

# Lifetime Test and Heritage On-Orbit of SHI Coolers for Space Use

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## ABSTRACT

Since 1987, Sumitomo Heavy Industries, Ltd. (SHI) has developed small Stirling coolers of two types and two Joule–Thomson (JT) coolers with operating temperatures ranging from 80 K to 1 K for space use. Ground lifetime tests of four coolers were conducted to demonstrate their long life and reliability. A single-stage Stirling cooler was tested for 113,640 hr. Two single-stage Stirling coolers were tested for 108,370 and 104,771 hr. Also, a two-stage Stirling cooler was tested for 72,906 hr. An advanced 4 K cooler with <sup>4</sup>He was tested for over 36,140 hr. Also, a 1 K-class cooler with <sup>3</sup>He was tested for 6721 hr from last year. All of these coolers, except for the 1 K-class cooler, have shown good results on orbit. Three single-stage Stirling coolers were carried on the “SUZAKU” X-ray astronomical satellite, the “KAGUYA” Japanese lunar polar orbiter, and the “AKATSUKI” Japanese Venus Climate Orbiter. Two units of a two-stage Stirling cooler were carried on the “AKARI” infrared astronomical satellite. Moreover, a 4 K cooler was carried on the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) aboard the Japanese Experiment Module (JEM) of the International Space Station (ISS). A Japanese X-ray astronomy satellite “ASTRO-H (Hitomi)” including a 4 K cooler, two sets of two-stage Stirling coolers, and two sets of single-stage coolers was launched on February 17, 2016. This report describes the updated results and operating status from an earlier report<sup>1</sup> of ground lifetime testing and achievements on orbit of SHI coolers for space use.

## INTRODUCTION

Since 1987, Sumitomo Heavy Industries, Ltd. has been developing small cryocoolers of four types for space use, with temperatures ranging from 80 K to 1 K. The single-stage Stirling cooler used for cooling to temperatures of 80 K was developed in 1987 for low-noise amplifier cooling in space by modifying a commercial cooler. Subsequently, its development has continued for space use.<sup>2</sup> In all, five coolers were loaded on SUZAKU, KAGUYA, AKATSUKI, and ASTRO-H for cooling detectors, thermal shields, etc. The first, SUZAKU, which launched in July 2005, is the fifth in a series of Japanese astronomy satellites designed for observations of celestial X-ray sources. A

single-stage Stirling cooler cools an outer vapor cooled shield to extend the observation lifetime. The second, KAGUYA, a Japanese lunar polar orbiter, was launched in July 2007. The gamma-ray spectrometer (GRS) in KAGUYA uses a 250 cc high-purity germanium (Ge) detector cooled to 80 K by a single-stage Stirling cooler. The third, AKATSUKI, is a Japanese Venus Climate Orbiter launched in July 2010. After five years, it entered an elliptical orbit around Venus on December 9, 2015. The mid-wave infrared camera (IR2: 2- $\mu$ m camera) of AKATSUKI uses a CCD camera cooled to around 65 K by a single-stage Stirling cooler. The fourth, ASTRO-H, is the sixth in a series of Japanese astronomy satellites devoted to observations of celestial X-ray sources. It was launched into low earth orbit with an altitude of 550 km on February 17, 2016. The CCD camera in a Soft X-ray Imager (SXI) of ASTRO-H is cooled to around 150 K by two reduced vibration models of single-stage Stirling coolers.

A two-stage Stirling cooler for space application with temperatures below 20 K began development for AKARI in 1991.<sup>3</sup> AKARI, the second infrared astronomy mission of the JAXA/ISAS, was launched into a sun-synchronous polar orbit at an altitude of 750 km for an infrared sky survey in February 2006. Two units of the cooler were used to cool the inner vapor cooled shield and extend the lifetime of the liquid helium of AKARI.

A 4 K cooler, which is a combination of a two-stage Stirling cooler and a JT cooler with <sup>4</sup>He, began development in 1993 to cool the submillimeter detectors for the SMILES mission.<sup>4</sup> SMILES, which was launched in September 2009, was aimed at highly sensitive observations probing chemical processes related to ozone depletion and used submillimeter technologies such as superconductor–insulator–superconductor (SIS) mixers and the 4 K mechanical coolers.

