Lifetime Verification and Applications of the 1K-Class Joule-Thomson Cooler for Space Science Missions

K. Shinozaki[1], Y. Sato[2], K. Tanaka[2], H. Sugita[2], N.Y. Yamasaki[3], T. Nakagawa[3], K. Mitsuda[4], S. Tsunematsu[5], K. Ootsuka[6], K. Kanao[6] and K.Narasaki[6]

[1]JAXA / R&D, Sagamihara, Kanagawa 252-5210, Japan
[2]JAXA / R&D, Tsukuba, Ibaraki, 305-8505, Japan
[3]JAXA / ISAS, Sagamihara, Kanagawa 252-5210, Japan
[4]NAOJ, Mitaka, Tokyo 181-5888, Japan
[5]Sumimec Engineering Co., Ltd., Niihama, Ehime 792-0003, Japan
[6]Sumitomo Heavy Industries, Ltd., Niihama, Ehime 792-8588, Japan

ABSTRACT

Space-qualified Joule Thomson coolers with significant cooling power below 2 K enable a variety of missions ranging from large infrared space telescopes, superconducting detectors for astrophysics and quantum applications. At JAXA, a 1 K-class Joule-Thomson cryocooler (1K-JT) has been developed with the specified cooling power of 10 mW at 1.7 K for upcoming next-generation astronomy missions. The lifetime test is one of most critical items to be verified, while mechanical tests, thermal vacuum environmental tests, and the electromagnetic noise and mechanical disturbance measurements were completed with the engineering models prior to the lifetime test.

This paper provides current status of the lifetime verification result with the engineering model. The lifetime test was started on May 2015, and recently achieved its fourth year continuous of operation without any critical degradations. Recent researche, 1K-JT applications including the cooler system demonstration for the ESA X-ray observatory ATHENA (Advanced Telescope for High Energy Astrophysics), and the cooling performance test with straight heat exchanger for the space infrared telescope mission SPICA are also presented.

INTRODUCTION

At JAXA, space-qualified mechanical coolers are being developed with Sumitomo Heavy Industries, Ltd. (SHI) for space science missions [1]. Two units of a 20 K-class two-stage Stirling cooler (2ST) were operated on the Japanese infrared astronomical mission AKARI, and four sets of a 2nd generation 2STs with improved reliability were launched on February 2016 by Japanese X-ray observatory Hitomi [2][3]. XRISM [4], a recovery mission of Hitomi is also a cryogenic mission with four 2STs. A 4 K-class Joule-Thomson cryocooler (4K-JT) which provides 4.5 K with the cooling power of 20 mW was developed and carried on the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) onboard the Japanese Experiment Module (JEM) of the International Space Station (ISS) [5]. Then, the 4K-JT was upgraded with higher cooling power (40 mW) and higher reliability, and successfully operated on Hitomi. The 4K-JT is also proposed, planned and developed to be mounted on XRISM, Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic microwave background Radiation Detection LiteBIRD [6], SPICA [7] and ATHENA [8].

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Table 1. The 1K-JT specification [10].

	1K-JT
Technology Readiness Level (TRL)	TRL 5[(1)], TRL 4[(2)]
Cooling power	10 mW at 1.7 K
Lifetime	5 years
Working gas	^{3}He
Operating temperature of compressors	0 °C to +30 °C
Driving power[(6)]	75 W
Mass	28 kg w/o precooler
Driving freq.	40Hz (low pressure compressors) and 52Hz (middle and high pressure compressors). 45 Hz as an option.
Number of compressors	4

(1) TRL with original design of HEX3 (toroidal shape).
(2) TRL with straight and longer HEX3.

This paper shows current status of the lifetime test of the space qualified 1K-JT engineering model (EM). The 1K-JT development began in 2001 with the study of the mechanical cooler system for SPICA, and the cooling power of 16 mW at 1.7 K was measured in the bread board model (BBM) performance test [9]. The reliability evaluation excluding lifetime was completed in the 1K-JT EM development. After that, several experimental demonstrations were also performed with the 1K-JT EM performance test model.

