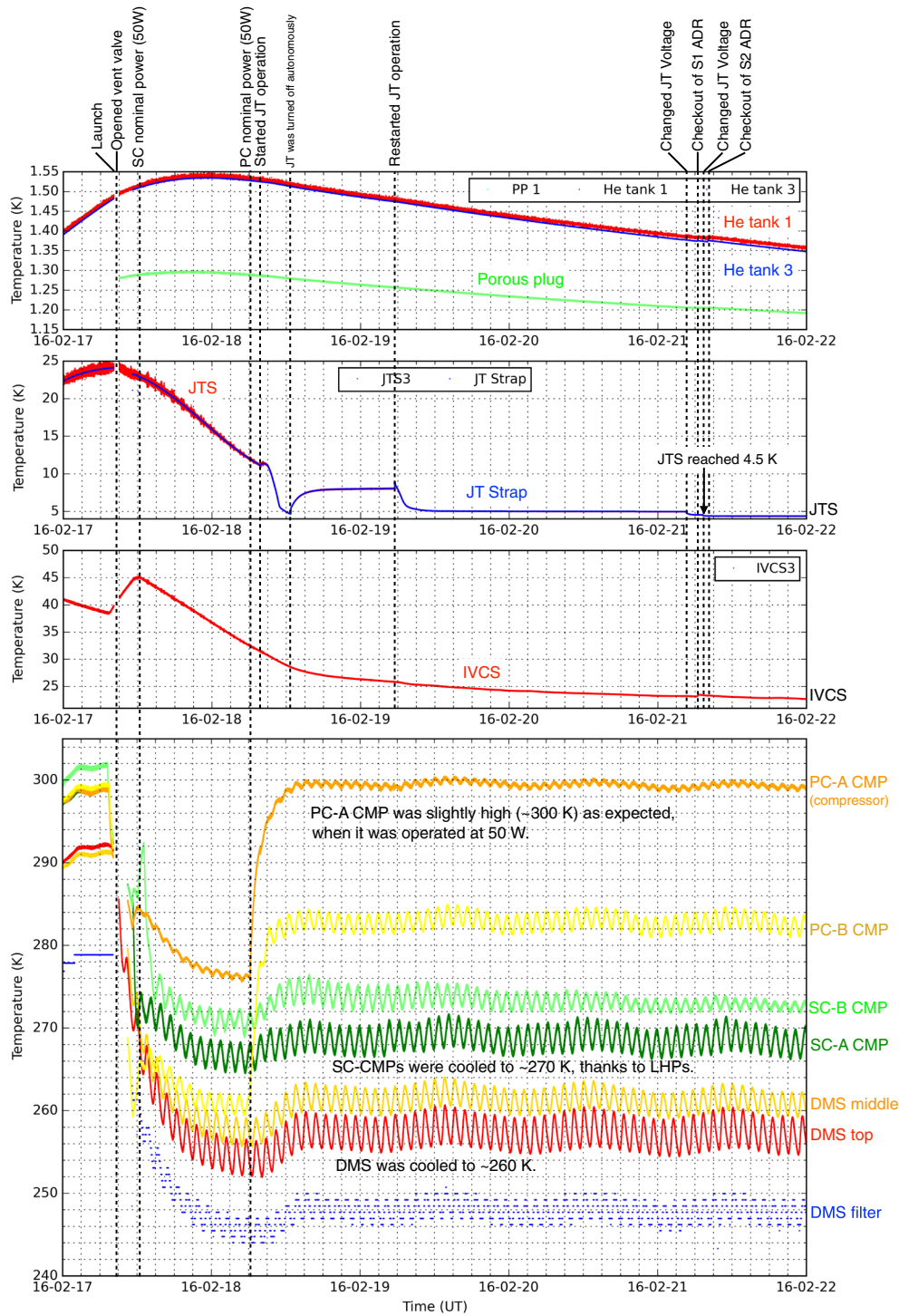
Fig. 4 Initial temperature profiles of the SXS dewar in orbit (He tank, JTS, IVCS, and external temperatures). Note that the JTS was cooled by the JT cryocooler, while the IVCS was cooled by two units of 2ST shield coolers.

