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Cryogenic System for the Interferometric Cryogenic Gravitational Wave Telescope, KAGRA - Design, Fabrication, and Performance Test -

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Abstract. KAGRA is the cryogenic interferometric gravitational wave telescope designed for the direct detection of gravitational waves from the astronomical sources. To achieve the best sensitivity, one of the most difficult challenges is cooling the mirrors to 20 K to reduce the thermal noise. We developed four cryostats and sixteen very-low-vibration cryocooler units to accomplish our purpose. In this paper, we describe the outline of the cryogenic design and fabrication, and the results of the cryogenic performance test of the cryostats and cryocooler units.

Keywords: gravitational wave, cryocooler, low-vibration
PACS: 04.80.Nn

INTRODUCTION

Large-scale Cryogenic Gravitational Telescope, KAGRA, is an underground gravitational wave detector under construction in Kamioka Mine in Japan. It will search for gravitational wave events from compact binary mergers, supernova, neutron stars, and other possible gravitational wave sources. The detection of gravitational waves will open a new window to astrophysics.

The design of KAGRA is based on the experience that our group has gained through construction and operation of the 100 m Cryogenic Laser Interferometric Observatory (CLIO) [1] between 2003 and 2009. KAGRA is a cryogenic power-recycled Fabry-Perot Michelson interferometer with arm length of 3 km. The target sensitivity is $3\times10^{-24}\,\mathrm{m\,Hz^{-1/2}}$ at 100 Hz. To accomplish the goal, the detector is located underground to be isolated from the seismic motion, and it is crucial to keep the mirrors of the interferometer as free as possible from noise which interferes with the detection of the gravitational wave. Cooling and keeping the mirrors at 20 K to reduce thermal noise is one of the most challenging task in the development of KAGRA.

The cooling system of KAGRA consists of three major components: cryostats, very-low-vibration cryocooler units (hereafter cryocooler units), and cryogenic ducts. In this paper, we describe the outline of the design and fabrication, and the results of the thermal performance tests on the cryostats and cryocooler units.

COOLING SYSTEM DESIGN

The main design objectives of the KAGRA cooling system are to cool and keep the mirrors at 20 K to suppress thermal noise and to reduce the mechanical vibrations resulting from the cryocoolers to smaller than sub-μm order. A mirror is made of sapphire and has a diameter of 220 mm, thickness of 150 mm, and weight of about 23 kg. This mirror will be suspended by the suspension mechanism (payload) in a cryostat. Since four cooled mirrors are used for the cryogenic dual-recycled Fabry-Perot Michelson interferometer, we prepare four cryostats. Four cryocooler units are required for each cryostat, then a total number of the cryocooler units is sixteen. We use only cryocoolers to cool the cryostats without using any cooling fluid (gas nor liquid). Since the cryostat is required to achieve the pressures

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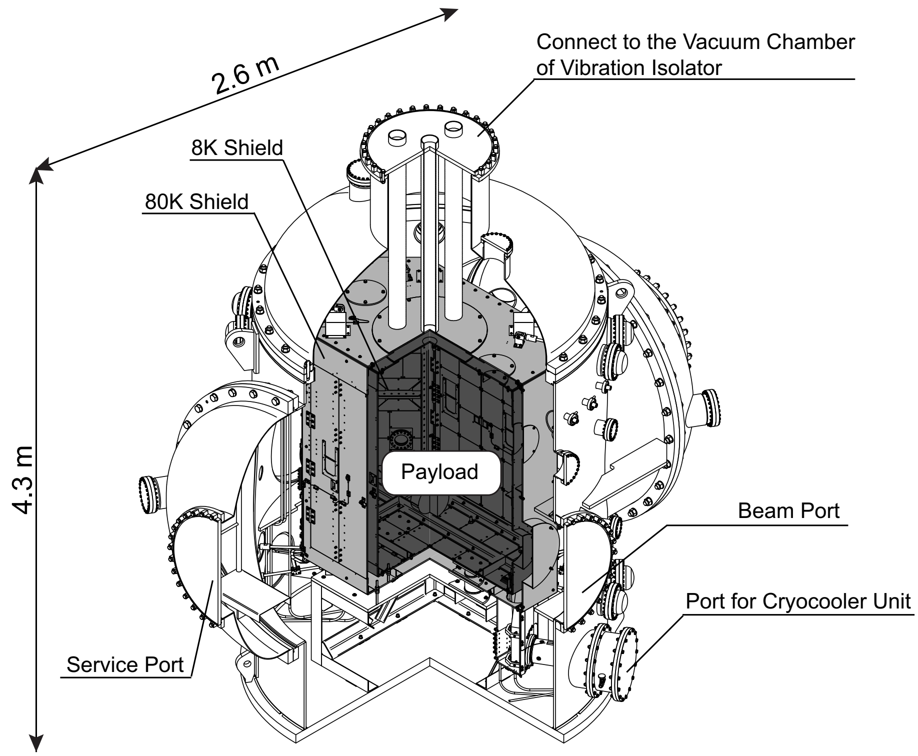