The soft X-ray spectrometer (SXS) of ASTRO-H is a high-resolution spectrometer using an X-ray microcalorimeter array. To achieve high energy resolution of 7 eV at 0.5–10 keV, the detectors must be kept extremely cold (50 mK), requiring a complex cryogenic system that includes a three-stage adiabatic demagnetization refrigerator (ADR), liquid helium (30 L), two sets of advanced two-stage Stirling coolers and an advanced 4 K-class cooler.<sup>5, 6, 7</sup>

The 1 K-class coolers with <sup>3</sup>He were developed, starting in 2001, for the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission.<sup>8</sup> Lifetime testing started this past year.<sup>9</sup>

## HIGH-LEVEL DESCRIPTION OF COOLERS

### Single-Stage Stirling cooler

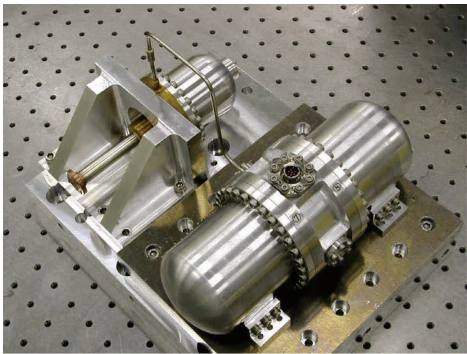
For cooling at 80 K temperature levels, SHI has a split type single-stage Stirling cooler with the specifications shown in Table 1. A photograph of the original cooler is presented in Figure 1(a). The cooler, which consists of a cold head unit with a single-stage displacer, a compressor, and a gas feed connecting tube, has a moving cylinder, a clearance seal by diaphragm springs, a twin pole magnet system, and a pneumatically driven displacer. The compressor has two oppositely moving cylinders to reduce the vibration level. For reducing the induced vibration in the drive axis of the cold head, the cooler was improved by adding an active counter balancer mechanism to the cold head of the original model. A photograph of the reduced vibration model is shown in Figure 1(b). The specifications are shown in Table 1. The mechanical vibration forces are reduced below 0.1 N at the operating frequency of 52 Hz.

### Two-Stage Stirling cooler

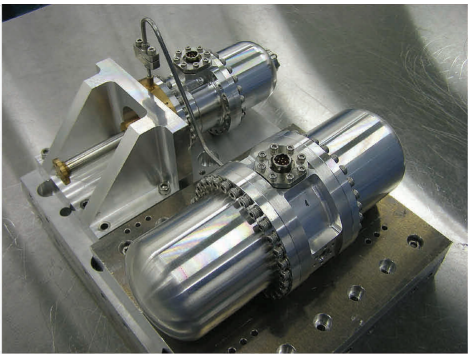
Table 1 shows the cooling temperature specifications for the 20 K split two-stage Stirling cooler. The cooler consists of a cold head unit with a two-stage displacer, a compressor, and a gas feed connecting tube. The compressor has two opposed pistons mounted on a drive shaft to reduce the vibration level. The drive shaft is supported by two sets of linear ball bearings. This linear-ball-bearing supporting system achieves the piston clearance seal, long piston stroke operation, and low-frequency operation. These features present benefits for a long useful life, compactness, light weight, and high efficiency of the second regenerator at low temperatures.

**Table 1.** Specifications of single-stage and two-stage Stirling coolers.

Item	Single-stage Stirling Cooler (1ST)	1ST (Reduced vibration model)	Two-stage Stirling Cooler (2ST)
Cooling Capacity	2 W at 80 K	2 W at 80 K	200 mW at 20 K 1000 mW at 100 K
Environment Temp.	200 K – 300 K	200 K – 300 K	200 K – 300 K
Power Consumption	50 W	50 W	90 W
Size	Compressor: φ 98×230 L (mm) Cold Head: φ78×181 L (mm)	Compressor: φ 98×230 L (mm) Cold Head: φ82×236 L (mm)	Compressor: φ 108×400 L (mm) Cold Head: φ81×329 L (mm)
Mass	4.2 kg	5.0 kg	9.5 kg
Drive Frequency	52 Hz	52 Hz	15 Hz



