The 4 K outer cryostat for the CUORE experiment: construction and quality control

F. Alessandria, M. Biassoni, G. Ceruti, A. Chiarini, M. Clemenza, O. Cremonesi, V. Datskov, S. Dossena, M. Faverzani, E. Ferri, A. Nucciotti, M. Perego, E. Previtali, M. Sisti, L. Taffarello, F. Terranova

a INFN Sez. di Milano, Milan, Italy
b INFN Sez. di Milano-Bicocca, Milan, Italy
c Dipartimento di Fisica, Università di Milano-Bicocca, Milan, Italy
d INFN Sez. di Bologna, Bologna, Italy
e CERN, Geneva, Switzerland
f INFN Sez. di Padova, Padova, Italy

Abstract

The external shell of the CUORE cryostat is a large cryogen-free system designed to host the dilution refrigerator and the bolometers of the CUORE experiment in a low radioactivity environment. The three vessels that form the outer shell were produced and delivered to the Gran Sasso underground Laboratories in July 2012. In this paper, we describe the production techniques and the validation tests done at the production site in 2012.

Keywords: Cryogenics, Neutrinoless double beta decay

1. Introduction

CUORE [1] [2] [3] is a ton-scale neutrinoless double-beta decay experiment currently under construction in the Gran Sasso Underground Laboratory (Laboratori Nazionali del Gran Sasso, LNGS, Italy). The detector will consist of 988, $5 \times 5 \times 5$ cm$^3$ TeO$_2$ bolometers operating at very low temperature ($T \approx 10$ mK). The active mass of CUORE (740 kg) exceeds the mass of its precursor (40.7 kg [4]) by more than one order of magnitude and sets unprecedented challenges both in terms of material radiopurity and cooling power. The CUORE cryostat [5] [6] must deliver appropriate cooling power to keep the bolometers and their support structure (about 1500 kg overall mass) at 10 mK base temperature. In addition, the cryostat operation must be reliable enough to guarantee year-long data taking and must not introduce microphonic noise, which translates into instabilities in the detector readout. Finally, the materials have to be carefully chosen in order to reach background levels $\leq 10^{-2}$ counts/keV·kg·y [7]. The design of CUORE has taken advantage of the progresses in cryogen-free refrigerators over the last twenty years [8]. The CUORE cryostat is made up of two vacuum tight vessels and four thermal shields (Fig. [1]). The two outer vessels and the shield between them constitute the outer cryostat which will maintain a 4 K environment (“4 K cryostat”) by means of two stage Pulse Tube refrigerators [9] which will cool the inner vacuum tight vessel to about 4 K; the inner thermal shields will be cooled by the thermal stages of a He$^3$/He$^4$ Dilution refrigerator as well as the detector. Radiopurity requirements for the 4 K cryostat are less demanding since the inner volume is screened by a low activity lead shield. Nevertheless, the use of steel cannot be afforded and special care must be put in the welding procedures to avoid presence of contaminants. In this paper we describe the design of the outer 4 K cryostat and its requirements to operate in the cryogenic apparatus of the CUORE experiment (Sec. [2]). Sec. [3] describes the fabrication of the 300 K and 4 K vessels, the 40 K thermal shield and the technical choices employed to fulfill the above requirements. The cleaning procedure is detailed in Sec [4]. Finally, the validation tests done at the production site are described in Sec. [5] and [6].

2. The 4 K cryostat: design and specifications

The CUORE cryostat consists of six nested vessels and shields. The three outermost ones are included in the outer Cryostat. Two of them (300 K and 4 K) are vacuum tight: the space between the 300 K and 4 K vessels constitutes the Outer Vacuum Chamber (OVC).
of the cryostat and the 300 K vessel operates at room temperature. The volume inside the 4 K vessel represents the Inner Vacuum Chamber (IVC) and in normal running condition this vessel is thermalized to 4 K. Between the 300 K and 4 K vessel there is a thermal radiation shield at 40 K covered with multi-layer aluminized superinsulation. Up to five pulse tubes (PT) mounted on the OVC top plate provide the cooling for the 40 K radiation shield (PT first stages) and the IVC (PT second stages). The IVC encloses the detector and the shielding lead with a volume of about 3 m$^3$.