FIGURE 1. One-quarter cut section view of the cryostat. The dark-gray color is on the 8 K shield and the light-gray color is on the 80 K shield. Mirror and other components for the interferometer are not shown in this figure. MLI is also not shown here.

lower than 10^{-7} Pa, selection, fabrication, and handling of materials are strictly limited and required extraordinary procedures for both cryostats and cryocooler units. For the details of KAGRA's vacuum design, see [2].

Cryostats

Figure 1 shows the one-quarter cut section view of the cryostat. The cryostat is 4.3 meters in height and 2.6 meters in outer diameter, and it weighs 11000 kg. It is made of stainless steel 304. Inside the cryostat, double shields and payload are the main structures. One shield is called the "8 K shield" in which the payload including mirror and its suspension mechanism will be suspended. The operating temperature is around 8 K. The mirror is kept at 20 K by the thermal conduction transferred by the dedicated cooling lines for the payload from the cryocooler units. The main role of the 8 K shield is to absorb the heat from the scattering lights of the interferometer, and the role of the dedicated cooling line for payload is to absorb the heat generated inside the mirror by the light of the interferometer. The amount of deposition inside the mirror is estimated at 1 W per mirror, and heat from the scattering light is estimated at several watts. Another shield is called the "80 K shield" which surrounds the 8 K shield as the radiation shield and its operating temperature is around 80 K. The shield beams are made of 6000 series of aluminum alloy for its stiffness, and 1000 series aluminum plates are attached to the beams for its higher thermal conductance, so that we can cool the walls uniformly. Since the specific heat of aluminum becomes very small at lower temperature, response to the input heat is expected to be small and quick. The inner surfaces of the both shields are covered by 1000 series aluminum plates with plating of the Diamond-Like Carbon (DLC) to absorb the scattering lights. The total weight of the double shields is about 1400 kg. The shields are multiply-supported by the posts and rods made of DuPont Vespel®SP-1 by taking account of low thermal conductivity and low outgassing. The outer surface of the shields are covered by multi-layer insulations (MLI). Thus, the cryostat has the heat-insulated structures by taking advantage of ultra-high vacuum (UHV), hard radiation shield, and MLI. See also [3] for the detailed design of MLI.

As the design for serviceability, it is designed to accommodate up to four persons working inside the cryostat.

