

# Developments of 1-4 K Class Space Mechanical Coolers for New Generation Satellite Missions in JAXA

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## ABSTRACT

Mechanical coolers are a key enabling technology to utilize low temperature scientific instruments for the new generation of space science missions, such as the new X-ray astronomical satellite Astro-H, and the new infrared astronomical satellite SPICA. In particular, 1-4 K class mechanical coolers are required as a precooler for the low temperature detector's cooling system and to cool a space telescope with a very low radiation background. In JAXA, two-stage Stirling coolers (2ST) for 20 K and a <sup>4</sup>He Joule-Thomson (J-T) cooler for 4.5 K have been successfully developed and operated in space, e.g. Akari (Astro-F) and the Japanese Experiment Module/SMILES. Based on this heritage, the 2ST coolers and the <sup>4</sup>He J-T coolers have been modified and upgraded to achieve high reliability, more cooling power, lower mechanical vibration, and longer life time.

In performance tests of upgraded prototypes of the mechanical coolers, the required cooling power of each cooler has been obtained. The engineering model of the 4 K class cooler, consisting of two 2ST coolers and a <sup>4</sup>He J-T cooler for the Astro-H payload will be fabricated, and undergo performance tests, including the level of vibration and cooling behavior at the expected heat load in Astro-H. In this paper, the R&D status and performance test results of the 2ST coolers and the <sup>4</sup>He J-T coolers are reported. We also report on the development of <sup>3</sup>He J-T cooler for the SPICA detectors.

## INTRODUCTION

Mechanical cryocoolers are required to maintain a low temperature with longer orbit time in comparison to a solid or liquid cryogen in space. In past space missions, a large cryogen tank was installed to cool a telescope or detectors, and the cryogen's lifetime limits the mission life of the astronomical satellite. Instead, the use of the mechanical coolers can provide a mission life of 3-5 years or longer with lower mass, and with no lifetime failure caused by a thermal short in the stored cryogen.<sup>1</sup> However, reliability and vibration must be considered, since moving parts exist in mechanical coolers.

The Soft X-ray Spectrometer (SXS) on-board the 6<sup>th</sup> Japanese X-ray astronomy satellite, Astro-H, is a high resolution spectrometer utilizing a microcalorimeter array.<sup>2-3</sup> A resolving power of 1000 or larger at 6 keV of X-ray energy can be achieved by cooling down and operating at very low

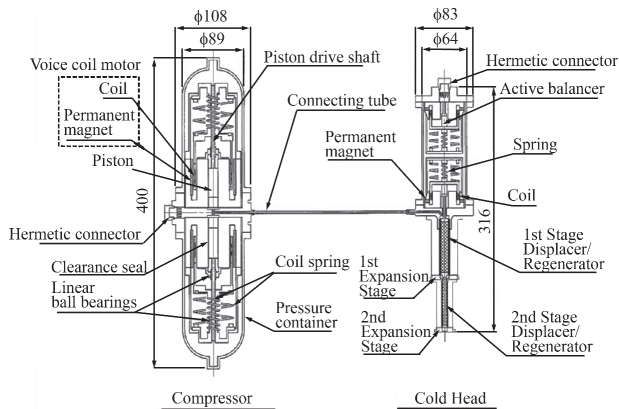
temperature of 50 mK. The SXS cooling chain from room temperature to 50 mK, provided by an adiabatic demagnetization refrigerator (ADR), includes a 1.3 K pumped liquid He and a mechanical cryocooler as a precooler for the liquid He.<sup>4-5</sup> In the baseline design of the SXS cooling system, two 2ST coolers are used to cool the radiation shields (IVCS and OVCS), while one <sup>4</sup>He J-T cooler is used to reduce the parasitic heat load to the liquid He tank. The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission has been proposed as the new-generation infrared (IR) space telescope led by JAXA with the participation of ESA.<sup>6-7</sup> The thermal environment at a halo orbit around the Sun-Earth second Lagrangian point (L2) enables the large IR telescope to be cooled down to 4.5 K with advanced mechanical cryocoolers and effective radiation cooling instead of a massive and short-lived cryogen. In the thermal design study of SPICA, two <sup>4</sup>He J-T coolers are needed to cool down the IR detectors as well as the large telescope, while the 1.7 K cold temperature region provided by two <sup>3</sup>He J-T coolers are also required to cool the far infrared detector and act as a precooler for the lower temperature cooling devices.