The mass to be cooled and the tight requirements on the bulk radioactivity strongly constraint both the material choices and the production techniques that can be employed for the outer cryostat. In fact, in order to preserve radiopurity the use of copper for the vessels and shields is mandatory and therefore stainless stainless steel cannot be used. Most conventional welding techniques cannot be employed since potentially they can increase the bulk radioactivity due to filler materials and electrodes. In addition, the 4 K cryostat will be operated both in PT-cooling mode and in fast cooling mode. When cooling power is provided just by the pulse tubes (PT-cooling mode), both the IVC and OVC must be under vacuum ($< 10^{-4}$ mbar at room temperature).

However, to speed up the cooling of the shielding lead (fast cooling mode), cold Helium gas will be injected into the IVC. For proper operation, the Helium in the IVC will be maintained at an absolute pressure of about 130 kPa (1.30 bara). Hence, the mechanical properties and vacuum tightness must be sustained by the IVC and OVC separately and under overpressure conditions.

The most relevant specifications for the 4 K outer shell can be summarized as follows:

- **Vacuum** Both the 300 K and 4 K vessels must be able to stand vacuum at room temperature ($p < 10^{-4}$ mbar); the vacuum tightness of the weldings and of the seals (elastomer orings for the OVC, indium and metallic gasket for the IVC) must be kept at the $10^{-9}$ mbar · l/s level.

- **Pressure** The 4 K and 300 K vessels must be able to stand both internal and external overpressure according to the design specification of Tab. 1 without mechanical deformations or worsening of the above-mentioned vacuum specifications.

- **Thermal properties** The vessels must be able to preserve vacuum and pressure specifications after multiple thermal cycles down to 4 K.

- **Radiopurity** The $^{232}$Th and $^{238}$U contamination of all cryostat thermal shields/vessels must be $< 2 \times 10^{-6}$ Bq/kg and $< 10^{-4}$ Bq/kg, respectively.

The vacuum and pressure specifications were tested in a direct manner at the production site and are described in Sec. 5 and 6. In addition, since thermal contraction effects saturate already at liquid Nitrogen temperature (77 K), a dedicated colt test at 77 K was also done, as described in 6.3. The bulk radiopurity of the copper selected for the production of the 4 K cryostat (see Sec. 3) was sampled during the material procurement. No additional radiopurity tests were performed at the production site and the contributions due to machining and surface cleaning will be determined during the commissioning runs at LNGS.

| vessel | $\Delta P_{\text{max}}$ [bar] |
|--------|-----------------------------|
| OVC    | 0.1 internal 1.01 external  |
| IVC    | 1.5                        |

Table 1: Design operating pressure for OVC and IVC vessels.
3. Production of the 4 K cryostat

The vessel shells and torispherical heads are made of selected high purity copper produced by Norddeutsche Affinerie [10]; the chosen copper alloy for the outer cryostat is the Oxygen Free Electrolytic (OFE) one. Assays of Cu-OFE samples set only an upper limit of about $2 \times 10^{-11} \text{ g/g}$ for the $^{232}\text{Th}$ content, which is appropriate for the CUORE background requirements mentioned in Sec. 2. The 300 K vessel is also made of Cu-OFE, except for the upper flange, which is built from austenitic stainless steel (EN 1.4307, AISI 304L). Similarly, the top plates for the 40 K shield and 4 K vessel are copper-made, while the top plate of the 300 K vessel is made of stainless steel. The mechanical properties of the copper and stainless steel alloys employed are listed in Table 2; the Cu-OFE R220 copper alloys have been used exclusively for the torispherical heads to ease the forming. The use of stainless steel for the top flange and plate of the 300 K vessel guarantees a better mechanical stability and vacuum tightness. The same choice was not possible for the 4 K vessel because of the poor thermal conductance of stainless steel. Table 3 summarizes the main mechanical parameters of the outer cryostat. The wall thicknesses were determined by the operating pressure requirements (Table 1) and were calculated according to the ASME code [11]. A linear buckling analysis performed with ANSYS [12] gives a limiting differential pressure of 2.0 and 2.3 bar for the OVC and IVC vessel, respectively. For what concerns the top 300 K and 4 K plates, dimensions were chosen accounting for the static mechanical loads (vessels and lead shield) and possible additional loads induced by seismic events.