(a) Original model



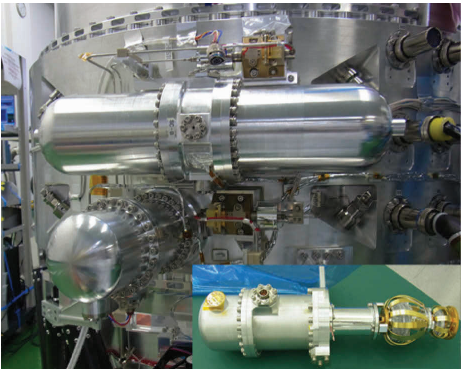
(b) Reduced vibration model

**Figure 1.** Single-stage Stirling cooler on test bench.

The advanced two-stage Stirling cooler has been improved from the original cooler for AKARI as described below.<sup>5</sup>

- Change from contact seal to clearance seal at displacer of cold head for reducing abrasion
- Re-selection of materials with lower outgassing and reduced adhesive amount
- Improvement for managed processes of baking and methods of purification

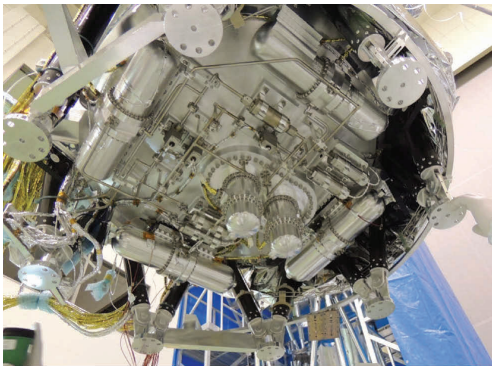
Additionally, it is important to reduce the total time during cooler assembly under atmosphere condition for reducing outgassing. Because the main gas impurities that degrade cooling performance are CO<sub>2</sub> and H<sub>2</sub>O, the allowable concentrations of CO<sub>2</sub> and H<sub>2</sub>O contamination are set respectively as 500 ppmv during operation. The newest model of two-stage Stirling coolers is used for the ASTRO-H project. A photograph of a flight model cooler is presented in Figure 2.



**Figure 2.** Two-stage Stirling cooler on the cryostat of ASTRO-H/SXS.

**Table 2.** Specifications of Advanced 4 K Cooler and 1 K Class Cooler.

Item	Advanced 4 K Cooler	1 K-class Cooler
Cooling Capacity	40 mW at 4.5 K	10 mW at 1.7 K
2-stage Stirling Cooler		
Cooling Capacity	0.2 W at 20 K, 1 W at 100 K	0.15 W at 15 K, 1 W at 100 K
Power Consumption	90 W	90 W
JT Compressor		
Pressure	Supply: 2 MPa, Return: 0.1 MPa	Supply: 0.7 MPa, Return: 7 kPa
Mass Flow Rate	2.0 NL/min (=6 mg/s) of <sup>4</sup> He	1.0 NL/min (=2.23 mg/s) of <sup>3</sup> He
Power Consumption	90 W	90 W
Heat Exchanger		
Efficiency	97%	97%
Pressure Drop	0.03 MPa on the low-pressure side	3 kPa on the low-pressure side
JT Orifice Diameter	20–30 μm	20–30 μm
Mass	30 kg (excluded cryostat)	30 kg (excluded cryostat)



**Figure 3.** 4 K cooler for ASTRO-H.

**4 K Cooler from SMILES to ASTRO-H**

The 4 K cooler consists of a JT cooler with <sup>4</sup>He as the working fluid and a two-stage Stirling cooler as a precooler. Major components of the JT cooler are two JT compressors, three coaxial-double-tube heat exchangers, an orifice type JT valve, and a bypass route to shorten the cooling time in the precooling process. The JT compressor system comprises two units connected in tandem. The 4 K cooler was developed originally to achieve a cooling capacity of 20 mW at 4.5 K for SMILES.<sup>4</sup> The 4 K cooler for SMILES used linear ball bearings as the piston support in the JT compressors, which is the same as the two-stage Stirling cooler. To improve the cooling power and long life operation, the JT compressors were changed, in terms of the piston supporting mechanism, from linear ball bearings to flexure bearings; this reduced mechanical abrasion. Moreover, low-outgassing materials were adopted to avoid cooling performance degradation caused by impurities. In addition, a “getter” was mounted upstream of the JT closed cycle to trap impurity molecules.<sup>6</sup> Managed baking processes, gas purification, and limited time during cooler assembly under atmospheric pressure were also incorporated to further reduce internal contaminants in the JT coolers.

