arXiv:1306.1351v1 [physics.ins-det] 6 Jun 2013

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

F. Alessandria[a], M. Biassoni[b,c], G. Ceruti[b], A. Chiarini[d], M. Clemenza[b,c], O. Cremonesi[b], V. Datskov[e], S. Dossena[b], M. Faverzani[b,c], E. Ferri[b,c], A. Nucciotti[b,c], M. Perego[b], E. Previtali[b], M. Sisti[b,c], L. Taffarello[f], F. Terranova[b,c]

[a] *INFN Sez. di Milano, Milan, Italy*
[b] *INFN Sez. di Milano-Bicocca, Milan, Italy*
[c] *Dipartimento di Fisica, Universitá 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

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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)

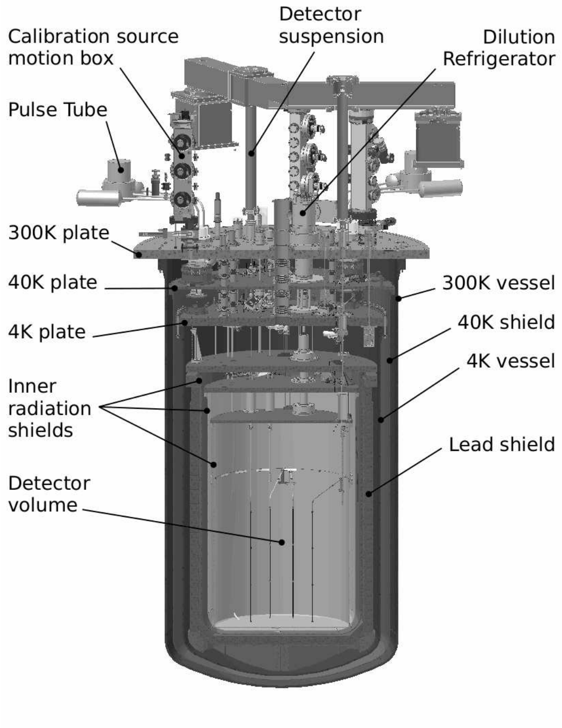

Figure 1: The CUORE cryostat.

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 $10^{-9}\mathrm{mbar} \cdot \mathrm{l/s}$ 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.

	ΔP_{max} [bar]	
vessel	internal	external
OVC	0.1	1.01
IVC	1.5	1.1

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 2×10^{-11} g/g for the ^{232}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 build 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° at a distance of 500 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.

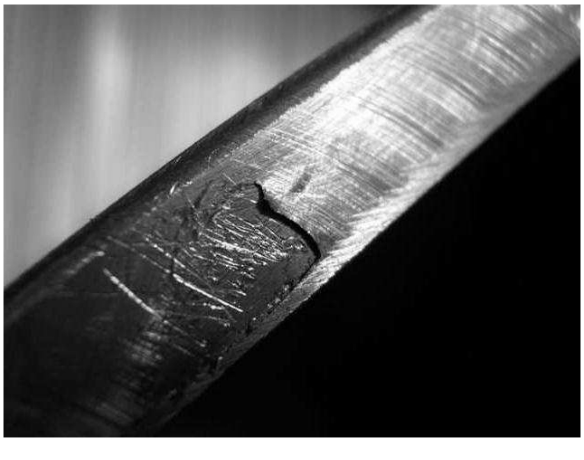

Figure 2: Defective welding at the steel-copper interface of the 300 K vessel.