The vessels, shields, and plates were produced, calendered and machined by Simic s.p.a. [13] in 2010-2012. In order to minimize radioactive contamination, the copper plates were joined by electron beam welding (EBW). In fact EBW is a contactless welding technique which does not require either filler materials or electrodes and which minimizes the heat affected zone [14, 15]. It is also particularly suited for vacuum applications; still, EBW in CUORE required special care since there is little experience in welding thick copper plates. All copper-copper weldings were carried out by Pro-beam GmbH [16] employing the EBW technique. The steel-copper interface for the 300 K vessel was welded by Pro-beam GmbH through EBW, too. Vessel and shield shells are fabricated starting from two copper plates which are first calendered and longitudinally welded. The cylinder pairs are then joined together, to the heads, and to the top flanges by three radial weldings. The quality of all welding seams was assessed at Pro-beam by means of dye penetration tests and X-rays. All weldings were also individually tested for helium leaks with a specially designed tool at Simic. Both type of weldings required several iterations to be tuned. In particular, the steel-copper weld turned out to be quite challenging mostly due to an uncompensated deflection of the electron beam in the proximity of the Cu-304L interface that resulted in a significant lack of fusion during the first welding attempt (Fig. 2). The problem was solved using an inclined beam ($5^\circ$ at a distance of 300 mm) and re-tuning the electron accelerating parameters of the Pro-beam machines. In order to achieve a larger margin of safety, the EBW was done joining the copper vessel with a 10 cm high steel ring. The steel flange of the 300 K vessel was joined to the ring later on, using standard Gas Tungsten Arc welding (GTAW). All GTAW weldings were performed using radiopure tungsten electrodes; they were selected by the INFN Radioactivity Laboratory located at University of Milano-Bicocca. Some of the Cu-Cu welds of the 300 K and 4 K vessel showed a significant level of porosity, which required two additional EBW passages. A second EBW passage was applied also to the steel-copper weld. The final quality assessment of the welds and, in particular, X-ray checks excluded lack of fusion. However, shallow and mid-depth porosities were still visible (Fig. 3). Direct vacuum and pressure tests (see Sec. 6 below) demonstrated that these porosities do not weaken neither the vacuum tightness nor the structural properties of the vessel.

Figure 2: Defective welding at the steel-copper interface of the 300 K vessel.
Table 2: Mechanical properties of the steel and OFE copper.

| Material            | Ultimate Strength Rm [N/mm²] | Yield Strength Rp0.2 [N/mm²] | Elongation A5 [%] |
|---------------------|-------------------------------|-----------------------------|------------------|
| 1.4306 304L         | 520-670                       | 200                         |                  |
| C10100 (Cu-OFE) R240| 240-300                       | > 180                       | > 15             |
| C10100 (Cu-OFE) R220| 220-260                       | > 100                       | > 30             |

Table 3: Main mechanical parameters of the 4 K cryostat components.

| Inner diam. (mm) | Height (mm) | Thickness (mm) | Weight (kg) | Material          |
|------------------|-------------|----------------|-------------|-------------------|
| 300 K vessel     | 1603        | 3030           | 12          | 1942              | Cu-OFE+304L       |
| 40 K vessel      | 1503        | 2765           | 5           | 681               | Cu-OFE            |
| 4 K vessel       | 1363        | 2471           | 10          | 1142              | Cu-OFE            |
| 300 K plate      | 2060        | -              | 63          | 1532              | 304L              |
| 40 K plate       | 1573        | -              | 20          | 308               | Cu-OFE            |
| 4 K plate        | 1473        | -              | 59          | 870               | Cu-OFE            |

Figure 3: X-ray mark of the steel-copper welding. The gray spots pointed by the arrow are indication of shallow and mid-depth porosities.

The outer 4 K cryostat components are held by the 300 K plate, which in turn is connected to the main support structure of the experiment. The 300 K plate holds the corresponding vessel by bolts and an elastomer seal. The 40 K and 4 K plates are held below the 300 K plate by three 8 mm diameter steel bars: the “A-bars” that link the 300 K plate to the 4 K plate and the “B-bars”, linking the 300 K plate to the 40 K plate. The bars are made of EN 1.4429 (AISI 316LN) steel for cryogenic applications. Vacuum tightness of the 4 K vessel at the plate-vessel interface is obtained employing a tubular metallic seal (Garlock Helicoflex®, model HNV 200) mounted inside a centering ring (stainless steel 316 LN). The bars are linked to the plates by tilting Cu-Be joints. Both the A-bars and the B-bars, when loaded, can be tilted with respect to the vertical by at most 1.5° without damage. This design allows the system to withstand seismic events with a peak ground acceleration as large as about 0.08g. Finally, several feedthroughs will be employed in CUORE for pumping, fast cooling with cold He and for the electrical leads of the detector (Fig. 4). During the tests at the production site we mounted only a few of them: the vacuum ports for the IVC and OVC, the two ports of the fast cooling and one wiring port. Fig. 5 shows the 300 K and 4 K plates connected by the A-bars with the above-mentioned ports before closing the chambers (see Sec. 5).

