Reduction of Radioactive Backgrounds in Electroformed Copper for Ultra-Sensitive Radiation Detectors

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Abstract

Ultra-pure construction materials are required for the next generation of neutrino physics, dark matter and environmental science applications. These materials are also important for use in high-purity germanium spectrometers used in screening materials for radiopurity. The next-generation science applications require materials with radiopurity levels at or below 1 $\mu\text{Bq/kg}$ ^{232}Th and ^{238}U . Yet radiometric analysis lacks sensitivity below ~ 10 $\mu\text{Bq/kg}$ for the U and Th decay chains. This limits both the selection of clean materials and the validation of purification processes. Copper is an important high-purity material for low-background experiments due to the ease with which it can be purified by electrochemical methods. Electroplating for purification into near-final shapes, known as electroforming, is one such method. Continued refinement of the copper electroforming process is underway, for the first time guided by an ICP-MS based assay method that can measure ^{232}Th and ^{238}U near the desired purity levels. An assay of electroformed copper at a $\mu\text{Bq/kg}$ level has been achieved and is described. The implications of electroformed copper at or better than this purity on next-generation low-background experiments are discussed.

Keywords: low background, copper, electroforming, thorium, uranium, ICP-MS.

1.0 Introduction

The success of modern experiments to detect neutrino recoils [1], double-beta decay [2; 3], dark matter [4], radiopurity assay in support of these, and studies of terrestrial and extra-terrestrial constituents for many purposes Laubenstein *et al.*, Plastino and Kaihola, Hult *et al.* and Arnold *et al.* [5; 6; 7; 8] all depend on materials selected for purity, or purified through a chemical process. Some materials of the desired purity can be found, such as those recovered from sources of ancient natural gas uncontaminated by cosmic-ray spallation or debris from anthropogenic sources such as nuclear weapons explosions and nuclear accidents. Other materials must undergo extensive purification before they can be included in detectors. Thus, a focused effort to create ultra-pure material using a chemical purification process has intensified to respond to the need for ever-purer construction materials.

1.1 The challenge of greater purity

Sources of obscuring signals, e.g., background, in radiometric measurements can be classified into three areas:

- a. Signals arising from cosmic rays.
- b. Signals arising from radioactivity in the detector and shield system.
- c. Signals created by uninteresting radioactivity within the sample being measured.

Moving a detector system underground is an excellent strategy to lower the overall background if cosmic-ray-associated background is a large contributor. However, Laubenstein *et al.* [5] presented an intriguing analysis of the full-spectrum count rate of several detectors in which below ~500 meters water equivalent (mwe) increasing depth did not result in a decreasing trend in background count rate. One reasonable conclusion is that materials in the detector and shield were the dominant source of background

below that depth. Counting rates from additional detector systems developed by Pacific Northwest National Laboratory (PNNL) and collaborators are shown in Figure 1 with similarly integrated count rates. This generally strengthens the conclusion that the majority of the background results from materials contamination, even though these detector systems have little in common in their production process with those discussed in Laubenstein *et al.* [5].

One might conclude that overall detector purity needs to be from 100 to 1000 times better to take full advantage of deep underground science laboratories, i.e., spaces deeper than 500 mwe. In reality, materials contamination is likely spread unevenly between a variety of components such as structural materials, external gamma ray shielding, surface coatings, electronics, and other components. In addition to materials contamination, surface contamination also has the potential to be a major contributor and can be impacted by handling, reagents, aerosols, or by exposure to ambient radon and its decay products. Because of this, clean rooms, radon-scrubbed air, reduced exposure time, highly purified reagents, and other surface mitigation preparations are important [9; 10] . For contaminants that include alpha decay, this can strongly influence the selection of detector technology to minimize surface alpha sensitivity, e.g., p-type vs. n-type high purity germanium detectors (HPGe).