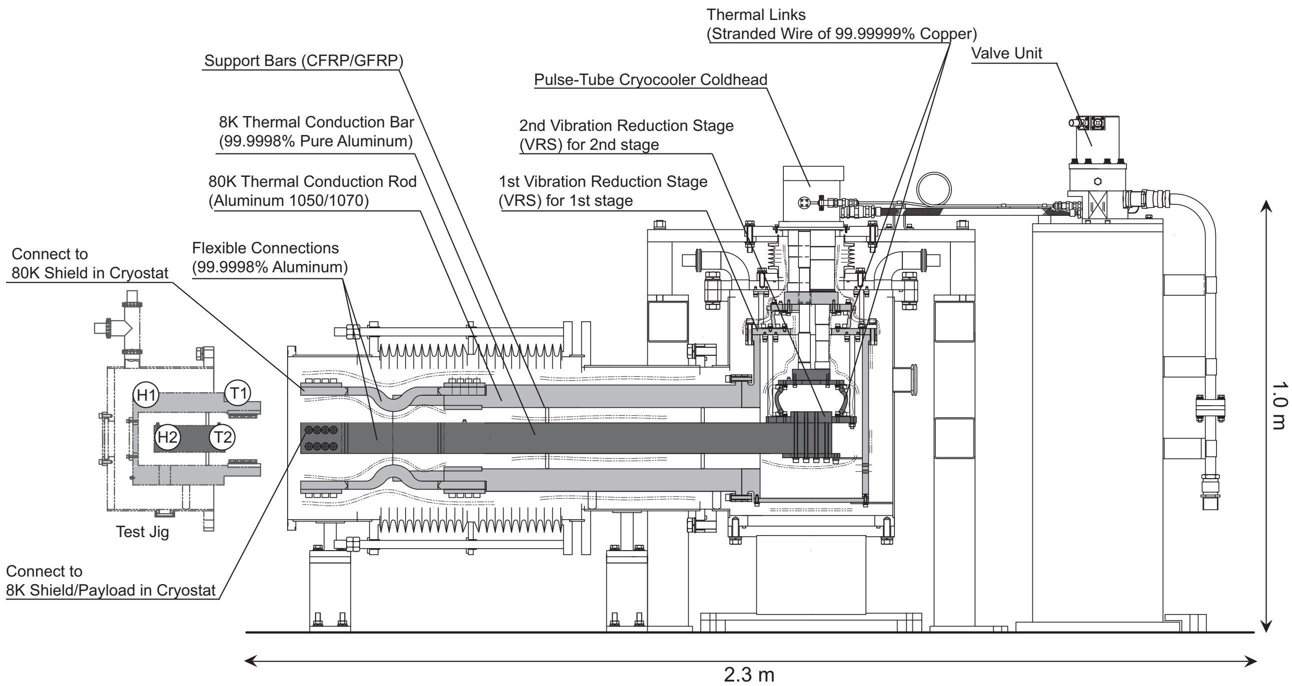


FIGURE 2. The sectional view of the very-low-vibration cryocooler unit. 8 K thermal conduction bar is colored in dark gray and the 80 K thermal conduction rod is colored in light gray. Test jig is attached to the end of the thermal paths for stand alone performance tests. T1 and T2 represent the location of temperature sensors for the test, and H1 and H2 represent that of heaters.

Cryocooler Units

Pulse-Tube (PT) cryocoolers are known for relatively low vibration in comparison to other types of cryocoolers such as Gifford-McMahon (GM) cryocooler since PT cryocoolers have no moving displacer. While it is reported that the typical displacement of cold head of PT cryocooler is about $\pm 10\ \mu m$ at the 1st stage and $\pm 15\ \mu m$ at the 2nd stages [4], our requirement for the vibration performance is that the maximum amplitude is not larger than $0.1\ \mu m$ at the thermal connecting area between the cryocooler units and cryostats. Thus, the cryocooler units are required to maximize the heat transfer, and at the same time, to reduce the vibration from the cold head less than one-hundredth.