An advanced type of two-stage Stirling cooler is used as the precooler for the advanced 4 K cooler. Design specifications of the advanced 4 K cooler are presented in Table 2. A photograph of the advanced 4 K cooler for ASTRO-H is presented in Figure 3. The 4 K cooler for ASTRO-H consist of a JT cooler and two units of advanced two-stage Stirling coolers as the precooler (PC-A and PC-B).

**1 K-Class Cooler**

The 1 K-class cooler comprises a two-stage Stirling cooler and a JT cooler with <sup>3</sup>He as the working fluid. The 1 K-class cooler is an improved type of 4 K cooler. <sup>3</sup>He is used in the JT cooler

Table 3. Summary of Operating Hours.

Test Model or Project	Temp. Level	Operating hours			Remark
		Earth	Orbit	Total	
Single-Stage Stirling Cooler					
1 EM	80 K	113640	N/A	113640	1999 Nov.-2015 Jan.: Stopped
2 PM-1	80 K	108370	N/A	108370	2001 Nov: Operation Start
3 PM-2	80 K	104771	N/A	104771	2002 May: Operation Start
4 SUZAKU/XRS	150 K	2000	51400	53400	2009 June: Mission Completed
5 KAGUYA/GRS	80 K	9200	12600	21800	2009 June: Mission Completed
6 AKATSUKI/IR2	65 K	500	3570	4070	2010 July: Operation Start
7 ASTRO-H/SXI - A&B	150 K	443	456	899	2016 March : Operation Start
Two-stage Stirling Cooler					
8 EM for AKARI	20 K	72906	N/A	72906	1999 March – 2008 August
9 AKARI-A	20 K	2098	40350	42448	2010 May: Mission Completed
10 AKARI-B	20 K	2121	13800	15921	2007 October : Operation Stop
11 PM&PC for SMILES	20 K	22283	N/A	22283	2007 May – 2010 Sep.: Stopped
12 PC for SMILES	Part-1	2250	6035	8285	2009 Sep. – 2010 June
	Part-2	2250	16124	18374	2009 Sep. – 2014 March
13 EM for ASTRO-H	20 K	36140	N/A	36140	2010 January : Operation Start
14 ASTRO-H/SXS SC-A&B	30 K	5746	902	6648	2016 Feb.: Operation Start
15 ASTRO-H/SXS PC-A&B	15 K	5746	902	6648	2016 Feb.: Operation Start
16 PC for 1K-level Cooler	20K	6721	N/A	6721	2015 May: Start
JT Cooler with <sup>4</sup> He for 4 K level					
17 EM for SMILES	4.5 K	9315	N/A	9315	1998 Sep. – 1999 Dec.: Stopped
18 PM for SMILES	4.5 K	22283	N/A	22283	2007 May – 2010 Sep.: Stopped
19 SMILES	Part-1	1172	6010	7782	2009 Sep. – 2010 June
	Part-2	20 K	1172	30428	32200
20 EM for ASTRO-H	4.5 K	36140	N/A	36140	2010 January: Operation Start
21 ASTRO-H/SXS	4.5 K	5746	863	6609	2016 Feb.: Operation Start
JT Cooler with <sup>3</sup> He for 1 K level					
22 EM for SPICA	1.7 K	6721	N/A	6721	2015 May: Start

Note: EM, Engineering Model; PM, Prototype Model; SC, Shield Cooler; PC, Pre-Cooler

instead of <sup>4</sup>He. The JT compressor capacity and pressure drop in the heat exchangers on the low-pressure side are redesigned to reach temperatures below 2 K. The selection of <sup>3</sup>He as the working fluid was made based on much higher vapor pressure than <sup>4</sup>He by about one order of magnitude at 1.7 K. Design specifications of the 1K-class cooler were described in an earlier report.<sup>8</sup> The updated model<sup>6</sup> was designed and tested to improve its performance and reliability.<sup>9</sup>