Figure 4: The wiring port, the IVC vacuum pumping port and the Fast Cooling System port.

4. Cleaning

The production of the vessels from the pre-cut copper plates includes calendering, welding and machining. Similarly, the plates were machined and drilled,
and several flanges were gold plated in order to improve thermalization (Fig. 5). The copper has been selected for its very low bulk radioactivity, therefore special care has been put into the welding and milling procedures to preserve its purity. However, surface treatment after machining is needed to remove surface contaminations that can compromise radiopurity, vacuum (surface degassing) and thermal (emissivity) properties. In fact, from the radioactivity point of view, the surface cleaning of the cryostat outer shell is not particularly critical in CUORE since none of these parts are directly facing the bolometers. Unlike the innermost CUORE copper pieces [17] in contact to the detector, here the removal of surface contaminants was achieved by standard metal treatment for industrial applications. Still, degreasers, acids and solvents used during the processing of the metals were pre-selected for radiopurity.

In particular, we have applied the treatment of the copper successfully employed for CUORICINO [4].

The cleaning of the vessels and copper plates were performed by BAMA s.r.l. [18] employing a procedure that can be summarized as follows:

- **Degreasing** The degreaser employed in this phase is a general purpose decontamination solution (Radiacwash®) used in nuclear medicine for the removal of radioactive contaminants. It was diluted (10% in weight) using purified water with a conductivity < 5 µS · cm⁻¹. The solution was sprayed on the vessels.

- **Flushing** Performed with purified water (conductivity < 5 µS · cm⁻¹) at high pressure (>100 bar).

Three to four degreasing and flushing cycles were performed per vessel.

- **Pickling** Pickling was carried out by nitric acid in water solution (10% weight). For all vessels, the degreasing and pickling procedure was performed twice.

- **Passivation** All copper parts were treated with citric acid in water solution (10% weight).

- **Final flushing** The last flushing of each item was done by high purity water (conductivity < 0.5 µS · cm⁻¹, Grade 2 ISO 3696).

- **Packing** All vessels and plates were packed in Nitrogen atmosphere using an aluminized wrapping. The wrapping has been tested for radiopurity before the start of the cleaning procedure.

The surface contamination of the vessels was mainly due to machine oil deposited during calendering (Fig. 7). In most cases, pre-processing was necessary to remove the bulk of the machine oil. Such pre-processing was done with degreaser (10% weight), nitric acid (~1% weight) in hot (~ 40°C) unpurified water solution. All gilded parts were protected by a peelable rubber coating (Green Maskant), which was removed before the installation at the production site (see Sec. 5). The 300 K plate, which is made from AISI 304L steel, was cleaned by INFN personnel at the production site. In this case, only the degreasing cycles and the final flushing with Grade 2 water were performed (Fig. 8).

The effectiveness of this procedure in terms of radiopurity will be tested at LNGS during the commissioning of the apparatus while the vacuum tests at the
production site have shown that the degassing rate is low enough to achieve the required vacuum level (see Sec. 6.1).

5. Test setup

The CUORE Collaboration and Simic s.p.a. have built a dedicated test facility to assess the quality of the produced items before final assembly at LNGS. The aims of the tests were the evaluation of the vacuum, pressure and thermal requirements described in Sec. 2. As mentioned above, thermal properties were tested only at liquid nitrogen temperature, where most of the thermal stresses have already occurred. No radiopurity tests were performed in this site.