THE 1K-JT LIFETIME TEST

Development of the 1K-JT Engineering Model

The 1K-JT cooler consists of four-staged linear compressors and a closed cycle loop with three staged heat exchangers, a JT orifice and a bypass valve. There are two thermal interfaces between these heat exchangers, and these are needed to precool the JT working gas. As a baseline design, the 2ST is used as the precooler and the 2ST 2nd stage temperature is 15 K at maximum as the prior condition of the 1K-JT design.

The development of the 1K-JT EM was started in 2011 after the technology demonstration using the BBM [10]. Table 1 shows the specification of the 1K-JT. In this EM development phase, two sets of the 1K-JT EM with the 2ST precooler were fabricated for use in the qualification tests. One EM, called the performance model, was dedicated to mechanical and thermal environmental tests, electromagnetic compatibility (EMC) tests, and the cooling performance test including the thermal transient measurement. The other unit was used for the lifetime test after mechanical environment testing the acceptance level and an outgas assessment[10].

The Lifetime Test

The cooling performance degradation of the mechanical coolers during the continuous operation is mainly caused by impurities in the working gas and the mechanical wear of the moving parts. A lifetime test is needed through continuous operation for the verification of the specified lifetime and for studying the performance change.

The lifetime test of the 1K-JT EM began on May 2015 at SHI Niihama plant. The 1K-JT cold tip and the 3rd heat exchanger (HEX3) are surrounded by the inner thermal shield which is cooled by the 2ST precooler 2nd stage, and the 2ST 1st stage cools the outer thermal shield which covers the inner thermal shield. The Ground Support Equipment (GSE) thermal shield cooled by a commercial GM cooler was also assembled around the outer thermal shield on March 2017 because the reduction of radiative heat load into the 2ST 1st stage should be needed, while MLI (Multi-Layer Insulation) was only used until the assembly of the additional shield. The heat input of the heater at the 1K-JT cold tip was maintained at 5 mW.

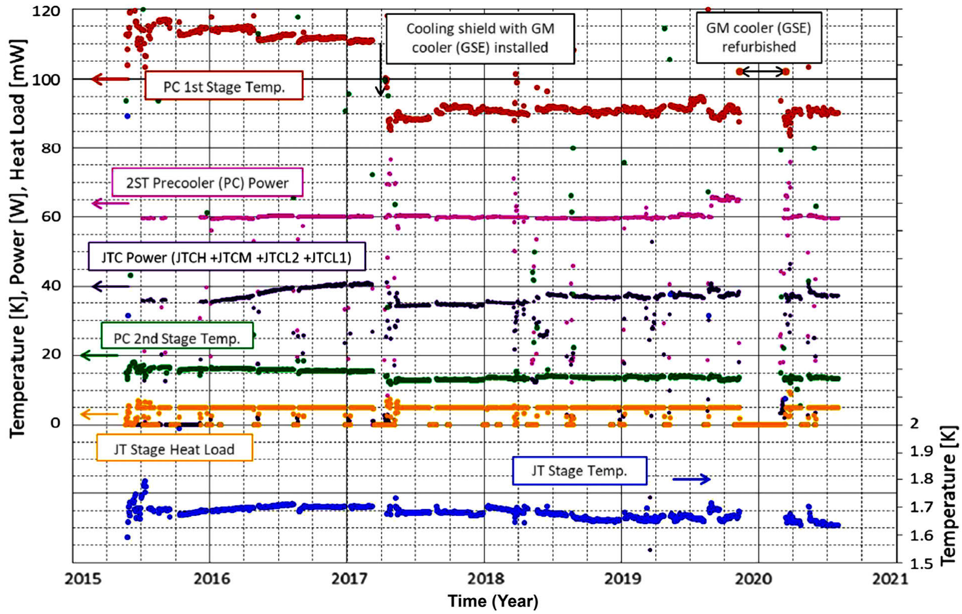

Figure 1. The 1K-JT lifetime test result. The cooling shield was added on March 2017.