For this work, the focus is the reduction of impurities in copper. Copper can be the most massive component in many ultra-low-background cryostats including those produced by PNNL for experiments such as the MAJORANA DEMONSTRATOR [11]. However, copper radioactivity reduction should be considered in the context of a complete background budget, and a comparison will be made between copper contributions and other materials at published radioactivity levels.

2.0 Methods for the production of pure copper

Unfortunately, most desirable materials for detector parts and cryostat construction suffer from one or more modes of contamination. Copper suffers activation due to reactions with cosmic-ray-produced secondary neutrons (e.g., $^{63}\text{Cu}(n,\alpha)^{60}\text{Co}$) as well as contamination with U and Th during the production and handling processes. Perhaps most damaging is the creation of ^{60}Co ($T_{1/2}=5.2\text{y}$, $Q_{\beta}=2.5\text{ MeV}$) in copper. Although some excellent sources of commercial copper can be found, the effects of cosmic-ray exposure are long-lived and preventing activation can be complex [12]. Thus, earlier basic copper purification efforts for cryostat and shielding purposes were carried out [13].

2.1 The electroforming method

The electroplating process is shown notionally in Figure 2, similar to that reported previously [13]. Two processes (“Reeves” and “Hoppe”) have been developed in parallel with a common assay method. The voltage and current plating waveform, temperature, conductivity, and other factors of the bath are monitored and controlled [14]. However, monitoring progress in the rejection of trace impurities can be quite difficult at the levels of interest, where levels of ^{232}Th or ^{238}U of 1 $\mu\text{Bq/kg}$ copper (or 0.25 $\text{pg } ^{232}\text{Th/g}$ and 0.08 $\text{pg } ^{238}\text{U/kg Cu}$) or better are required. Direct radiological measurements employing ~10 kg of copper measured for ~100 days on the world’s lowest background gamma-ray assay detectors have resulted in limits on the ^{232}Th chain from less than 9 $\mu\text{Bq/kg}$ to less than 28 $\mu\text{Bq/kg}$ [15; 16; 17; 18].

2.2 Using ICP-MS to measure thorium and uranium

To obtain assay sensitivity well below 10 $\mu\text{Bq/kg}$ in a reasonable time frame, an inductively coupled-plasma/mass spectrometry (ICP-MS) approach was explored. At

first glance, this may seem straightforward, since instrumental sensitivity can be as much as a thousand times better than the goal. Unfortunately, reagents, containers, tubing, dust, and ion exchange resins can contribute to a ubiquitous background of Th and U at obscuring levels. For example, some lab ware was found to reliably yield a small quantity of Th and U at each leaching with ultra-pure reagent, even after dozens of leaching preparation steps. Many of the materials in the process, notably plastic tubing inside the system, can function like exchange resins, retaining and releasing Th at varying pH. In addition, since the column material is designed to bind Th, it is always possible that some residual Th will be released in the elution step [19]. The notional sample preparation and ICP-MS scheme is shown in Figure 3.

To estimate the sensitivity of the assay system, process blanks were frequently measured during the analysis of samples. The samples included both starting anode and the electroformed copper product resulting from the electroplating procedure. Instrumental background was measured at an average of approximately 8 fg ^{232}Th and ^{238}U /g Cu equivalent. Process blank levels are detailed in the next section.

3.0 Results

3.1 An improved analytical method for thorium

To improve over the previous [19] best results of 2-4 $\mu\text{Bq/kg}$ (or $\sim 1 \text{ pg/g } ^{232}\text{Th}$) several ion exchange systems have been investigated to perform separation of copper from Th. Thorium background from the exchange resin, eluting complexant solution, and many components of the sample flow path seem to be particularly problematic.