The test setup was built using the 300 K and 4 K vessels with their plates. The 300 K plate was connected to the 4 K plate using the A-bars, as in the final CUORE setup, while the 40 K vessel and plate were missing. The two plates were first connected together by the A-bars with the selected ports in place, then they were lowered onto the 4 K vessel. The vessel was sealed with the Helicoflex and, later on, the 300 K plate and the 4K plate-vessel assembly were positioned on top of the 300 K vessel. This setup was held in vertical position by an iron support structure located near the pumps and the cooling system (see Fig. 9). Only a few selected ports (see Sec. 2) were employed during the tests, the 300 K and 4 K opening of the others were sealed with blanks. The use of the ports varied during the tests as described in Secs. 6. Before closing the 4 K chamber, each port was individually tested for helium tightness of all sealings to a level of about $10^{-9}$ mbar·l/s. High vacuum (down to $10^{-6}$ mbar at room temperature) was achieved using a 0.017 m$^3$/s rotary pump coupled with a 0.3 m$^3$/s hybrid turbo-molecular pump (ATH300, Adixen). The turbo-molecular pump was mounted just on the top of the IVC or OVC ports, to reduce flow impedance. The rotary pump was located on the ground floor and connected to the turbo through a DN25 flexible line. The cooling system was based on regulated flux of liquid Nitrogen (LN$_2$) stored in a 3000 l dewar and connected by a flexible line to the input port of the fast cooling system (FCS). A second port was employed as exhaust to keep the IVC at atmospheric pressure during cool-down. The LN$_2$ flow was regulated by a cryogenic solenoid valve positioned on the output line of the dewar. The cryogenic valve was driven by a set of thermometers located inside the test setup as described in Sec. 6.3.

6. Quality control tests

6.1. Vacuum tests

Vacuum tests at room temperature were performed both for the IVC and the OVC. To test individually each welding of the 4 K vessel, part of the tests were performed before the insertion inside the 300 K vessel. The 4 K vessel was, hence, evacuated until it reached
a stable pressure of $6 \times 10^{-6}$ mbar in 15 hours. A leak detector was positioned on the back of the turbo pump in replacement of the rotary pump. The sensitivity reached by the detector (background leak) was $< 4 \times 10^{-10}$ mbar $\cdot$ l/1/s. Gas tightness of the welding was tested using plastic films stuck to the vessel along the welding seams using adhesive tape to form bags. Helium was injected into the bags and the growth of the background leak was measured for no less than 2 minutes. No leak signal over the background was observed for any of the 4 K vessel weldings. The same tests were performed after the pressure tests and two thermal cycles. In this case the background leak was significantly larger ($4 \times 10^{-9}$ mbar $\cdot$ l/1/s) because the IVC was previously flushed with a He (50%) - Ar (50%) gas mixture during the pressure tests (see below). Again, no leaks were observed for any of the weldings. Similarly, a vacuum test of the OVC was performed using an independent vacuum system with the turbo pump located near the rotary pump. Due to the impedance between the pump and the OVC port, the pressure reached by this system was $6 \times 10^{-4}$ mbar. Each welding was tested individually and no leak above the background ($1.3 \times 10^{-9}$ mbar $\cdot$ l/1/s) was observed. The same test was performed after the pressure test of the OVC. This time the turbo pump was located near the OVC port and a vacuum of $8 \times 10^{-5}$ mbar was reached in 15 hours; the leak background was $6 \times 10^{-9}$ mbar $\cdot$ l/1/s and no increase of the leak rate was observed during the He tests with plastic bags.

The quality of the seals was also assessed. The sealing of the metallic gasket (Garlock Helicoflex®, model HNV 200) was checked with special care due to the unusual configuration employed in CUORE. The gasket is positioned on top of the 4 K flange, on a 0.5 mm relief machined in the flange of the vessel. The measured surface roughness of the relief is 0.78 $\mu$m RA [19]. The gasket is fixed by a centering ring running outside the Helicoflex (height 5.7±0.1 mm). Another 0.5 mm relief (surface roughness 0.59 $\mu$m RA) is machined in the 4 K plate and during the sealing of the vessel, the 6.9 mm thick gasket is pressed and reaches a height of 5.7 mm. The 4 K plate is fixed on the vessel with 80 M12 bolts tensioned with nuts and equipped with washers made of Ti-6Al-4V ELI alloy to compensate for the difference in the steel and copper thermal contraction. The bolts were tensioned using three hydraulic tensioners positioned 120° apart. Three rounds of tensioning were performed to reach uniformly the nominal distance between the 4 K vessel and plate. The bolts were tensioned to about 60 bar, which corresponds to a load of about 10 kN.