Figure 1 shows the temperature behavior and the driving power during the 1K-JT lifetime test. Temperature at the 2ST 1st stage and the 2nd stage were reduced by the addition of the GSE thermal shield. Particularly, the 2ST 2nd stage temperature was changed to be lower than 15 K, while it was higher than 15 K without the additional shield. This indicated that the precooling temperature condition of the 1K-JT until March 2017 was more severe than the precooling temperature in the prior condition of the design. After that, the 1K-JT driving power could be reduced. The 1K-JT EM has successfully achieved more than four years of continuous operation without any major problems. The measured outlet pressure (PH) and the pressure at bypass line (PJ) showed slight increase, likely caused by the slight increase of the precooling temperature, while the flow rate of the working gas shows stable behavior as shown in Figure 2.

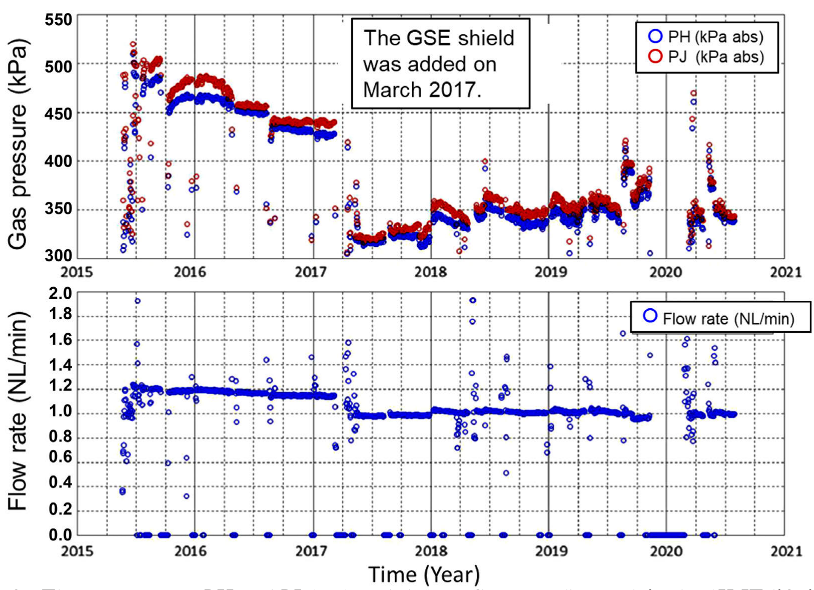

Figure 2. The gas pressure PH and PJ (top) and the gas flow rate (bottom) in the 1K-JT lifetime test.

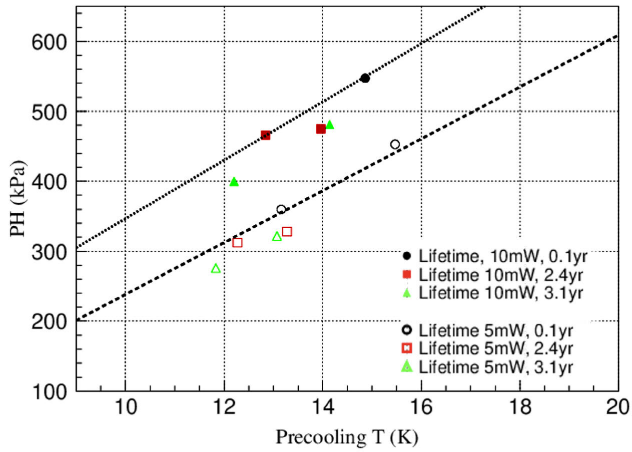

Figure 3. The outlet pressure PH needed to obtain the cooling power of 10 mW or 5 mW in the performance measurement of the lifetime test model. The dotted line and the dashed line show reference relation with the heat input of 10 mW and 5 mW respectively obtained by the 1K-JT performance model.