LIFETIME TEST AND OPERATION RESULTS ON ORBIT

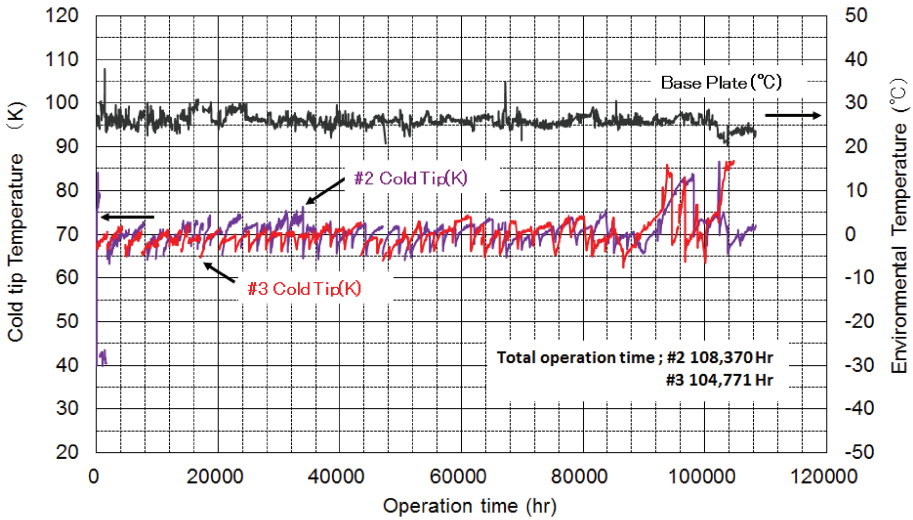
Table 3 presents the number of operating hours of coolers until April 29, 2016. Specifically, the table presents the operating hours of lifetime tests of coolers under the development phase, along with the operating hours in ground tests and operating hours on-orbit for launched projects. The 4 K and 1 K-class coolers are divided into the JT cooler and the precooler in Table 3.

Lifetime test results and operation results on orbit of Nos. 1, 4, 5, 8, 9, 10, 11, 12 (Part-1), 17, 18 and 19 (part-1) in Table 3 were presented in an earlier report.<sup>1</sup>

Single-Stage Stirling Cooler

Three lifetime tests of single-stage Stirling coolers using an engineering model (EM) cooler and two prototype model (PM) coolers demonstrate reliability of greater than 100,000 hr. Figure 4 depicts lifetime test results obtained for two PM coolers (Nos. 2 and 3 in Table 3). Figure 4 shows the temperature of the cold stage and the environment temperature. The test conditions are input





**Figure 4.** Status of ground lifetime tests of two single-stage Stirling coolers (PM).

power of 40 W (nominal), heat load of 1 W on the cold tip, and normal environment temperature of  $295 \pm 5$  K. Slow and repeatable temperature degradation was observed, with recovery following restart of operation after power interruption. The cooler is still functioning, providing good cooling performance. Therefore, we infer that a mechanical fault is unlikely. At around 90,000 hr and later, disturbing performance degradation was observed, although the temperature maintained the 80 K level. The behavior might be mostly attributable to internally cooled condensation in the displacer because these units were not baked out sufficiently. The internal gas was insufficiently purified. The flight model coolers (Nos. 4 to 7 in Table 3) have been built with improved and managed processes of baking and methods of purification to reduce outgassing.

Although the mid-wave infrared camera (IR2) of AKATSUKI operated minimally during more than five years of space transit, the cooler (No. 6 in Table 3) started to operate after entry into the ellipsoidal orbit around Venus. During operation, the CCD camera is cooled to around 65 K using the cooler with an input power of 45 W. From now on, we look forward to obtaining useful observation results for Venus.

### Two-Stage Stirling cooler

The lifetime test on the ground of two advanced models of the two-stage Stirling coolers (Nos. 13 and 16 in Table 3) have been conducted as a precooler for the JT cooler of the advanced 4 K cooler and the 1 K-class cooler reported respectively hereinafter.