The Helicoflex showed no evidence of leaks at the level of $4 \times 10^{-10}$ mbar $\cdot$ l/1/s (background of the IVC vacuum test). Some problems were experienced, however, with the indium flanges of the IVC central port and the FCS ports and for the s-shaped bellows of the FCS. The former was traced back to a mechanical mismatch between the steel flange of the bellows and the design of the copper flange, resulting in a larger gap for the indium. It was cured increasing from 1 to 1.5 mm the diameter of the indium wire. The defective s-shaped bellows was due to porosities in the bulk material, which was temporary fixed (at room temperature) using a vacuum plasticine. After these treatments, vacuum tightness was recovered at the $4 \times 10^{-9}$ mbar $\cdot$ l/1/s level.

### 6.2. Pressure tests

Pressure tests are aimed at inducing mechanical stresses on the vessels and evaluating the occurrence of permanent deformations or worsening of the vacuum tightness at the weldings. They also conservatively test the design specifications of Tab[1]. Since during thermal cycles the IVC undergoes further stresses, the pressure test was carried out for the IVC before and after the cold tests. In particular, we performed the following tests:

- over-pressuring the OVC by 0.3 barg, i.e. by a relative pressure of 30 kPa (absolute pressure: $p_{OVC} = 130$ kPa = 1.3 bara) while pumping the IVC ($p_{IVC} \approx 0$ bara)
- over-pressuring the IVC by 0.5 barg ($p_{IVC} = 1.5$ bara) while pumping the OVC ($p_{OVC} \approx 0$ bara)
Since more than 90% of the linear thermal contraction contractions at cool-down and expansions at warm-up. mal cycles induce stresses in the weldings due to copper to about 82 K and back to room temperature. Ther-

6.3. Cold tests

0.1 mm for the diameter and 0.6 mm for the roundness.

dedicated campaign was taken to check microdeforma-

Figure 10: Pressure versus time in the IVC and OVC.

- over-pressuring both the IVC and the OVC by 0.5 barg ($p_{IVC} = p_{OVC} = 1.5$ bara)

Overpressure was obtained injecting a He (50%) -Ar (50%) gas mixture in the IVC (OVC) port, while pumping the OVC (IVC). For greater safety, the test was performed filling a buffer bottle from a high pressure reservoir. The pressure of the buffer bottle ($p_b$) was chosen so that the expansion of the gas into the IVC (or OVC) was enough to bring the IVC to the sought-for pressure ($p_{IVC} = p_bV_b/V_{IVC}$, $V_b$ and $V_{IVC}$ being the volume of the buffer bottle and IVC respectively). In this way, there is no risk of accidental overpressure in the vessels even in case of a malfunction of the pressure reducer at the reservoir. During the expansion, the pressure at IVC/OVC was monitored by a digital pressure gauge and recorded by the DAQ system. The overpressure was kept for ~30 min in each cycle and every cycle was repeated twice (see Fig. 10).

No visible deformation was observed during any of the cycles and, as mentioned in Sec. 6.2, vacuum tightness at the weldings was preserved. In addition, a dedicated campaign was taken to check microdeformations of the IVC at the end of the thermal and pressure tests. The measurements were taken using a Laser Tracker and compared with the data recorded at the end of the vessel production (Nov 2011). The maximum difference with respect to previous measurements was 0.1 mm for the diameter and 0.6 mm for the roundness.

6.3. Cold tests

Two thermal cycles were performed bringing the IVC to about 82 K and back to room temperature. Thermal cycles induce stresses in the weldings due to copper contractions at cool-down and expansions at warm-up. Since more than 90% of the linear thermal contraction of copper already occurs at 77 K, cooling with LN$_2$ is adequate to test the outer cryostat of CUORE.

As anticipated in Sec. 5 cooling was achieved circulating LN$_2$ from the input port of the FCS. The Nitro-
gen was extracted by the dewar at a pressure of 2 bar at the entrance of the cryovalve. The opening of the cryovalve was driven by four PT100 thermometers (T1, T2, T5, T7 in Fig. 11). T1 and T2 were located at the bottom and top of the 4 K vessel, respectively. T5 and T7 at the end and at the beginning of the line connecting the cryovalve to the FCS port. The cryovalve was opened/closed through a relay by a Lake Shore model 218 Temperature Monitor. The valve was open when the following conditions were fulfilled: T2>80 K (no LN$_2$ accumulating in the bottom of the vessel), T1-T2<30 K (temperature gradient along the height of the vessel <30 K), T5-T7<200 K (a safety condition to test the integrity of the transfer line). In addition, the temper-