This paper describes the current development status of 1-4 K class mechanical cryocoolers serving as an engineering model for the new generation of Japanese satellites. We initially describe the improvements to the 2ST cooler and the performance test results. The development status of the <sup>4</sup>He J-T cooler is also shown. Then, the requirements, the preliminary test results of the prototype model and the current status of <sup>3</sup>He J-T cooler will be described.

## DEVELOPMENT OF DOUBLE-STAGE STIRLING COOLER

### Original Design

The 20 K class 2ST cooler was originally developed for the first Japanese infrared astronomy satellite Akari<sup>8-10</sup> launched on February 2006 based on a two-stage small Stirling-cycle cooler with temperature below 20 K for space applications developed in 1991.<sup>11</sup> Figure 1 shows a cross-sectional view of the existing 2ST cryocooler for Akari. This cooler is a split-Stirling cycle cooler composed of a double-staged cold head with two expansion stages, a linear compressor and a connecting tube. The compressor has two opposing pistons to cancel dynamic vibrations. The piston drive shaft is supported by two sets of linear ball bearings to maintain the clearance seal, and is driven by a voice coil motor and coil springs. The cold head consists of a two-stage displacer and an opposing active balancer that works as a counterweight to cancel the dynamic vibration of the displacer. The displacer uses stainless steel meshes for the regenerator and is supported by Teflon contact seals. It's driven by a voice coil motor and coil springs are the same as the compressor. The total weight, the driving frequency, and the gas pressure are 9.5 kg, 15 Hz, and 1.0 MPa at 240 K, respectively. The input power is 90 W and it provides 200 mW of cooling power at 20 K. The Akari cooler has been in continuous operation for more than 3 years, which exceeds the original specification of 1.5 years.<sup>12</sup>



**Figure 1.** Schematic drawing of the Akari double-stage Stirling (2ST) cooler

### Requirements for Future Space Mission

From the orbital performance result of the 2ST cooler, more reliable and larger cooling power with longer life time are needed for the next generation satellite. Basic requirements are as follows; (1) longer life time (3 years is required, 5 years is a goal), (2) 200 mW of cooling power at 20 K, and (3) lower mechanical vibration. On the other hand, the improvement in the cooling performance of the 2ST cooler can directly increase the J-T cooling power, and can improve the thermal margin which will accommodate design uncertainties and incidents.

### Fabrication and Performance Test of 2ST Cooler

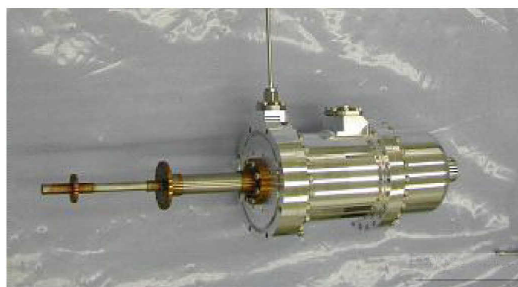
Improvements in the 2ST cooler design are divided into three sections. One is the displacer's support mechanism to reduce the risk of mechanical abrasions based on the experience with the Akari 2ST cooler. Since the 1<sup>st</sup> and the 2<sup>nd</sup> stage displacer design of Akari 2ST cooler are supported by contact seals, mechanical abrasions can occur in orbit due to the slide contact on the inner surface of the displacer cylinder, which significantly affects the degradation of the cooling performance during long term operation. As a new design, flexure springs are used for the displacer drive shaft support to keep the driving axis aligned. As a consequence, the compressor's pistons have to be supported by linear ball bearings for long piston strokes with 15 Hz of low-drive frequency.

The second improvement is the selection of components to reduce outgassing in the 2ST cooler. Increases in the working gas impurities can strongly affect cooling performance, making it critical to minimize outgassing from internal components to maintain the nominal cooling power for more than 3 years with margin. We selected low-gassing materials and the working gas was substantially purified before assembly. The amount of glue used to fix the permanent magnet was reduced, and the baking process for degassing in the cooler was also optimized.

The third improvement is the diameter of the 2<sup>nd</sup> stage displacer. The diameter was increased to 8 mm to enlarge the gas expansion volume. A cooling power of 325 mW at 20 K was achieved with this design change, while the heat load through the 2<sup>nd</sup> stage cold head must be increased in the case of the failure of the 2ST cooler. The upgraded design of the 2ST cold head is shown in Figure 2.