The 1K-JT cooling performance was also measured periodically in the lifetime test. Figure 3 shows the measured PH as a function of the precooling temperature (the 2ST 2[nd] stage). The dotted line and dashed line are the relations with the heat input of 10mW and 5 mW respectively obtained by the 1K-JT performance test model and these lines can be used as a reference. The measured pressure has uncertainty of about 30 kPa, which is provided by different conditions (the compressor temperature, the different temperature distribution of the inner thermal shield around the cold tip, etc..). If showed degradation at low temperature components in the lifetime test, the measured PH to obtain the specified cooling power becomes higher. As a result, the required PH to obtain the cooling power of 10mW and 5 mW after 3.1 year of operation is nearly identical to that obtained at beginning of life (BOL) and after 2.4 years of operation. It was also verified that the relation between the flow rate and the PH produced by the 1K-JT compressors after three years of operation was almost consistent with that at BOL and after 2.4 years. These results indicate that there is no major degradation of components at low temperature components including the cold tip and heat exchangers during the four year life test.

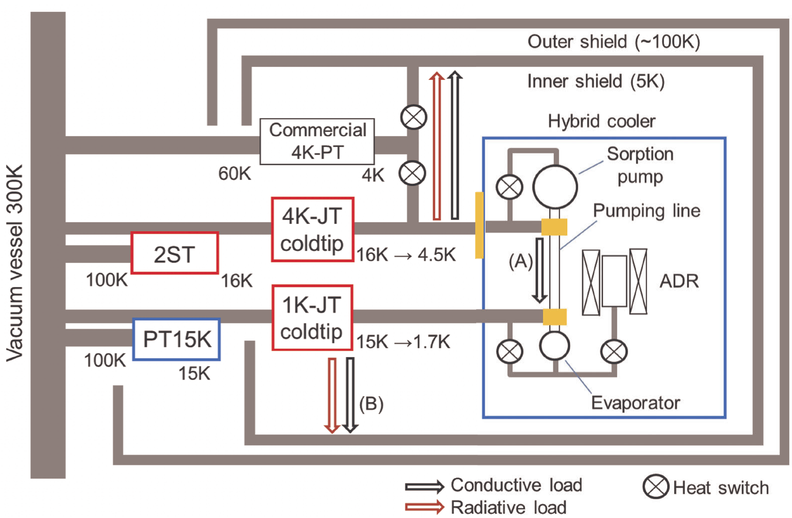

Figure 4. Schematic drawing of the cryostat1 setup. The 1K-JT temperature region is connected with the 4K-JT temperature region by the sorption gas pipeline [16].

Table 2. Pros and Cons of the pre-shipment test items.

	Pros	Cons
Plan 1: Conduct cooling test using a commercial 4K-GM cooler.	The cooling performance including the heat exchanger can be verified.	Additional GSE cryostat and GSE cooler are needed. Impact for cost and schedule. Remaining risk at interface (thermal conductance).
Plan 2: The compression performance test at room temperature (no cooling test).	Cost and schedule can be reduced.	Remaining risk in cooling performances (too low thermal conductance for precooling, too low heat exchange efficiency, unexpected parasitic heat load).

THE COOLER SYSTEM DEMONSTRATION WITH THE 1K-JT

The detector cooling demonstration campaign from 300 K to 50 mK started in 2016, under the framework of the ESA's Core Technology Program (CTP) for the X-ray Integral Field Unit (X-IFU) of ATHENA. As the intermediated step in the CTP, a 300K – 50mK cooling chain demonstration called "cryostat1" with the dedicated cryostat in France (CEA Grenoble) was planned and space-qualified mechanical coolers were coupled [11]. In the cryostat1 test, the engineering models of the 4K-JT with the 2ST precooler and the 1K-JT were integrated with the 50 mK hybrid cooler (a combination of 300 mK sorption cooler and 50 mK single stage adiabatic demagnetization refrigerator) and the 15 K-class pulse tube cooler (PT15K). The 50 mK hybrid cooler was jointly developed by CNES and the French Alternative Energies and Atomic Energy Commission (CEA) in the framework of SPICA SAFARI instruments project [12], and the PT15K was developed by ESA / CEA / Air Liquide / Thales Alenia Space [13]. Figure 4 shows the schematic drawing of the experimental setup between the hybrid cooler and JT coolers in cryostat1. Details of the cooler system design are described in Prouvé et al. [14].