A cryocooler unit consists of a double-stage pulse tube cryocooler cold head with a separated valve unit (SHI RP-082BS, 0.90 W at 4 K, 35 W at 45 K), a vibration isolation structure, and a heat conduction structure with vibration-reduction mechanisms. Figure 2 shows the sectional view of the cryocooler unit. It is about 2.3 meters long and 1.0 meter high and width, and total weight is about 1.2 tons. There are two different paths: "80 K thermal conduction path" led from the 1st cold head and "8 K thermal conduction path" led from the 2nd cold head. The paths of four cryocooler units are assigned as follows. Two 8 K thermal conduction paths cool the 8 K shield in the cryostat, another two 8 K paths cool the payload including the mirror, and all four 80 K paths cool the 80 K shield. In this way, we ensure the independent dedicated cooling lines for the payload to keep 20 K with enough cooling power margin to handle an unexpected heat load from the interferometer. The cold head is mounted on a rigid support frame which is separated from a vacuum vessel to avoid propagating of the vibration of the cold head. The valve unit is also structurally-isolated from the cold head and vacuum vessel. The vacuum vessel and support frame are made of stainless steel and the mount of valve unit is made of steel. Inside the vacuum vessel, the vibration isolation structures and thermal conduction structures are the essential components. Two Vibration Reduction Stages (VRSs) are fixed to the vacuum vessel rigidly by the rods made of baked glass-fiber reinforced plastics (GFRP) or polyacrylonitrile based carbon fiber reinforced plastics (CFRP). The 1st stage of cold head is connected to the 80 K thermal conduction rod by way of the 1st VRS, and 2nd stage of cold head is connected to the 8 K thermal conduction bar by way of the 2nd VRS. Between the VRSs and each stage, there are thermal links made of stranded wire of annealed seven-nines pure copper (99.99999 % purity, residual resistivity ratio (RRR) > 5000). As the extremely high-purity copper wires are very soft, these thermal links are expected not only to conduct heat but also to reduce the vibration from the cold head. The 8 K

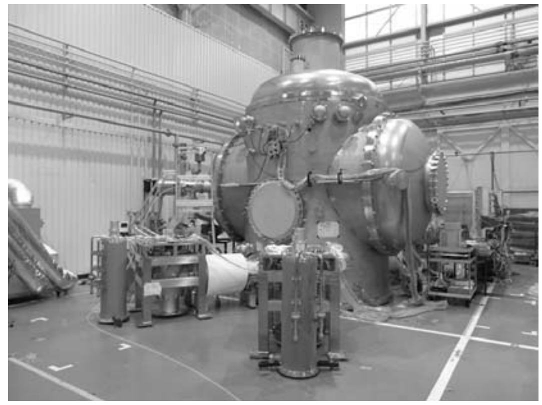


FIGURE 3. (LEFT) Pictures of the cryocooler unit testing its thermal and vibration performance. The test jig was attached to the end of thermal paths for the stand alone test. (RIGHT) Picture of the cryostat. Three of four cryocooler units are shown around the cryostat. Round-shape closing flanges at side will be connected to the beam tubes.

thermal conduction bar is made of five-nines eight pure aluminum (99.9998% purity) and the 80 K thermal conduction rod is made of 1000 series of pure aluminum. There are also flexible connections at the far end of thermal conduction paths, where the layers of five-nines eight pure aluminum (99.9998%) sheet are used for the same purpose as the stranded copper wires. The 8 K/80 K thermal conduction paths are 1.2 meter long. They are cantilevered and held steady by support bars made of CFRP/GFRP used for its properties, such as low thermal conductivity, mechanical strength, and low outgassing. The outer surface of the 8 K thermal conduction bar and 80 K thermal conduction rod are wrapped with MLI for thermal insulation.

During the design of the cooling system, we conducted mechanical and thermal analysis to feedback the results to the design. Moreover, we conducted performance tests on the first few units to improve the design for the later ones. The early phase design and experiments of the cryocooler units are described in [5].

FABRICATION

It took two years to design, fabricate, and evaluate the performance of the four cryostats and sixteen cryocooler units. In the first year (2011), seven cryocooler units were designed and fabricated at the JECC Torisha (Japan) and were tested for thermal and vibration performance at the KAGRA's laboratory in Kashiwa. At the same time, design and fabrication of the four cryostats had proceeded at the Toshiba Keihin Product Operations (Japan). In the second year (2012), the remaining nine cryocooler units were fabricated and evaluated as well, and fabrication of all the cryostats was finished. Then performance tests of all the four cryostats with the cryocooler units were conducted.