In a performance test of a breadboard model (BBM) of the upgraded 2ST cooler, a cooling power of 200 mW at 16 K was achieved at the 2<sup>nd</sup> stage at the same time that 1 W of cooling power at 83.6K was successfully obtained at the 1<sup>st</sup> stage, by optimizing the drive conditions of 90 W of input power. The working gas pressure was 0.9 MPa (1.0 MPa in nominal) and the voltage phase angle difference between the compressor and the displacer in the cold head was 170 degree (180 degree in nominal) for the best performance.

The engineering model of the 2ST cooler with upgraded design was then fabricated as an evaluation test model for Astro-H/SXS. The cooling performance test was conducted under the thermal conditions of its operating temperature of -70 to +30°C. The 2ST cooler test model was mounted on the test plate where the temperature of these interfaces to the 2ST cold head and the compressor were controlled using a laboratory Gifford-McMahon (GM) refrigerator in the vacuum vessel. A working gas pressure of 1.4 MPa was charged at room temperature to ensure the cooling performance at a pressure of 1.0 MPa and a temperature -70°C. The test results at each condition are shown in Figure 3.



**Figure 2.** Photograph of cold head of upgraded 2ST cooler

The relationship between the 2ST 2<sup>nd</sup> stage temperature (lower temperature stage) and 1<sup>st</sup> stage in the case of 50 W and 90 W of input power was successfully obtained. A nominal cooling power of 200 mW at 20 K of the 2ST 2<sup>nd</sup> stage temperature under the condition of 90 W of input power was achieved within the operating temperature range. In this measurement, the lowest temperature of the 2<sup>nd</sup> stage with 200 mW of cooling power with 1 W of cooling power of 1<sup>st</sup> stage (83.4 K) was 17.0 K. A life test was also begun, and the detailed status is described in the next section.

Mechanical vibration induced by the 2ST coolers as well as the <sup>4</sup>He J-T coolers is one of the critical issue for Astro-H/SXS, since the vibration may strongly affect the detector performance. The dynamic vibration force must be measured with a three-axis piezoelectric dynamic force sensors. In this design, fine tuning of the driving voltage amplitude and the phase angle difference can be optimized to balance the dynamic motion of the active balancer relative to that of the displacer. Consequently, the dynamic force in the direction of the driving axis of the 2ST cooler cold head could be reduce to about 10% with fine tuning relative to the case of when the input voltage of the displacer and the balancer were merely synchronized. The driving electronics, which can adjust the input voltage to optimize for vibration reduction of the cold head, is being investigated and an improvement is expected for SXS.

## DEVELOPMENT OF J-T COOLER

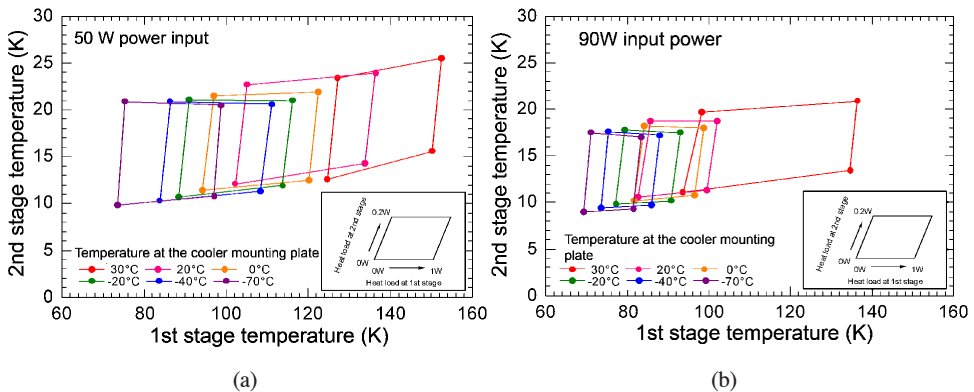
### <sup>4</sup>He J-T Cooler for SMILES Mission

The <sup>4</sup>He J-T cooler has been originally developed for the SMILES mission for the JEM-EF of the International Space Station (ISS).<sup>13-15</sup> The cooler was launched in Sep 2009.

