Cryogenic thermometry for refrigerant distribution system of JT-60SA

K Natsume, H Murakami, K Kizu, K Yoshida, Y Koide
Department of Tokamak System Technology, Japan Atomic Energy Agency, 801-1 Mukoyama, Naka-shi, Ibaraki-ken, 311-0193 Japan
E-mail: natsume.kyohei@jaea.go.jp

Abstract. JT-60SA is a fully superconducting fusion experimental device involving Japan and Europe. The cryogenic system supplies supercritical or gaseous helium to superconducting coils through valve boxes or coil terminal boxes and in-cryostat pipes. There are 86 temperature measurement points at 4 K along the distribution line. Resistance temperature sensors will be installed on cooling pipes in vacuum. In this work, two sensor attachment methods, two types of sensor, two thermal anchoring methods, and two sensor fixation materials have been experimentally evaluated in terms of accuracy and mass productivity. Finally, the verification test of thermometry has been conducted using the sample pipe fabricated in the same way to the production version, which has been decided by the comparison experiments. The TVO sensor is attached by the saddle method with Apiezon N grease and the measurement wires made of phosphor bronze are wound on the pipe with Stycast 2850FT as the thermal anchoring. A Cernox sensor is directly immersed in liquid helium as a reference thermometer during the experiment. The measured temperature difference between the attached one and reference one has been within ±15 mK in the range of 3.40-4.73 K. It has satisfies the accuracy requirement of 0.1 K.

1. Introduction
JT-60SA is foreseen in the Broader Approach Agreement as the satellite tokamak for ITER [1]. The upgrade to a superconducting device is underway using infrastructure of the existing JT-60. The superconducting coil system for JT-60SA consists of 18 Toroidal Field (TF) coils and 10 Poloidal Field (PF) coils. PF coils include a Central Solenoid (CS) with 4 modules and 6 Equilibrium Field (EF) coils. Mass production of magnet components is progressing in Japan and Europe [2].

The coils are all superconducting with forced-flow cooled conductors. The current of TF and PF coils are 25.7 and 20 kA, respectively. The current feeding system consists of in-cryostat feeders and Coil Terminal Boxes (CTBs). CTBs contain feeders and High Temperature Superconductor Current Leads (HTS CLs). All the manufacturing processes concerned were proof-tested [3].

The cryogenic system is under installation at Naka Site since April 2015. The helium refrigeration capacity is equivalent to about 9 kW at 4.5 K. It will supply refrigerant to the cryopump panels at 3.7 K, superconducting magnets and cold structures at 4.4 K, HTS current leads at 50 K, and thermal shields at 80 K. The specification of the cryogenic system was defined by CEA [4].

The refrigerant is transferred from the cryogenic system to cold components. The Valve Boxes (VBs) for the cryogenic distribution are installed just outside the main cryostat. The cooling pipes are installed in the cryostat between the transfer line, VBs, CTBs, and cold components because of the
available space in the existing tokamak building [5]. The 11 VBs and 5 CTBs are spread around the cryostat as shown in Figure 1.

1.1. Thermometry of a refrigerant pipe
The cryogenic system of JT-60SA supplies supercritical or gaseous helium to superconducting coils through valve boxes (VBs) and coil terminal boxes (CTBs). There are 86 temperature measurement points at about 4 K and 76 points at about 80 K along the cryogenic distribution pipes in vacuum in VBs, CTBs, and the in-cryostat piping displayed in Figure 1. Two thermal sensors are installed at almost all the points for redundancy. The requirement of the measurement accuracy for the magnet coil temperature control loops at 4.2 K for JT-60SA is ±0.1 K, which is the same as the one for ITER, described in the Design Description Document: DDD11-9 Instrumentation and controls. It is also required that the temperature acquisition period per thermometer should be less than 2 seconds. The time constant of temperature response should be the same or less than the order of the period. The refrigerant distribution system will be difficult to be accessed after the construction of JT-60SA completes. For the thermometry, maintenance-free is generally required in the whole operation period of JT-60SA of about 10 years.