### 4 K Cooler

After 9 months (6,480 hr) from the operation start, SMILES stopped operation because of a disorder related to the water cooling system for JEM. The cryogenic system returned to room temperature level. By that time, the cryogenic system for SMILES had demonstrated sufficiently good cooling performance for the submillimeter atmospheric observation. The sum of real operating hours including the ground operation was 8,285 hr for the precooler and 7,782 hr for the JT compressors (Part-1 of Nos. 12 and 19 in Table 3). After restoration of the water cooling system, the SMILES cryogenic system was restarted for cooling in July 2010. However, it did not achieve a temperature of the 4 K level. When the temperature of the 100 K-stage reached around 150 K, the lower stage temperatures were still warm, and the gas flow in the JT cooler seemed to have stopped. The cessation was indicated by a change in suction pressure at the lower side of the JT compressor and by the bypass valve temperature. We believe the cause to be blockage by internal solidification of a

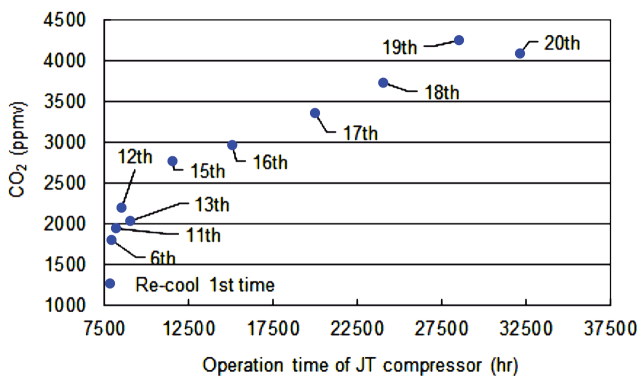


Figure 5. Status of CO<sub>2</sub> contamination concentration in the 4 K cooler of SMILES on orbit.

contaminant gas in the narrow high-pressure piping around the 100 K stage. The main gas impurity was CO<sub>2</sub>, which becomes solid at such temperatures and its saturation pressure region. The CO<sub>2</sub> contamination concentration was estimated as about 1264 ppmv from the 100 K stage temperature of 147.2 K, which is an unexpected amount. Because the cooling capability of the precooler and the performance of the JT compressors showed no degradation, re-cooling for SMILES has been attempted by changing various procedures of the cooling process. However, it did not achieve a temperature of the 4 K level again. Subsequently, the 4 K cooler of SMILES has been investigated to analyze the CO<sub>2</sub> contamination concentration depending on the operation time and to confirm the mechanical reliability and performance for the future of cooler development through March 2014 (Part-2 of Nos.12 and 19 in Table 3). Figure 5 shows that the CO<sub>2</sub> contamination concentration increases with the operation time of the JT compressors. The maximum value is estimated as about 4251 ppmv from 100 K stage temperature of 156.0 K at the 19th investigation period. It is apparently saturated between 19th and 20th. The total operation duration of the two-stage Stirling cooler was 18,374 hr. That of the JT compressors was 32,200 hr without remarkable degradation of performance such as pressure, cooling temperature, or current.