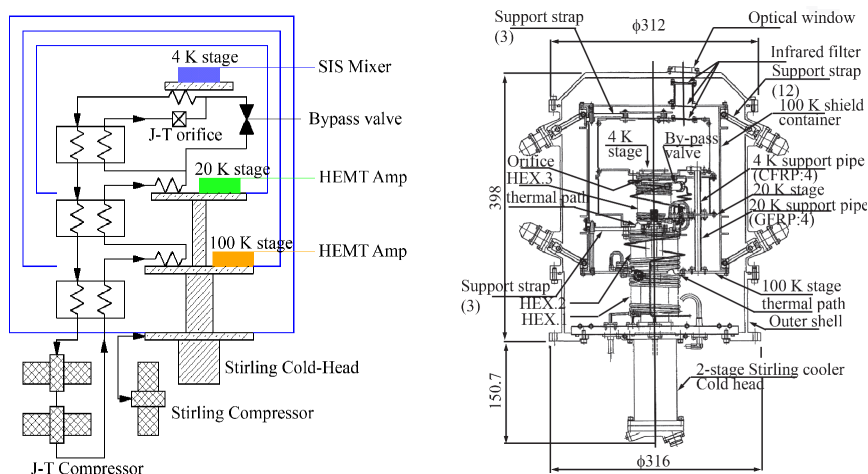
The design concept including the J-T circuit and the cross section of SMILES is shown in Figure 4. The J-T cooler system is composed of a 2ST cooler as a precooler for the J-T, multi-staged compressors, heat exchangers (HEX1-3), a bypass valve and a J-T orifice. The compressors consist of two linear compressor units, with each stage designed to supply an adjustable pressure balance. The heat exchangers are counter-flow type and have coaxial double tubes to achieve an efficiency of 97%. The exits of HEX 1 and HEX 2 at the high pressure side are connected conductively with the 1<sup>st</sup> and 2<sup>nd</sup> stage of the 2ST precooler. The bypass valve can switch the <sup>4</sup>He working gas flow to the J-T orifice the precooling is completed. In the SMILES mission, the <sup>4</sup>He J-T cooler has 30 mW of nominal cooling power at 4.5 K. The temperature at <sup>4</sup>He J-T cold stage was successfully obtained in orbit and is now being continuously operated.

### Requirements for Future Space Mission

From the design of Astro-H/SXS, the requirements to upgrade the <sup>4</sup>He J-T cooler are as follows, 1) longer life time (3 years is required, 5 years is a goal), 2) 40 mW of higher nominal cooling power at 4.5K of operational temperature, and 3) maximum input power is 90 W.



**Figure 3.** Performance test result of 2ST cooler. a) test case of 50W input power, b) test case of 90W input power.



**Figure 4.** Design concept and cross section of SMILES and the  $^4\text{He}$  J-T cooler

### Fabrication and Performance Test of $^4\text{He}$ J-T Cooler

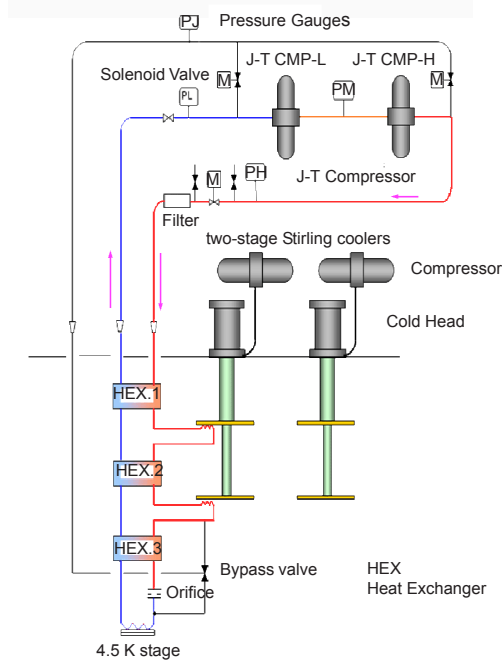
A combination of flexure springs and coil springs are the improved design to support the piston driving shaft for higher mechanical reliability and to increase the driving frequency. Outgassing from the internal components was investigated and low-gassing materials were selected for the long term operation. In the SXS cooler system, two 2ST coolers are used as pre-coolers with redundancy in the configuration of the  $^4\text{He}$  J-T cooler. In the thermal analysis, the 2ST 2<sup>nd</sup> cold stage exceeds 23 K when one of the 2ST pre-coolers fails, and the J-T expansion effect cannot occur. However, heat load to the J-T shield around the liquid He tank through the J-T circuit is rather small, so the life time of the liquid He cryogen can be achieved even if the J-T cooler does not operate.