Cooldown started with a pressure in the OVC of $p_{OVC} = 3.8 \times 10^{-5}$ and $1.8 \times 10^{-5}$ mbar in the first and second cycle, respectively. During cooldown it reached a minimum value of $p_{OVC} = 5 \times 10^{-8}$ mbar. The cooldown rate was stable (see Fig. 13) at about

$^1$For Cu, the total linear contraction $\Delta L/L \equiv (L_{293K} - L_T)/L_{293K}$ is $3.24 \times 10^{-3}$ at $T = 4$K and $3.02 \times 10^{-3}$ at $T = 77$K.
3 K/h and the opening of the cryovalve was driven by the T1-T2<30 K condition until T1≈110 K, i.e. when the temperature at T2 was close to LN$_2$ temperature. Then, cool-down was mostly driven by the T1>80 K condition. The temperature reached at the end of the cooling was 82.5 K (84 K) at T1 and 77 K (77 K) at T2 during the first (second) cycle. The LN$_2$ consumption per cycle was about 1800 l, the total mass to be cooled being 2012 kg. As expected, LN$_2$ consumption was ~2 times larger than for an ideal cooling system that uses only the latent heat of vaporization (900 l [14]). Warm-up was purely passive (no use of heaters) in both cycles. While keeping high vacuum in the OVC ($p_{OVC}=5 \times 10^{-3}$ mbar with the turbo pump off) the warming rate was about 3 K/h and it reached 4 K/h when $p_{OVC}$ was brought to 1 mbar. In the final phase of the warm-up (T1≈260 K), in order to increase the heat exchange and maintain a warming rate of 4 K/h, $p_{OVC}$ was brought to 50 mbar.

In both cycles, a leak was observed at low temperatures. The leak developed at 170 K (160 K) at the first (second) cycle and worsened the OVC vacuum up to $p_{OVC}=1 \times 10^{-3}$ mbar at the end of the cooling. The integral leak rate was measured injecting the He-Ar mixture in the IVC (see Sec. 6.2) and measuring the He flow in the OVC with the leak detector positioned at the back of the turbo pump; at 77 K the leak amounted to $3 \times 10^{-4}$ mbar · 1/s. During the warm-up the integral leak rate decreased but was still visible at room temperature ($1.4 \times 10^{-7}$ mbar · 1/s). Finally, in both cycles the leak ($1 \times 10^{-7}$ mbar · 1/s) was located at the FCS indium flanges and s-tubes using He injected into plastic bags. No additional leaks were observed in any other port, in the Helicoflex and in the weldings. After the first cycle, the leak at the FCS was temporary fixed tightening the screws of the indium flanges but due to the mechanical defects of the FCS tubes (Sec. 6.1) a full repair was not possible. The FCS ports are therefore the most likely explanation of the deterioration of $p_{OVC}$ observed during the cooling.

6.4. Final tests and delivery to LNGS

As mentioned above (see Sec. 6.2), after the second thermal cycle and warm-up, a pressure test was performed on the IVC ($p_{IVC}=1.5$ bara, $p_{OVC}=4 \times 10^{-2}$ mbar), followed by a leak test of the weldings and the measurement campaign performed with the laser tracker. The system was hence dismounted and packed under Nitrogen atmosphere using the same
packing selected for BAMA s.r.l. Finally, a mechanical test, i.e. a mounting test of the plate on its vessel, was performed for the 40 K shield, which does not require vacuum tightness. The vessels and plates were delivered to LNGS on July 19, 2012.

7. Conclusions

In this paper, we described the construction and the validation tests of the outer cryostat for the CUORE experiment. In particular, we have demonstrated that the electron-beam welding (EBW) is an affordable technique for the assembly of large copper cryostats when radioactive contaminants from filler metals or electrodes must be avoided. The quality of the EBW welding has been tested with a measurement campaign carried out at the production site (Camerana, Italy). The campaign included mechanical and vacuum tightness tests of the weldings and of the whole vessels. Vacuum tightness has been demonstrated at the level of $10^{-9}$ mbar · l/s both for the copper-steel Outer Vacuum Chamber (OVC) and for the all-copper Inner Vacuum Chamber (IVC) of CUORE. The IVC and OVC were mechanically stressed by overpressure cycles at 1.3 and 1.5 bara and add two thermal cycles at 82 K. The vessels withstood the overpressure and underpressure conditions without structural collapse or permanent deformations. In particular, no deformations of the IVC larger than 0.6 mm were observed after pressure and thermal cycles. Similarly, vacuum tightness of all components was preserved during the tests with maximum leak rate less than $10^{-9}$ mbar · l/s. The only anomaly reported is a vacuum leak that developed at T<170 K; this anomaly has been traced back to the defective fast cooling tubes for the IVC. Finally, the A-bars and the 4 K metallic seal (Helicoflex) have been tested in the same conditions as for CUORE and were shown to be compliant with specifications.