To achieve the required cooling performance under the UHV environments, we have given considerable attention to the material selection and handling procedure for all the components inside the cryostats and cryocooler units. Inner surface of the cryostats and cryocooler units are electrolytically-polished to prevent from long-term outgassing from greases, abrasive grain, and other contaminations. The assembly of the cryostat and cryocooler units was done in a clean room classified as ISO 14644-1 Class 7.

PERFORMANCE TESTS

To evaluate the cooling performance of the cooling system, we conducted three steps of testing in a stepwise manner: performance tests of the pulse-tube cryocooler itself, cryocooler units (Left on Figure 3), and the cryostats (Right on Figure 3). For all the cooling performance tests, calibrated silicon-diode temperature sensors (Lakeshore DT-670 series, calibrated range 3.2 K to 300 K) are used where high accuracy is required, and platinum-cobalt resistance temperature sensors (Netsushin Pt-Co-100Ω, measurement range 13 K to 373 K) are used in the other places. The cryocoolers operate at 50 Hz for all the tests described in this paper. Note that the utility power frequency is 60 Hz at the KAGRA site.

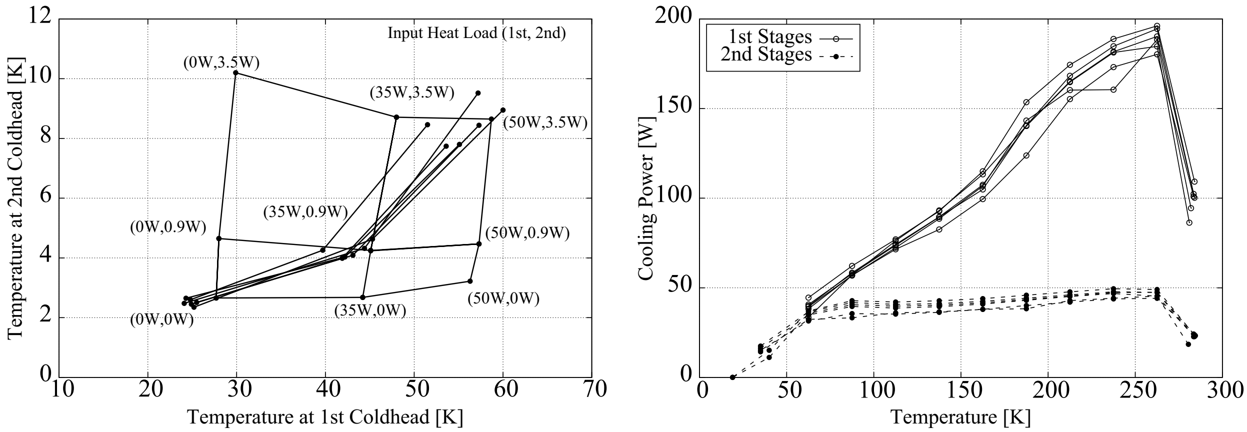


FIGURE 4. (LEFT) Measured load map of the SHI RP-082B PT cryocoolers. Seven cryocoolers out of sixteen were measured by two different heat load such as 35 W/0.9 W and 50 W/3.5 W for 1st/2nd stage respectively, and one of them was measured in detail by giving additional heat loads. (RIGHT) Measured cooling power of the cryocooler units at each temperature [6].

Performance Test on the Pulse-Tube Cryocoolers

We measured the stand-alone performance for some of the sixteen cryocoolers using a small test cryostat. Left on Figure 4 shows the resulting loadmaps of the cryocoolers. The cryogenic design of the cryocooler units was determined on the basis of these results.