Figure 5 shows the functional diagram of the  $^4\text{He}$  J-T cooler for the performance test of Astro-H/SXS. An engineering model was fabricated to verify the cooling performance and reliability of the  $^4\text{He}$  J-T cooler for the SXS. In preliminary tests, 50 mW of cooling power was obtained at 4.5 K for the  $^4\text{He}$  J-T cold stage, when an orifice size of 20-24  $\mu\text{m}$  was selected. The compressor performance will be investigated at an operating temperature range of 0 to 30  $^{\circ}\text{C}$ .

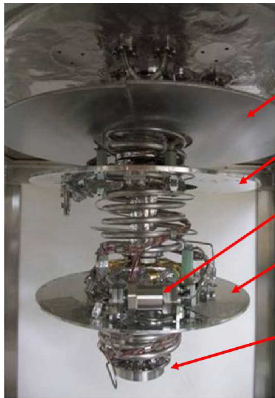
A  $^4\text{He}$  J-T cooler engineering model was also fabricated for a life test. This model consists of a  $^4\text{He}$  J-T cooler and one 2ST cooler as a pre-cooler. The 2ST cooler has the upgraded design, 20 K and 100 K radiation shields were installed, and it was thermally connected to each cold stages of the 2ST cooler in order to reduce the parasitic heat loads to the  $^4\text{He}$  J-T cold stage. A laboratory GM refrigerator was also installed to cool the outer radiation shield to fix the test environment temperature around the 100 K shield. Consequently, a cooling power of 50 mW at 4.3 K for the  $^4\text{He}$  J-T cold stage was obtained at the maximum cooling performance, as shown in Figure 6. The life test was started at the end of January 2010, and more than 3 months has passed. The heat load at the 4.5 K stage was set to 22 mW according to the estimated heat load in the SXS cryogen-free operation. 22 mW of the stable cooling power at 4.4 K is now obtained with power input of 60 W for the 2ST pre-cooler and 52 W for the J-T compressors.

### Development of $^3\text{He}$ J-T Cooler

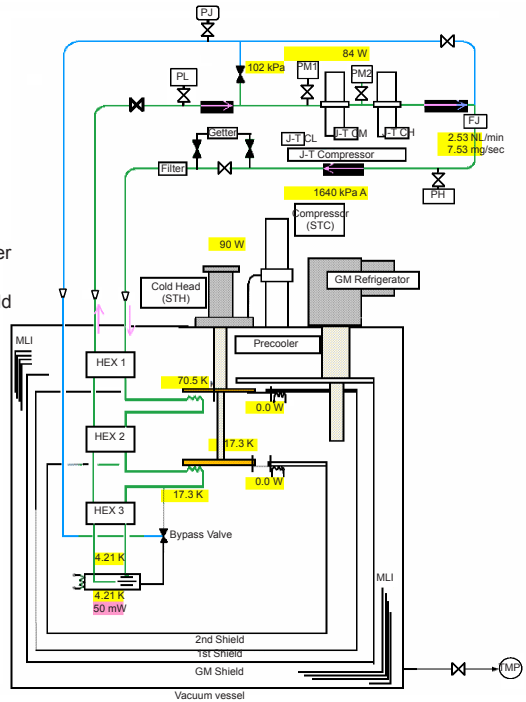
The 1 K class J-T cooler is an improved type of  $^4\text{He}$  J-T cooler. The development was based on requirements and the unique features of the SPICA mission, in which the cryogenic system launched warm and is cooled in orbit.<sup>16-17</sup> Requirements of the 1 K class cryocoolers are as follows; 1) operating temperature is 1.7 K with 10 mW of cooling power; 2) 3 years of life time is required, and 5 years is a goal; 3) maximum power consumption is 90 W. In the 1 K class J-T cooler,  $^3\text{He}$  is used in the J-T circuit instead of  $^4\text{He}$ . The selection of the working gas is made on the basis of a higher saturated vapor pressure than  $^4\text{He}$  by one order of magnitude at 1.7 K. Four-stages of compression are achieved



**Figure 5.** Functional diagram of EM <sup>4</sup>He J-T cooler performance test for Astro-H/SXS cooling system. Two 2ST units are used as a pre-cooler. Four pressure gauge and three solenoid valves are required for the cooling down operation.