Since the PT15K was used as the precooler for the 1K-JT, the first and second heat exchangers (HEX1 and HEX2, respectively) in the 1K-JT were modified for coupling with the PT15K. In the 1K-JT pre-shipment test, there were two test cases for the test item as shown in Table 2, as the PT15K could not be used. The first case performs the 1K-JT cooling performance test using a commercial 4K-GM cooler. In this case, a new cryostat for the cooling test is needed in Japan and impacts schedule. Furthermore, there is a remaining risk of the thermal interface, particularly the thermal contact conductance between PT15K and the 1K-JT. The second case performs the compression performance test at room temperature instead of the cooling performance test. As a conclusion, the latter case was selected as the pre-shipment test, because there were no major concerns at low temperature design of the 1K-JT had not experienced gas leaks during the JT cooler development. The dummy of the PT15K was used for the fit check and the shipment from Japan to France.

After transport, the PT15K dummy coupled with the 1K-JT was replaced with the PT15K after the transport, and the reception test was made to confirm the JT cooling performance after the assembly in the cryostat. The reception test confirmed that the 1K-JT cooling performance was almost consistent with the performance when integrated with the 2ST in the engineering model development as shown in Table 3. The PT15K precooler has a large cooling capacity compared to the 2ST, the 1K-JT performance with lower precooling temperature between 10 K and 15 K was also measured.

Table 3. The performance test result of the 1K-JT in the cryostat1. The same EM compressors were used in both cases.

	Precooler	**Heat input**	**JT cold tip**	**Precooler 2^{nd} stage**	**Precooler 1^{st} stage**	**JT driving power**
In cryostat1	PT15K	10 mW	1.72 K	14.9 K	92.2 K	40W
EM development	2ST	10 mW	1.68 K	14.3 K	94.3 K	44W

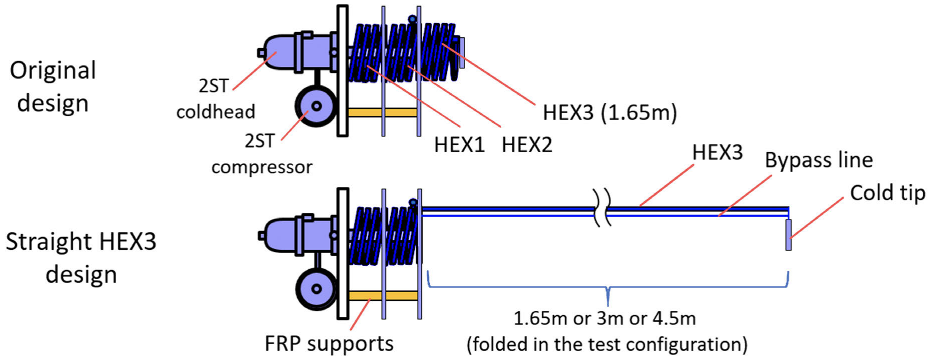

Figure 5. Schematic drawing of the JT cooler with the original design (top) and the straight HEX3 design (bottom).

The cooling performance, particularly the recycling of the hybrid cooler was demonstrated. Both JT coolers were operated with proposed interface conditions and successfully achieved a temperature of 50 mK was successfully achieved. Any piston collisions in the compressors or dry-out of the working gas at the JT cold tip were not detected. This is a milestone to demonstrate the future cooler system with the 1K-JT [15].

THE 1K-JT COOLING DOWN EXPERIMENT

In principle, the cooling capacity of a Joule Thomson cooler is lower at higher temperature. The cooling power *Q* is determined by the operating temperature, entropy variance *dS* and the mass flow rate of the working gas *m*. The inlet pressure is higher and lower *dS* results in lower cooling capacity at higher temperature, while the 1K-JT design including the orifice size and the filling pressure is optimized to obtain the specified cooling power of 10 mW at 1.7 K. Hence, the heat load into the 1K-JT must be lower than the cooling capacity between 1.7 K and the precooling temperature.