Performance Test on the Cryocooler Units

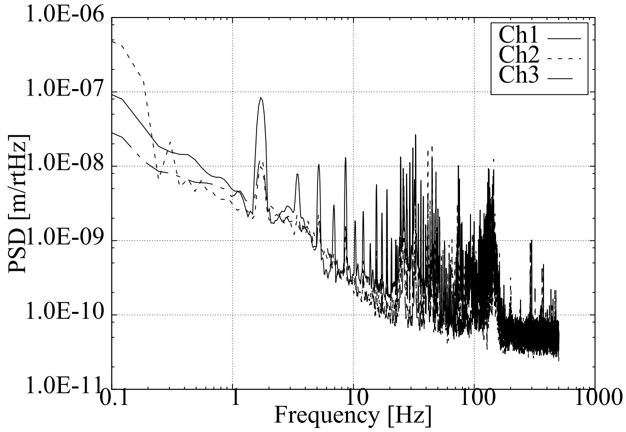
We conducted a heat load test on all the cryocooler units. The test jig is attached to the end of vacuum vessel when we test the cryocooler unit alone. It provides heater inputs to the thermal paths and three view ports. The general cooling time of the cryocooler units was about 70 hours. Right on Figure 4 shows the measured cooling power at each temperature. The achieving temperatures were around 3.5 K at the end of 8 K path and 33 K at that of 80 K path with no heat load. Then, the heat loads were applied at the connection area in place of heat load of the cryostat. We use heaters for the tests. The results are listed on Table 1.

In parallel with the cooling test, we measured the vibration of the connecting area when the cryocooler units are cooled at their minimum temperature. Using three sets of the laser displacement meters (LV-9300, Ono Sokki, range: $\pm 200\mu$m, resolution: 3 nm, frequency range: DC-100 kHz) we measured the vibrations of the connecting area directly from the three orthogonal directions through the viewports. The directions are along the 8 K thermal conduction bar (Ch 1), horizontal perpendicular to the bar (Ch 2), and the vertical (Ch 3). The measuring beams are entering into the vessel through the view ports and irradiate the surface of the connecting area. The reflected beams at the

TABLE 1. Achieving temperatures when the heat input of 0.9 W for 8 K path and 35 W for 80 K path were added at the same time on the cryocooler units performance tests. The locations of temperature sensors (T1 and T2) are shown at Figure 2.

	Unit ID	A	B	C	D	E	F	G	H
0.9 W@H2 (8 K Path)	Temperature (T2)	7.86	8.68	7.40	8.88	8.49	8.76	7.92	8.99
35 W@H1 (80 K Path)	Temperature (T1)	63.4	62.2	62.9	66.2	N/A	68.9	66.4	69.8

	Unit ID	I	J	K	L	M	N	O	P
0.9 W@H2 (8 K Path)	Temperature (T2)	8.98	8.98	8.98	8.67	8.92	8.40	8.97	8.10
35 W@H1 (80 K Path)	Temperature (T1)	69.7	69.9	69.9	65.0	60.0	66.7	66.6	69.6



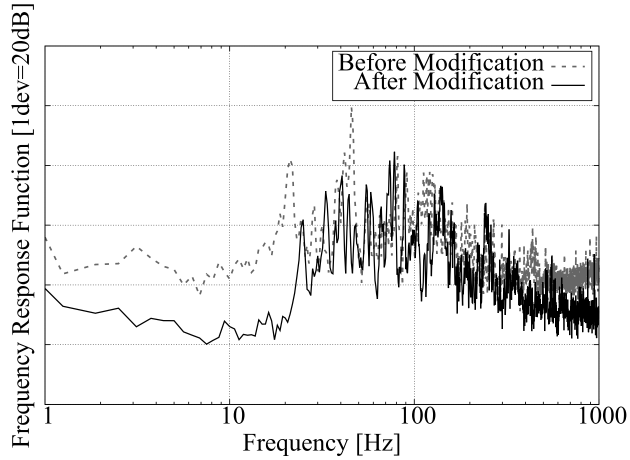


FIGURE 5. (LEFT) Measured typical power spectral density (PSDs) for the direction along the 8 K thermal conduction bar (Ch 1), horizontal perpendicular to the bar (Ch 2), and for the vertical (Ch 3). This is measured after the modification of the support structure. (RIGHT) The frequency response functions (FRFs) of the cryocooler unit obtained by the hammering test. The results before and after the modification of supporting structures are shown.