conditions. Average heat loads of ADR were used, which were measured in orbit.[5] For the analysis, heat loads from the DA and the third stage of the ADR, including conduction through mounting structure and through heat-switches 3 and 4, were those estimated from ground tests. The resultant heat flow diagram is shown in Fig. 6. Since the JTS temperature was determined by the JT cryocooler, and its power was adjusted to achieve similar temperatures to those seen during the ground tests, the heat load from the JTS was basically unchanged. On the other hand, heat load of the ADR decreased significantly, because the hold time increased as the He tank temperature decreased and the average heat load decreased. The IVCS temperature decreased because the DMS temperature decreased while the cooler operation power was unchanged. This led to a decrease of the heat load of the DA, which was electrically connected to the IVCS via the JFET boards. As a result, the
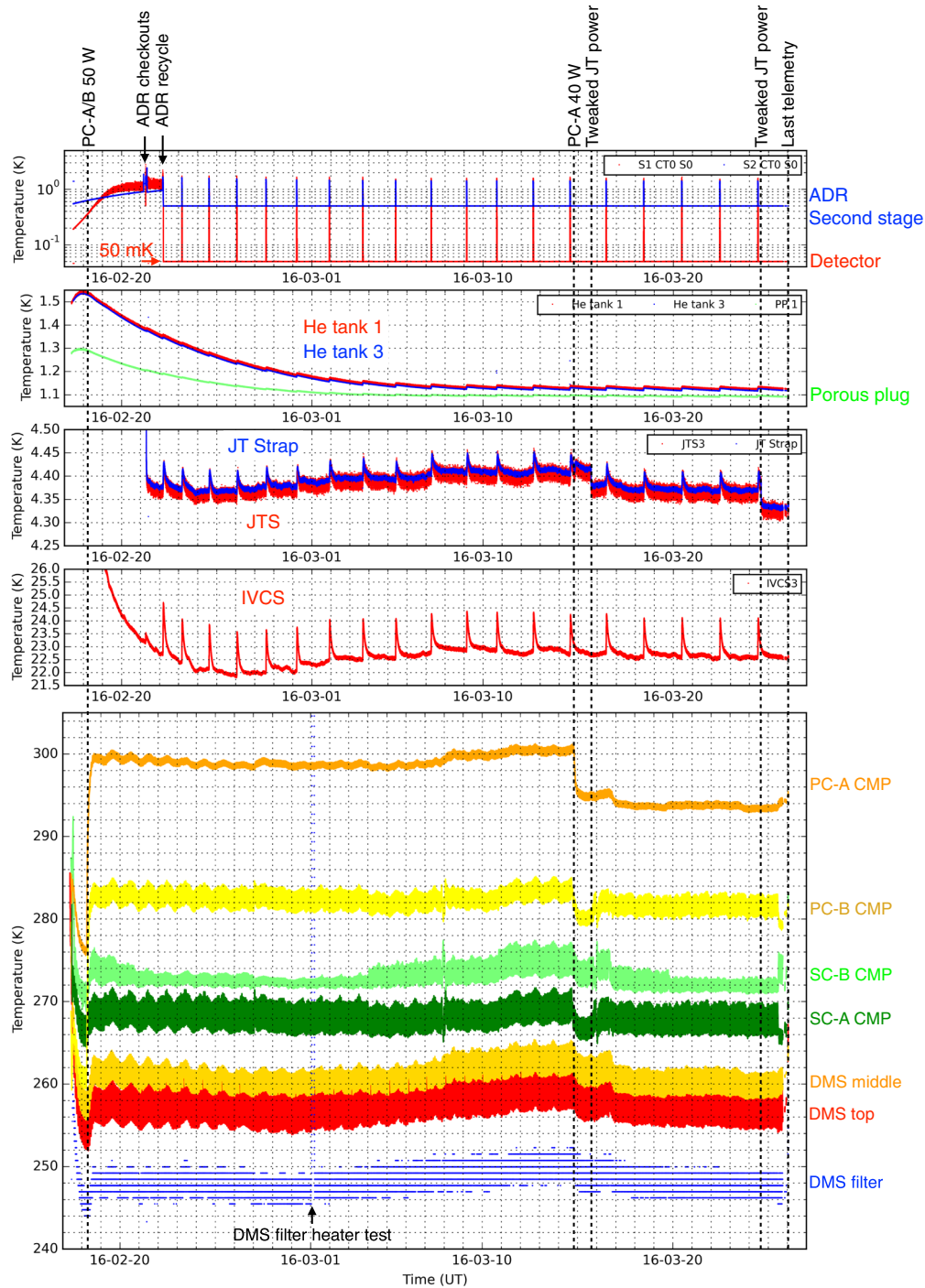
Fig. 5 Temperature profiles of the SXS dewar in orbit (He tank, JTS, IVCS, and external temperatures), from February 17, 2016, to March 26, 2016. Note that a heater to warm the DMS filter was tested on March 1, and a temperature rise of the DMS filter is seen.