1.1.1. Attachment method.
Two installation methods of thermal sensors are well known. A schematic view of two concepts is shown in Figure 2. One is "the well method" of which the sensor is installed in a narrow stainless steel capillary that is inserted into a cryogen pipe and welded with the pipe. This method is relatively conventional and yields accurate measurement, but extra technical inspections have to be imposed in order to confirm the leak tightness because of machining and welding pipes.

The other is called "the saddle method" in this paper. The sensor is installed in a copper block which is attached on the pipe by silver brazing. This method is easy to manufacture and does require

Figure 1. Drawing of the Cryogenic distribution system for JT-60SA: Transfer Line, In-Cryostat Piping, Valve Boxes, and Coil Terminal Boxes. The Tokamak body is partially transparent.

Figure 2. Schematic views of two types of attachment concept
specific inspections, but it provides a relatively inaccurate measurement because of less thermal contact between the sensor and the fluid. This kind of method was developed by CERN as cryogenic vacuum thermometer kits with three heat-sink blocks and serpentine leads in Print-Circuit Board (PCB) cards [6] [7]. The similar kit will be adopted to the cryogenic thermometry of ITER.

The well method was adopted for the inlet and outlet lines for the PF coils of JT-60SA because relatively higher accuracy is required for the magnet control. On the other hand, the mass productivity is also important if there are many measurement points. The high accuracy is not strictly required for the other lines. In this work, a saddle method which is less complex than one of the CERN thermometer kit has been examined. The conventional well method and the saddle method have been experimentally evaluated in terms of accuracy and mass productivity. Additionally, the materials used to fix the sensor to the holder installed on the pipe have been also tested.

1.1.2. Thermal anchoring of measurement wire. One of the main factors of accuracy for cryogenic thermometry is reducing the heat flux to the sensor. The essential error of thermometry is caused by the difference between the heat flux and the cooling capacity to the sensor. The cooling capacity is dependent on the sensor attachment method. On the other hand, the heat flux to the sensor is dependent on the conduction and radiation heat load to the sensor. For comparison, two thermal anchoring ways of measurement wires are experimentally tested in this work.

1.1.3. Thermometer sensor. Resistance temperature sensors will be installed on cryogen pipes in vacuum. In this work, The accuracies of Cernox and TVO sensors [8][9] have been experimentally examined simultaneously. TVO stands for initials of Heat resistant Waterproof Volumetric in Russian.

Figure 3. Drawing of the experimental apparatus. The sensors are installed in and on the sample pipe.

Figure 4. Setup of the sensor holders and the measurement wires thermally anchored with PCB. This sample pipe is connected to the LHe reservoir and the return pipe. (*PCB = Printed-Circuit Board)

2. Experiments and results
A measurement apparatus was fabricated for testing thermometers in the similar situation to the actual one of JT-60SA refrigerant distribution system. Figure 3 shows a drawing of the apparatus. It is mainly composed of flanges, thermal baffles, a Liquid Helium (LHe) reservoir, a sample pipe, and a return line. The sample pipe is connected to the LHe reservoir and the return line. These connections are detachable by VCR® Metal Gasket Face Seal Fittings. The LHe reservoir has a Standard Liquid
Helium Level Sensor (American Magnetics Inc.) and is filled up to 5 litter with LHe during operation. The LHe reservoir is welded to the top flange, which has evacuation lines, inlets of LHe and liquid nitrogen (LN₂), and feed-through ports for measurement wires. This apparatus is installed in a cryostat, which has outer cylinders for LN₂ and vacuum. The space around the sample pipe, the LHe reservoir and the return line is vacuumed by a turbo-molecular pump with a rotary pump.

2.1. Comparison of "well method" and "saddle method"
An experiment has been conducted in order to compare the accuracies of the saddle method with that of the well method. Two sensors attached on a sample pipe by these methods are tested at the same time using liquid helium. Additionally, a thermal anchoring method using a PCB is tested.