surfaces outgo from the view ports and relative displacement between the displacement meters and the surfaces are detected. On another hand, since the displacement meter and cryocooler unit are rigidly mounted on the concrete floor, low-frequency components of the floor vibration are given in the same phase and compensated. Then, while the low-frequency components of the floor vibration are not affected on the relative displacement, the high-frequency components are small enough to affect them. Thus, the effect of the floor vibration to the measured displacement is expected to be small. Measured signal is converted to a power spectrum density (PSD) by Fourier transformation. Left in Figure 5 shows the measured typical PSD for one cryocooler unit. The most dominant vibration is seen at the frequency of 1.7 Hz which occurs from the circulation of compressed helium gas of cold head. To suppress this vibration below 0.1 μm, we made some improvements to the support structure design. At the same time, we conduct hammering test to investigate characteristic vibrations of the structures. With the same setup as the vibration measurement, we hit some structures on the cryocooler unit and obtain the response spectra, that is the frequency response functions (FRFs), for the same three directions. From these results, we made further improvement on the stiffness of the structure. Right on Figure 5 shows the typical FRFs measured before and after the modification of the structure. You can see that the frequency with dominant peak shifted to the higher frequency after modification, that means the stiffness of the structure was enhanced.

Performance Test on the Cryostats

Finally we conducted the cooling performance tests of all the four cryostats at the Toshiba Keihin Product Operations in February and March 2013 (Right on Figure 3). It takes about 14 days to cool the 8 K shield to the lowest temperature. It turned out that all the cryostats have almost the same cooling time. Figure 6 shows the typical cooling curves obtained from the test with the calculated cooling curve of the 8 K shield. The estimation was calculated based on the cooling power (equivalent of that at two 8 K thermal conduction rods of the cryocooler units) divided by the total cooling mass (which is determined by multiplying the mass of the shield and specific heat capacity of aluminum, in this case). This rough estimation does not include the effect of radiation and the heat input from housekeeping and other individual components. The achieving temperatures were 4.3 - 6.3 K at the payload line where the heat link from the mirror will be transferred, 6.8 - 10.0 K at the top plate of 8 K shield, and 58 - 70 K at the top plate of 80 K shield. To evaluate the thermal response to the heat load, a few different heat loads were applied at the top plate of 8 K shield and the payload line. The heat loads correspond to the heat input from the scattering light and from the mirror, respectively. These results are useful for estimation and calibration of the amount of incoming heat. Note that there was no thermal mass connected to the payload lines for these tests. The results of heat load tests are listed on Table 2. From these results, we calculated the thermal budget to evaluate the performance of the cryostats and cryocooler units. Table 3 shows both designed and measured thermal budget. Since some major components like the duct shield, view ports, and payloads with mirrors (also laser beam with scattering light) are not installed in the cryostat, the evaluation is not enough at this