predicted total heat load decreased to 0.655 mW from the prelaunch prediction of 0.75 mW.[15] Note that the predicted IVCS temperature was lower than the measured by 0.6 K. The JTS shield temperature was also slightly underestimated, and the actual He tank temperature was still slightly decreasing on average. The total heat load could be underestimated by 0.026 mW. On the other hand, the mass flow rate estimated from the porous plug temperature and the He tank temperature was about 34 to 35 μg s^{-1} and the corresponding heat load on the He tank was 0.70 to 0.72 mW.[17,21] The predicted and the measured were consistent within 10%. The mass loss rate indicated from the ADR mass gauging was about 0.024 L day^{-1} or 0.83 mW,[5] and in this case, the difference was ≤20%. Note that the He tank was equipped with a mass gauge heater to measure the amount of LHe. However, the external harness of the mass gauge heater picked up noise, and it was grounded at the dewar external connector. Instead, we used temperature increase during ADR recycle to estimate the amount of LHe. See Ref. 5. In either
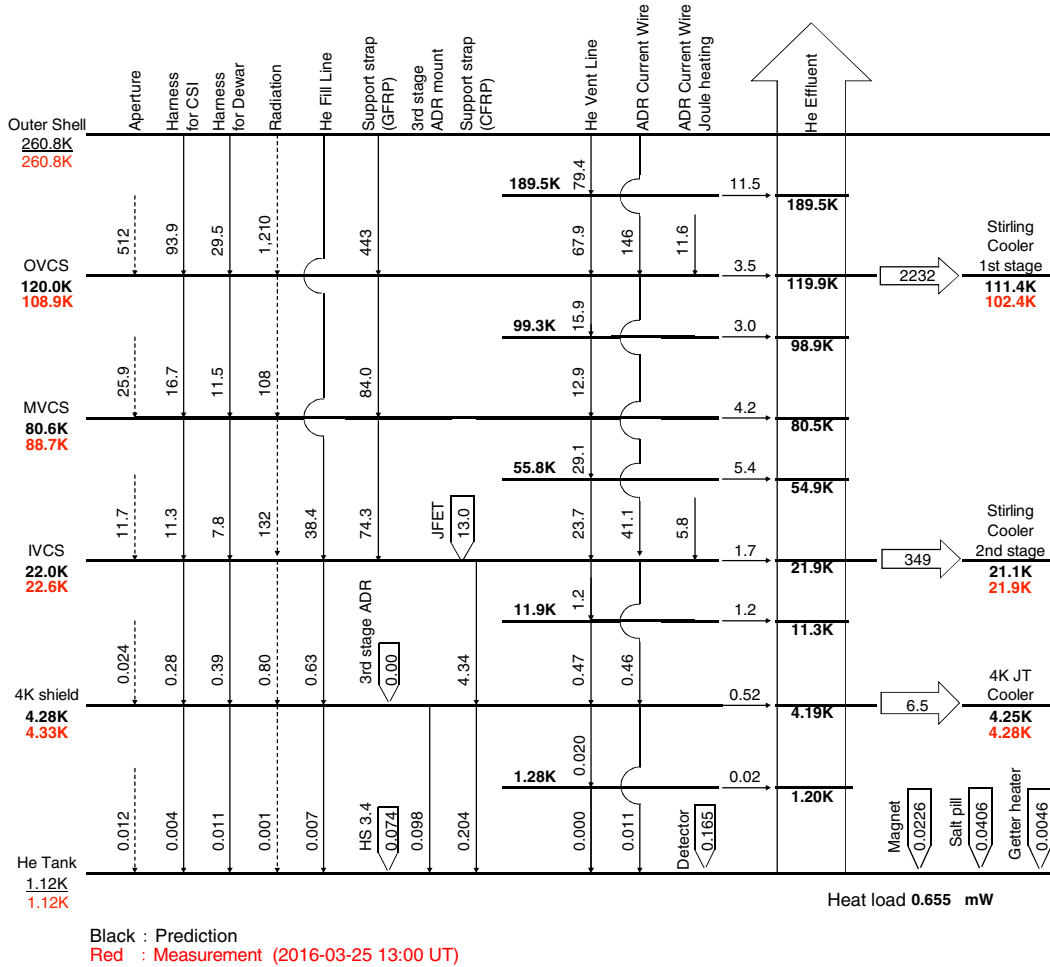
Fig. 6 Heat flow diagram in orbit.