- Radiation shield cooled by GM cooler
- 100 K stage shield
- Bypass valve
- 20 K stage shield
- 1 K stage



**Figure 6.** Photograph of the cold stage of the <sup>4</sup>He J-T cooler (left), and Preliminary result of EM for life time test (right). 50mW of maximum cooling power was obtained.



by using three compressor units, and each J-T compressor's capacity and pressure drop in the heat exchangers on the low-pressure side are redesigned to reach a lower temperature than 2 K. The detailed design study was described previously.<sup>18,19</sup>

In the cooling performance test of the bread board model (BBM), greater than 10 mW of cooling power was obtained at 1.7 K for the J-T cold stage. We also measured the gravitational effect of the J-T cooler's cooling performance by using a test apparatus, which can be rotated to set the cold stage forward or opposite the position to gravity (+/-1g). +1g means that a gas flow from the compressor to cold stage is in the same direction as gravity. Note that the driving axis of all 2ST and J-T compressors are horizontal in the case of +/- 1g. We used the two 2ST coolers as pre-coolers and these test results are shown in Table 1. There are no remarkable differences in both the +/-1g operating conditions to obtain the same cooling power (minimum temperature), but the 2ST 2<sup>nd</sup> stage temperature of the +1g case was slightly lower than the -1g case. One possible conclusion is that the cooling power of the 2ST 2<sup>nd</sup> stage becomes slightly higher since the displacer position was shifted by gravitational effect, and the J-T cooler's mass flow rate in the +1g case could be lower than that of -1g case (under discussion). This test will also be performed with the EM <sup>4</sup>He J-T cooler performance test model.

The <sup>3</sup>He J-T cooler has the same design as the <sup>4</sup>He J-T cooler between the ambient heat rejection stage and the J-T cold stage. As shown in Figure 6, the third heat exchanger (HEX 3) is of the coil-type and is located between the 2ST 2<sup>nd</sup> stage and the J-T cold stage. The total length of HEX 3 is 1.7 m, while the length between the 2<sup>nd</sup> stage of 2ST and the J-T cold stage is about 7 cm. On the other hand, in the design study of the SPICA mission, two <sup>3</sup>He J-T cooler cold stages should be mounted together close to the Instrument Optical Bench (IOB) to reduce the required mass of the thermal strap and for redundancy. Even if one <sup>3</sup>He J-T cooler fails, the heat load to the failed <sup>3</sup>He J-T cold stage is lower than 1 mW so that another <sup>3</sup>He J-T cooler can provide 1.7 K. The distance between the 2ST 2<sup>nd</sup> stage and the IOB is 40 cm and it becomes longer according to the position of <sup>3</sup>He J-T cold stage. A performance test model of the <sup>3</sup>He J-T cooler with a different HEX 3 design will be fabricated and tested. The <sup>4</sup>He J-T cooler cold stages also have the same requirements as the <sup>3</sup>He J-T cooler as the cryocoolers of SPICA.

## CONCLUSION

A 1-4 K class mechanical cryocooler system has been developed and tested for a new generation space missions. In the developments, the design of the 2ST cooler was improved with respect to mechanical vibration of the cold head, degradation of the working gas purity, and mechanical abrasion of the moving parts. We measured the engineering model of the 2ST cooler and achieved 200 mW of cooling power at 17.0 K with a reduction of 90 % of the mechanical vibration at the cold head. We also fabricated the EM <sup>4</sup>He J-T cooler with the upgraded design of these compressors and a reduction in the working gas purity, and a maximum cooling power of 50 mW at 4.5 K was obtained as a preliminary result. The cooling performance under the required conditions and life time are now being tested as an engineering model of Astro-H/SXS. On the other hand, the bread board model of <sup>3</sup>He J-T cooler with an upgraded design was also fabricated and tested. We confirmed that the gravitational effect of the <sup>3</sup>He J-T's cooling performance was quite small. The performance of a different heat exchanger design will be also measured for SPICA mission.

**Table 1.** Results of gravitational effect measurement

Input power of 2ST	2 × 50W	2 × 50W	2 × 90W	2 × 90W
	+1G	-1G	+1G	-1G
JT cold stage	1.58K	1.58K	1.56K	1.56K
2ST 2 <sup>nd</sup> stage	13.7K	14.5K	11.8K	12.5K
2ST 1 <sup>st</sup> stage	99.4K	98.3K	87.5K	84.4K
Gas flow rate	0.68NL/min, 1.52mg/sec	0.73NL/min, 1.63mg/sec	0.65NL/min, 1.45mg/sec	0.73NL/min, 1.63mg/sec
Input power of JT	24W	26W	20W	25W

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