A picture of sensor holders and the measurement wires thermally anchored with PCB is shown in Figure 4. Three Cernox thermometers are used for this experiment. Two of them are attached on the pipe by the two different methods. These two sensors are installed in holes of holders with Apiezon N grease as infill. Measurement wires from sensors to PCB are made of Phosphor bronze coated with polyimide and the wire diameter is 0.203 mm (32 American Wire Gauge). Base material of PCB is glass-reinforced epoxy resin (FR-4) and the dimension of a copper circuit is 0.8 mm × 35 μm. Measurement wires from the PCB to top flange are shielded four-core cable of which the core of 0.49 mm in diameter is made of copper covered with ETFE (Ethylene tetrafluoroethylene). The shielded cable is thermally anchored on the surface of the upper part of the LHe reservoir of which the estimated temperature is 80 K. A copper thermal shield covers on the sensor holders and the thermal anchor block. The other one of three sensors is installed in the pipe to be directly immersed in the liquid helium as the reference sensor. The specifications of sensors and measurement instruments are summarized in Table 1.

| Table 1. Specifications and configuration of measurement equipments for Cernox |
|----------------------------------|------------------|------------------|
| Type of Temperature Sensor       | Cernoxᵀᴹ RTD     |                  |
| Sensor Code                      | CX-1050-AA-1.4L  |                  |
| Temperature Monitor              | Lake Shore Model 332 Temperature Controller |
| Excitation                       | 10 μA            |                  |
| Current Reversal                 | On               |                  |
| Filter                           | Off              |                  |
| Data acquisition                 | Graphtec GL220   |                  |
| Sampling rate                    | 200 ms - 1 s     |                  |

The temperature of the LHe is varied by changing the pressure in the LHe reservoir. The differences between observed values of sensors attached on the pipe and immersed in LHe are evaluated to obtain the accuracy of the pipe attach methods.

The measured temperatures of three Cernox sensors are 4.220 K for the well method sensor, 4.233 K for the saddle method sensor, and 4.224 K for the reference sensor at the atmospheric pressure. These values are average for 200 seconds before varying the LHe temperature: data of 0-200 seconds shown in Figure 5 and Figure 6. The differences from the temperature of reference sensor are 4 mK for the well method and 9 mK for the saddle method. Typical sensor accuracy of Cernox is regarded as ±5 mK at 4.2 K [10][11][12]. It is verified that the measurement instruments, wire anchors, and both attachment methods of this experiment are properly conducted because these differences are within the sensor accuracy. Note that the LHe temperature at the standard atmosphere (101.3 kPa) is 4.224 K.

The measured temperatures in the range of 3.37-4.42 K are shown in Figure 5. The ramp rate is approximately 0.62 mK/s. Three measured temperatures look like to be merged to one line. The differences from the temperature of the reference sensor are shown in Figure 6. The well method
Temperature is about 5 mK below the reference one, and the saddle method temperature is 2-10 mK above the reference one. The measured temperatures in the range of 4.22-5.06 K are shown in Figure 7. The ramp rate is approximately 1.82 mK/s. The differences from the temperature of the reference sensor are shown in Figure 8. The temperature differences are less than 17 mK for the well method and less than 38 mK for the saddle method. Both results satisfy the requirement of ±0.1 K in accuracy. The saddle method has been selected for the thermometry because of higher mass productivity than the well method. The thermal anchoring method of measurement wires using PCB has been verified.

2.2. Comparison of two type of sensors

Two types of sensors, Cernox and TVO, have been experimentally tested in order to confirm their accuracies to be enough for the requirement of JT-60SA cryogenic thermometry. In addition, an anchoring method of measurement wires with Stycast 2850FT alternative to PCB has been examined.