In the cryostat1 test, the 1K-JT cooling measurement with constant heat input was made to confirm the cooling capacity between 1.7 K and 15 K. Because the 1K-JT was integrated with the 50 mK hybrid cooler and the 4K-JT, the experimental setup was also an opportunity to demonstrate the 1K-JT cooling from the precooling temperature with almost the same thermal environmental condition as that in ATHENA X-IFU. The heater power of 5 mW was applied for the 1K-JT cold tip, while the heater power for the 4K-JT was controlled to keep the 4K-JT cold tip temperature 1~2 K higher than the 1K-JT to reduce the heat load from the 4K-JT interface to 1K-JT. The 1K-JT successfully reached 1.7 K, and it was confirmed that the 1K-JT has a cooling capability of higher than 5 mW between 1.7 K and 15 K [16].

THE COOLING PERFORMANCE WITH THE STRAIGHT HEAT EXCHANGER

In a cryogenic system, it is better to locate a JT cold tip close to focal plane instruments. Then, in some cases, a major modification of a heat exchanger design is needed to mount compressors on the base plate which is operated at room temperature and far from a low temperature focal plane. In SPICA, cold tips of 4K-JT and 1K-JT are located close to scientific instruments, while compressors and coldheads are mounted on the cooler plate of the service module [7]. In the conceptual study of the heat exchanger pipeline routing, the required length of the heat exchanger is 4.5 m at maximum, while the length is 1.65 m in the original design. Hence, it was determined that the 3rd heat exchanger (HEX3) design should be modified to be longer and straight shape for adopting the payload module design. The development of the unique HEX3 is effective for other large payload missions too.

Figure 5 shows the schematic drawing of the JT coolers with the straight HEX3. The HEX3 design is modified, while the HEX1 and the HEX2 can be the same as original design for maintaining the heritage and to couple with the 2ST precooler. The straight HEX3 must be surrounded by the JT pipe shield with the temperature between 30 K and 40 K for the thermal environment, and thermally insulated mechanical supports are also needed in the mechanical consideration.

In the straight HEX3 demonstration test, three different lengths of the HEX3 test models (1.65 m, 3 m and 4.5 m) were fabricated to measure the dependence of the heat exchanger length in the cooling performance. The original design (1.65 m length and toroidal shaped HEX3) was also measured as a reference. As expected, the cooling performance with the 1.65 m length could not satisfy the specification, because the heat-exchange efficiency expected by 1.65 m is low in a straight shape. The specified cooling power of 40 mW was successfully obtained with the length of 3 m and 4.5 m, and the measured outlet pressure and the flow rate were acceptable since both parameters can be obtained by the 4K-JT lifetime test model after 5-year operation. In the 1K-JT case, the cooling power of 12.5 mW at 2.5 K with ^{4}He was verified, because the cooling power of 12.5 mW at 2.5 K with ^{4}He corresponds to 10 mW at 1.7 K with ^{3}He in the compressor design. The test model satisfied the cooling power of 12.5 mW and the measured outlet pressure was almost consistent with the 1K-JT lifetime test model after 3-year operation. The demonstration result is a good heritage for the engineering model development and useful for the thermal study of the large payload module.

CONCLUSION

The lifetime test of the 1K-JT developed for space science missions has successfully achieved more than four years continuous operation without any critical degradations. The performance results indicate that there is no major degradation at low temperature components including the cold tip and heat exchangers during the four years of operation. Several experiments were also performed with the 1K-JT EM performance test model. In the cryostat1 test, which was an intermediate step to demonstration of the cooler system demonstration for ATHENA X-IFU, the 1K-JT EM was coupled with the 4K-JT and the 50 mK hybrid cooler, and successfully obtained 50 mK. The 1K-JT cool down experiment from 15 K precooling temperature with the heat load of 5 mW was measured and successfully to reach 1.7 K. The cooling performance of the longer length straight heat exchanger test model was also measured, and the specified cooling power was obtained for the 1K-JT and the 4K-JT configurations. These experimental demonstrations give important knowledge for the cooler applications of future space cryogenic missions.

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