The 4 K outer cryostat of the CUORE experiment has been delivered to the Gran Sasso Underground Laboratories in July 2012 and is currently under commissioning.

Acknowledgments

We wish to express our gratitude to Simic s.p.a. for support during the tests at the production site. We are indebted to C. Bucci, A. Franceschi, S. Gazzana, P. Gorla, K. Heeger, R. Kadel, T. Napolitano, A. Pelosi, C. Zarra and S. Zucchelli for many useful remarks about the validation tests. We are also grateful to S. Castoldi and G. De Bernardi (BAMA s.r.l.) for suggestions during the setting up of the cleaning procedures. Finally, we thank our colleagues of the CUORE Collaboration and, in particular, C. Brofferio, A. Dally, K. Heeger, S. Sangiorgio and N. Scielzo for their careful reading of the manuscript.

References

[1] C. Arnaboldi et al. [CUORE Collaboration], Astropart. Phys. 20 (2003) 91.
[2] R. Ardito, C. Arnaboldi, D. R. Artusa, F. T. Avignone, III, M. Balata, I. Bandac, M. Barucci and J. W. Beeman et al., “CUORE: A Cryogenic underground observatory for rare events,” [hep-ex/0501010].
[3] F. Alessandria, E. Andreotti, R. Ardito, C. Arnaboldi, F. T. Avignone, III, M. Balata, I. Bandac, T. I. Banks et al., “Sensitivity of CUORE to Neutrinoless Double-Beta Decay,” [arXiv:1109.0494 [nucl-ex]].
[4] E. Andreotti, C. Arnaboldi, F. T. Avignone, M. Balata, I. Bandac, M. Barucci, J. W. Beeman, F. Bellini et al., Astropart. Phys. 34 (2011) 822.
[5] A. Nucciotti, D. Schaeffer, F. Alessandria et al., J. Low. Temp. Phys. 151 (2008) 662.
[6] A. Nucciotti, F. Alessandria, M. Ameri et al., J. Low. Temp. Phys. 167 (2012) 528.
[7] F. Alessandria, E. Andreotti, R. Ardito, C. Arnaboldi, F. T. Avignone, III, M. Balata, I. Bandac, T. I. Banks et al., Astropart. Phys. 35 (2012) 839.
[8] R. Radebaugh, J. Phys., Condens. Matter 21 (2009) 164219; T.A.M. de Waele, J. Low. Temp. Phys. 164 (2011) 179.
[9] E.I. Mikulin, A.A. Tarasov, and M.P. Shkrebyonock, Adv. Cryo. Eng., 31 (1984) 629.
[10] Now Aurubis AG, http://www.auerubis.com/.
[11] ASME, Boiler and Pressure Vessel Code (BPVC), Sec. VIII div. 1 and Sec. II. http://www.asme.org/.
[12] ANSYS Academic Research by ANSYS Inc. http://www.ansys.com/.
[13] Simic s.p.a., Via Vittorio Veneto, Camerana (Cuneo), Italy. http://www.simic.it/
[14] J. Ekin, “Experimental Techniques for Low-Temperature Measurements: Cryostat Design, Material Properties and Superconductor Critical-Current Testing”, Oxford University Press, 2006.

[15] H. Shultz, “Electron beam welding”, CRC press, 1994.

[16] Pro-Beam technologies GmbH, Lindenallee 22, Burg (bei Magdeburg), Germany. http://www.pro-beam.com/

[17] F. Alessandria, R. Ardito, D. R. Artusa, F. T. Avignone, III, O. Azzolini, M. Balata, T. I. Banks and G. Barì et al., “Validation of techniques to mitigate copper surface contamination in CUORE,” arXiv:1210.1107 [nucl-ex], to appear in Astrop. Physics.

[18] BAMA s.r.l., via Novara 20029 Turbigo (MI), Italy. http://www.bama-technologies.com/

[19] ISO 4287:1997. Geometrical Product Specifications – Surface texture: Profile method – Terms, definitions and surface texture parameters. Available at http://www.iso.org/.