A picture of the sample pipe setup is shown in Figure 9. One TVO is installed in the hole of the sensor holder with Apiezon N grease. The wires are wound with 5 turns on the pipe with Stycast 2850FT, which is cured at room temperature. One Cernox and another TVO sensors are directly immersed in LHe at the same time. Specifications and configurations of measurement equipments of TVO are summarized in Table 2. The LHe temperature can be estimated from the atmospheric pressure when the LHe reservoir is opened to the atmosphere. The differences between the measured
values and the estimated value are evaluated. Furthermore, measured values of two sensors are compared with each other when the LHe reservoir is pressurized or depressurized.

![Image of setup](image1.png)

**Figure 9.** Setup of the sample pipe for the wire anchoring test using Stycast 2850FT. One Cernox and another TVO are installed in the pipe to be directly immersed in LHe, although they are unseen here.

![Image of measured data](image2.png)

**Figure 10.** Measured temperature data when the LHe reservoir is opened to the atmosphere. The boiling temperature is estimated to be 4.215 K as the reference one at this time.

| Table 2. Specifications and configurations of measurement equipments of TVO |
|-------------------------------------------------|-------------------------------------------------|
| **Type of Temperature Sensor**                  | **TVO (Russian abbreviation)**                  |
| Sensor Code                                     | CCS-B (Carbon-Ceramic Cryogenic Sensor)         |
| Volt meter                                      | Keithley 2182A Nanovoltmeter                    |
| Constant current source                         | Accuracy                                        |
|                                                 | 10±0.001μA                                      |
| Current Reversal                                | N/A                                             |
| Data acquisition Interface                      | GPIB                                            |
| Software                                        | LabVIEW                                         |
| Sampling rate                                   | 100 ms - 1 s                                    |

The measured temperatures of sensors in LHe are 4.221 K for the Cernox and 4.238 K for the TVO at the atmospheric pressure. These are average values for 300 seconds. The boiling temperature of LHe is 4.215 K at 100.48 kPa of which the atmospheric pressure is measured by the nearest meteorological observatory at the time. This is the standard temperature reference. The differences from the standard are 6 mK for the Cernox sensor and 23 mK for the TVO sensor. In addition, the TVO sensor on the pipe in vacuum indicates 4.224 K as the average. The data of these measurements are shown in Figure 10. The measured temperatures in the range of 3.40-4.73 K and plots of Cernox temperature versus temperature differences are shown in Figure 11 and Figure 12, respectively. These differences are in the range of -28 mK to 26 mK. The difference between TVO on the pipe and Cernox in LHe is ±15 mK. It has been confirmed that TVO attached by the saddle method with the Stycast anchoring is applicable for the thermometry of JT-60SA refrigerant distribution pipes.
Figure 11. Measured temperatures in the range of 3.40-4.73 K. Around 50, 60, 65, and 90 minutes, the data acquisition stops then restarts.

Figure 12. Differences between measured temperatures. The larger differences around 4.2 K are caused by changing the temperature relatively quick.

Figure 13. Setup of the sample pipe for the thermal cycle test. TVO sensor is directly attached on the Cu block and fixed with Stycast 2850FT.

Figure 14. Calculated temperature from the measured resistance of the sensor which is in LN2. First and second plots are measured values before the sensor is fixed to the pipe.

2.3. Thermal cycle test of a sensor installed in epoxy resin
Temperature sensors are installed in the holes of the sensor holder on the pipe with Apiezon N grease as infill in our design. The dropping point of Apiezon N grease is 42-52 K, at which the grease passes from a semi-solid to a liquid state. The thermometry pipe will be completely manufactured in a factory, then will be supplied to the constructor of VBs, CTB, and in-cryostat piping. A sensor dropping from a holder is a concern when the temperature increases by welding of this pipe to connect to the distribution pipes in construction. If an epoxy resin can be used to fix the sensor on the holder directly, the concern can be solved, and moreover, the thermal contact between holder and sensor increases. However, the degradation of sensor is a potential problem due to the compression induced by the thermal contraction of epoxy resin.