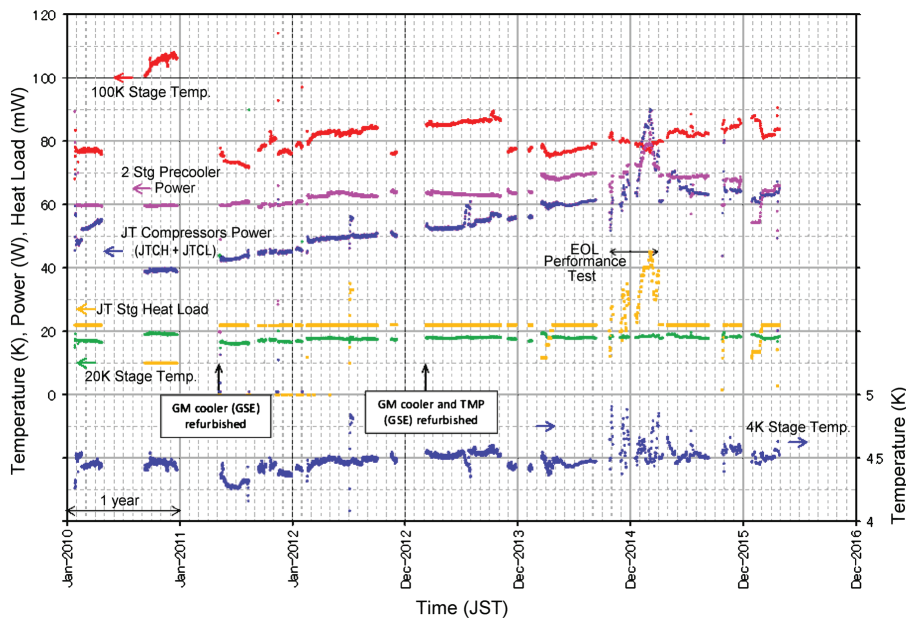
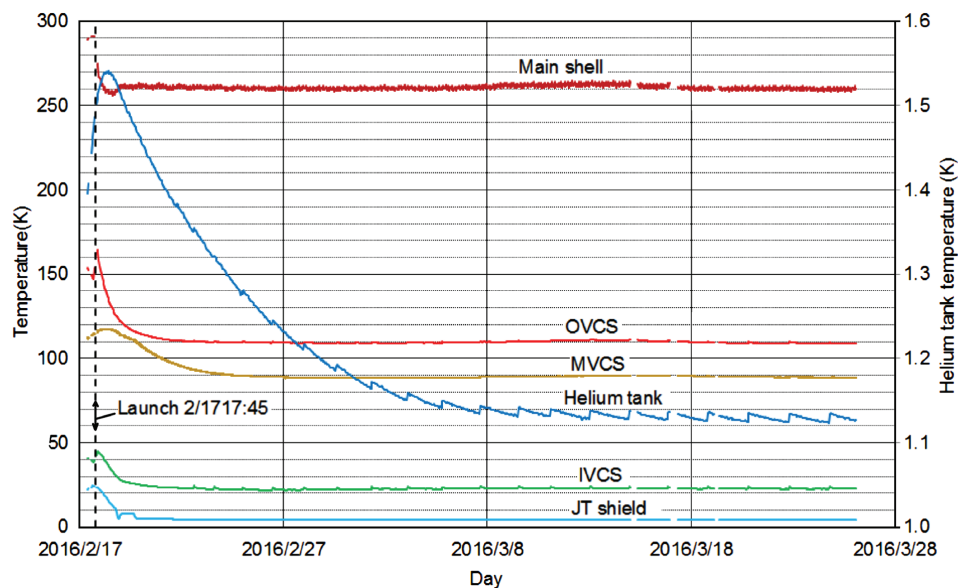


Figure 6. Lifetime test progress of an advanced 4 K Cooler (EM).



**Figure 7.** Status of early stages of cooling operation in Cryogenic system of STRO-H/SXS on orbit.

An engineering model of the advanced 4 K cooler with  $^4\text{He}$  (Nos. 13 and 20 in Table 3) has been tested under a room temperature environment to verify its cooling performance and lifetime. Figure 6 shows the lifetime test progress of the advanced 4 K cooler. The figure shows temperatures of 100 K, 20 K, and 4 K-stage, in addition to the input power to the JT compressors and precooler and heat load to the 4 K-stage. As of April 29, 2016, the total running time was over 36,140 hr, demonstrating three years of operation, which is the required design mission life of ASTRO-H. Furthermore, the design requirement for the cooling performance of 40 mW at 4.5 K at the end of life was also verified to have an input power of 80 W for the precooler and 85 W for the JT compressors. In the lifetime test, the input power to the EM cooler needed to increase from the beginning state to 10 W for the precooler and 20 W for the JT compressors to maintain constant cooling capacity at a temperature of the 4-K level.

The cooldown and initial cooling performance of the cryogenic system of the soft X-ray spectrometer (SXS) of ASTRO-H were completed successfully after launch. Figure 7 presents the status of early stages of cooling operation in the cryogenic system for the ASTRO-H/SXS. (Nos. 14, 15, 16 and 21 in Table 3) The figure presents temperatures of the main shell, three vapor cooled shields (OVCS, MVCS and IVCS), the JT shield, and the helium tank of the cryogenic system. The OVCS and IVCS are cooled by two units of advanced two-stage Stirling coolers (SC-A and SC-B) with the input powers of 46.6 W and 49.1 W. The JT shield is cooled by the 4 K cooler. The input power of the two pre-coolers A, B and the JT compressors are 42.5 W, 50.6 W and 15.2 W, respectively. Finally, the SXS detector was cooled to 50 mK by the two-stage ADR. The initial cooling results of the cryogenic system of the SXS of ASTRO-H are matched to the thermal design and demonstrated to fulfill the requirement of mission lifetime. Initial observations were performed successfully. However, ASTRO-H lost all its solar panels by an attitude rotation anomaly caused by an attitude anomaly on March 26, 2016. Consequently, with deepest regret, observations by ASTRO-H were given up on April 28, 2016.