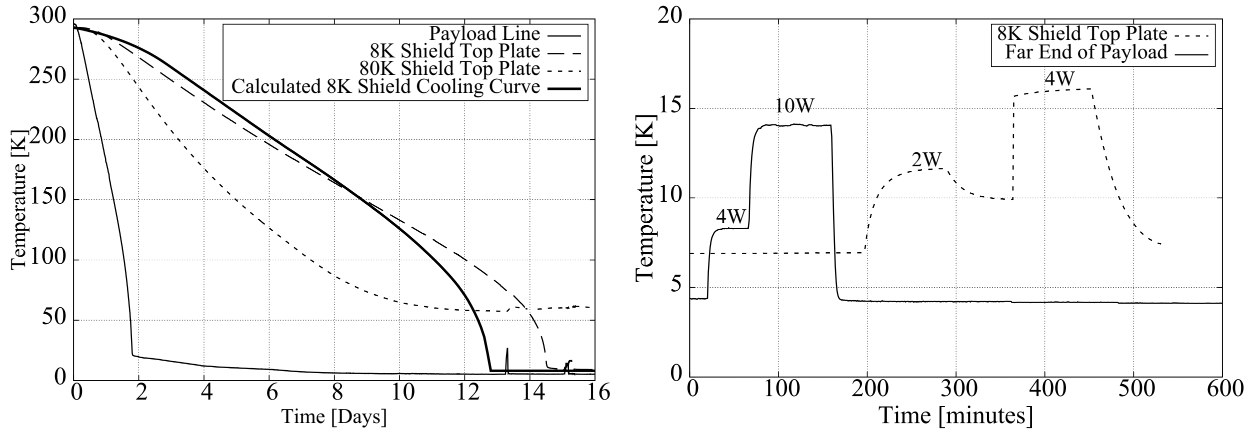


FIGURE 6. (LEFT) Typical cooling curves obtained from the cooling performance test of the cryostat No.2. (RIGHT) Typical temperature responses to the input heat load at the payload line and 8 K shield obtained from the test of the cryostat No.1.

TABLE 2. The results of thermal load tests. The tests are conducted to evaluate the thermal response to the heat load. Equilibrium temperatures with each heat load are written for each cryostat. All units are Kelvin (K).

Cryostat ID	Heat Load	1	2	3	4
Payload Line	0 W	4.3	4.4	6.3	6.3
	4 W	8.5	8.0	10.0	9.0
	10 W	13.5	13.5	14.0	14.0
8 K Shield Top Plate	0 W	6.8	9.5	10.0	8.2
	2 W	10.3	11.0	11.5	10.5
	4 W	11.8	N/A	N/A	N/A
	5 W	12.7	13.0	14.0	14.5
	10 W	16.1	16.0	18.0	16.5
80 K Shield Top Plate	0 W	63	58	50	70

time. However, we roughly confirmed that the cryostats and cryocooler units meet our specifications.

As described earlier, the mirror is cooled down to 20 K by both radiation to the inner surface of the 8 K shield and conduction by the heat link. Obviously the heat link is very thin to prevent it from propagating vibration. It is estimated that the cooling time of mirror is about two month, and that is not acceptable. So, shortening of the cooling time is a different challenge. During the above basic cooling performance tests, we conducted a series of cooling tests including radiation cooling test with using the test components with the different type of reflective coatings for such purpose. The details of the experiments will be described in [6].

CONCLUSION

The KAGRA, cryogenic gravitational wave telescope, is under construction in Japan. The most difficult challenge for KAGRA is to cool the four main mirrors of detector. Therefore, the cooling system of KAGRA has been developed, fabricated, and investigated their performance from 2011 to 2013. The measured performances met our specifications.

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TABLE 3. Estimated and roughly measured thermal budgets. Items marked with * are not included for this time. No thermal mass is connected to the payload line for this time.

	Components	Estimated Heat Load [W]	Measured Heat Load [W]
1st Cold Stage	80 K Shield	116	125
	(Load per Cryocooler	29 W/Unit	31 W/Unit)
	(breakdown)		
	- Eleven (11) View Ports	22 *	-
	- Radiation from 300 K	70	-
	- Support Posts/Rods	24	-
	- Electrical Wires	3×10^{-4}	-
2nd Cold Stage	8 K Shield	5	< 2.0
	(Load per Cryocooler	2.5 W/Unit	< 1.0 W/Unit)
	(breakdown)		
	- Duct Shields	< 0.05 *	-
	- Eleven (11) View Ports	0.4 *	-
	- Radiation from 80 K	2.2	-
	- Support Posts/Rods	2.4	-
	- Electrical Wires	3×10^{-4}	-
	- Scattering Light	Several watts *	-
	Payload	1 *	
	(Load per Cryocooler	0.5 W/Unit	0.4 W/Unit)
	(breakdown)		
	- Mirror Deposition	1 *	-

for our development environment. We would also like to appreciate Mr. Y. Kobayashi from the KEK Mechanical Engineering Center for making components for the performance test.

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