case, the lifetime requirement (3 years) would have been satisfied, even if degradation of the cryocoolers is considered.

6 Summary

The design, ground performance tests, prelaunch operations, in-orbit operation, and performance of the SXS cooling system from room temperature to the ADR heat sink have been described. The SXS cryogenic system, with a minimum of 30 L carried to orbit, was designed to achieve more than 3 years lifetime in orbit in the nominal case and over 9 months even in a contingency case of one cryocooler failure. Cryogen-free operation was also possible from room temperature to 50 mK in case the LHe was depleted. It adopted ≥30 L LHe and was equipped with 2ST and JT cryocoolers to suppress heat load on the He tank and to support cryogen-free operation of the ADR as needed. Its performance was verified during the ground tests of the dewar and the spacecraft system, from October 2014 to November 2015. After the postshipment test at Tanegashima in December 2015, the spacecraft was mounted on the H2A rocket. In February 2016, prelaunch activities involved a cool-down from room temperature, low temperature He top-off, and pump down to condition the liquid. The countdown sequence went smoothly. The He temperature at launch was slightly below 1.49 K. The rocket was successfully launched on February 17, 2016. He venting started properly and all the cryocoolers were operated without any problem.

The detector was cooled to 50 mK and the energy resolution of 4.9 eV was achieved,[11] which satisfied the requirement, and several astronomical objects were observed with this unprecedented resolution. The heat load estimated by thermal analysis was 0.66 mW. This was consistent with the number estimated from the porous plug temperature within 10%, and the lifetime requirement of 3 years would have been satisfied even if degradation of the cryocoolers was considered. Very unfortunately, the spacecraft lost its function on March 26, 2016 before we opened the aperture gate valve. Nonetheless, the on-orbit operation successfully demonstrated the design of the SXS cooling system, which reflected many improvements resulting from the failure of the Suzaku XRS design and lessons learned from it. It serves as a model for future flight cooling systems for x-ray microcalorimeters, with and without cryogen.

Disclosures

Acknowledgments

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