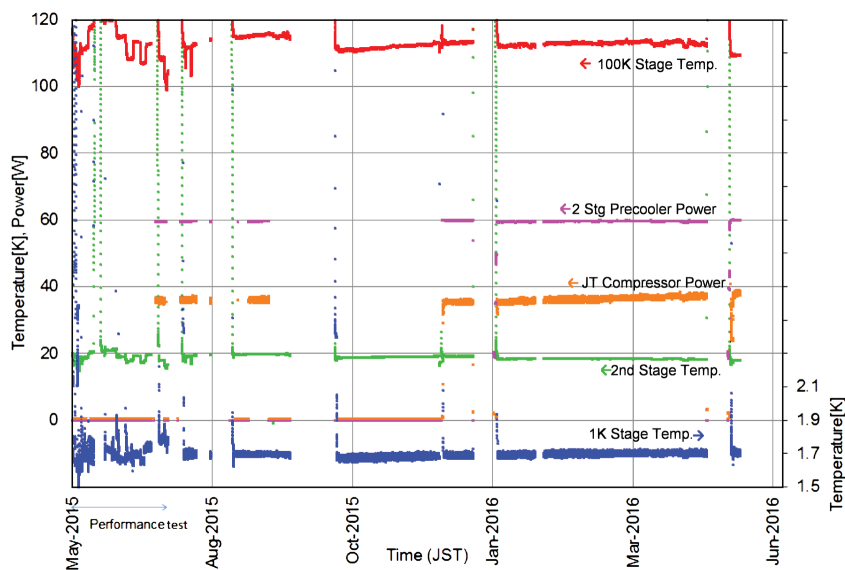
### 1K-Class Cooler

A lifetime test of a 1K-class cooler with  $^3\text{He}$  using an engineering model (Nos. 16 and 22 in Table 3) has continued since May 2015. Figure 8 shows a photograph of the engineering model of the 1K-class cooler. Figure 9 presents the lifetime test progress of the EM cooler, which passed 6721 hr with no degradation. The figure shows the cooler temperatures of the 100 K, 20 K, and 1 K-stage and





**Figure 8.** A photograph of the engineering model of the 1-K class cooler.



**Figure 9.** Lifetime test progress of a 1-K Class Cooler (EM).

the power consumption. The EM cooler, controlled by laboratory electronics, was tested under laboratory conditions with a local vacuum chamber around the cold stages. The environment temperature was  $295 \pm 5$  K. The heat load applied to the 1 K-stage was 5 mW. When the lifetime test started, the power consumption of the two-stage Stirling cooler and the JT compressors was 60 W (nominal) and 30 W (nominal), respectively. The operating voltage of the two-stage Stirling cooler has not changed during the test.

**CONCLUSIONS**

Ground lifetime tests were conducted of coolers of three types: a single-stage Stirling cooler, two-stage Stirling cooler, and JT cooler. Three single-stage Stirling coolers have been tested for over 113,640 hr, 108,370 hr and 104,771 hr. Advanced 4 K coolers with  $^4\text{He}$  have been tested for 36,140 hr. Results show proof of long life and reliability for space use. A lifetime test of 1-K class cooler with  $^3\text{He}$  has begun for future missions. Five single-stage Stirling coolers were carried on each of SUZAKU, KAGUYA, AKATSUKI, and ASTRO-H/SXI. Four sets of two-stage Stirling coolers were carried on AKARI and ASTRO-H/SXS. Two 4 K coolers were carried on SMILES

and ASTRO-H/SXS. These coolers produced useful results for future projects on orbit. From investigation results related to cooling performance degradation, we have learned that filled gas contamination, especially by  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , is crucially important. Advanced models of a two-stage Stirling cooler and JT cooler have been improved in terms of abrasion, and development and investigation are continuing to decrease filled gas contamination in the coolers.

## ACKNOWLEDGMENTS

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