A sample pipe is fabricated to conduct a thermal cycle test. The pipe has a copper block on which a TVO sensor is fixed with the Stycast 2850FT. It is cured at room temperature with Catalyst 23 LV as epoxy hardener. A picture of the pipe for the test is shown in Figure 13.
The procedure of thermal test is described below. At first, the sample pipe is immersed in LN2. Then the resistance of the sensor is measured. After that, the pipe is raised from LN2 and warmed by a blower. This procedure is repeated several times to examine the degradation of sensor by the thermal contraction.

The temperatures calculated by measured resistances are shown in Figure 14. The calculated temperature increases after the sensor is fixed with the Stycast and cooled down by LN2. It indicates that degradation of sensor is caused by the thermal contraction of the Stycast. Since TVO sensor is made of bulk of ceramic, fixation methods which induce the compaction force to the sensor should be avoided, after all.

3. Conclusion

Four comparisons of the thermometry of cooling pipes have been experimentally evaluated in terms of accuracy and mass productivity in order to decide the actual production design. The sensor accuracies are evaluated by the difference from the reference temperature in this work. The requirement of the thermometer accuracy is ±0.1 K.

- **Sensor Attachment: The well method and the saddle method.** The accuracies are ±17 mK for the well method and ±38 mK for the saddle method in the range of 3.37-5.06 K within 1.82 mK/s in the ramp rate. Both methods are acceptable in accuracy. The saddle method has been adopted for the cryogenic thermometry of JT-60SA refrigerant distribution pipes because of the higher mass productivity.

- **Sensor type: Cernox and TVO.** The difference between two types of sensor are ±28 mK in the range of 3.40-4.73 K within about 10 mK/s in the ramp rate. Both types of sensor are acceptable. The TVO sensor is adopted because of higher mass productivity.

- **Thermal anchoring way: PCB and phosphor bronze wires with Stycast 2850FT.** Both methods have been verified to be sufficiently accurate. Phosphor bronze wires with Stycast 2850FT has been adopted as the thermal anchoring because of higher mass productivity.

- **Sensor fixation material: Apiezon N grease and Stycast 2850FT.** The sensor fixed by the Stycast has been deteriorated by the thermal contraction with the thermal cycle. Apiezon N grease is adopted as the infill in holes for sensors.

The verification test of thermometry has been conducted using the sample pipe fabricated in the same way to production versions. The sensor attachment, wire anchoring, and thermal shielding method are confirmed to be acceptable in terms of accuracy and mass productivity. The thermometric pipes will be produced in this way for the JT-60SA construction.

References

[1] Kamada Y, Barabaschi P, and Ishida S 2013 Nuclear Fusion **53** 104010
[2] Yoshida K *et al* 2014 *IEEE Transactions on Applied Superconductivity* **24** 4200806
[3] Kizu K *et al* 2015 *Fusion Engineering and Design* (to be published)
[4] Michel F, Hitz D, Hoa C, Lamaison V, Kamiya K, Roussel P, Wanner M, and Yoshida K 2012 *Adv. Cryog. Eng., AIP Conf. Proc.* **1434** 78
[5] Yoshida K *et al* 2013 *Fusion Engineering and Design* **88** 1499
[6] Belle C and Casas J 1995 *Adv. Cryog. Eng.* **B 41** 1715
[7] Darve C and Casas J 2001 *Cryogenics* **41** 319
[8] Datskov V and Wisend J 1994 *Cryogenics* **34** 425
[9] Datskov V, Kirby G, Bottura L, Perez J, Bergonolletti F, Jenninger B, and Ryan P 2014 *IEEE Transactions on Applied Superconductivity* **24** 9000905
[10] *Temperature Measurement and Control Catalog*, Lake Shore Cryotronics, Inc
[11] Casas J 2014 *IEEE Instrumentation & measurement Magazine* **52** 57
[12] Courts S and Krause J 2012 *Adv. Cryog. Eng., AIP Conf. Proc.* **1434** 1329