The most promising technique utilized Eichrom TRU™ resin to bind Th from the copper samples in solution. Copper samples were dissolved in concentrated nitric acid and spiked with a ^{229}Th tracer. The resulting solution was then passed through the TRU™ column allowing the copper to elute through with virtually no retention. The

bound Th was then stripped from the column using recrystallized oxalate and mass to charge (m/z) 229 and 232 were measured via ICP-MS (PQ Excel, VG Elemental, Winsford, England) using an APEX (ESI, Omaha, NE, USA) high-efficiency sample introduction system.

The advantage of this approach is that by removing most of the copper from the solution prior to introduction into the ICP-MS, no dilution is required to overcome the loss of sensitivity due to ion suppression, which would be created by the presence of high levels (>10 ppm for this instrument) of copper. This was expected to allow the detection of Th at sub-pg/g concentrations in copper.

Because sensitivity at this level has not been previously demonstrated, uncertainty estimates were obtained using a recognized approach[20] where a series of analysis runs employing seven identical columns loaded with TRU resin is performed. After the initial reduction in background during the first three runs, presumably related to washing Th from the entire system, the quantity of Th in the blanks leveled off to an average equivalent concentration of $0.6 \mu\text{Bq } ^{232}\text{Th}$ per kg Cu, as shown in Table 1.

Although the ICP-MS analysis takes only minutes per sample, processing the sample solutions through the column, washing, stripping, and conditioning requires considerably more time. Results from simplified and smaller systems are promising and may speed up this process, and as confidence in the procedure improves, it is anticipated that fewer replicates per sample will be required.

After the blank analysis described above, two copper samples were analyzed. For each sample, a nominal 10 g of copper was dissolved in high purity nitric acid and seven aliquots of the resulting solutions were processed in a manner identical to the blank samples using the seven columns.

Table 2 shows the resultant concentration of ^{232}Th for two samples, one of starting anode copper and the other electroformed copper. The sample results in Table 2 have not been blank corrected (i.e. the blank value has not been subtracted from the sample result). As these data indicate, a statistically meaningful difference between the blank and samples is observed, but the difference in Th concentrations found between the two copper samples is not significant.

The relatively similar amounts of Th found in the two copper samples was unexpected as earlier work indicated that there should be a considerable rejection factor for Th during electro-deposition, i.e., Th in the electroplating bath is excluded or “rejected” from the growing copper matrix, leading to a net purification of the copper from Th. According to rejection factors calculated previously using a slightly higher concentration regime, the electrolyte from the plating bath should contain a thousand times more Th than the electroformed copper [14]. Although the concentrations being measured here were much lower than in the previous work, it was hypothesized that there was either a contamination or systematic error introduced during assay or that the Th concentration in the electroforming bath itself must be significantly higher than the starting anode copper.

To test the later hypothesis, duplicate samples of the bath solution were analyzed, and the results of 73.9 and 79.3 $\mu\text{Bq } ^{232}\text{Th}$ per liter were indeed much higher than expected. The rejection factor derived from these results of slightly over 100 following blank subtraction is somewhat comparable with the previous results although the difference suggests a slight high bias for the analytical method is still indicated. The range of these rejection rates still represents a useful level of purification for planned low-background experiments. It is also, as with prior results, much less than rejection rates predicted by classical thermodynamic models such as the Nernst equation, which further indicates

that other significant factors and/or non-classical behavior are involved in the deposition of Th during copper electro-deposition.

The high concentration of Th in the bath solution cannot be accounted for by build-up from dissolving anode copper. It is also unlikely that it could come from dust since the baths, pumps, filters and tubing are initially leached, then kept covered and purged with pure nitrogen. The levels observed would have required ~100 mg of dust containing 1 µg/g Th to deposit in the bath solution, considered very unlikely given the better than class 10,000 clean room status of the laboratory. Additionally, all of the bath materials are repeatedly washed with successively more pure nitric acid and then rinsed with high-purity water. The remaining possibility was that the source of thorium was from the recrystallized copper sulfate used in the initial formulation of the baths.

Although some researchers purify CuSO₄ crystals via repeated recrystallization, in this case the practice was not sufficient to produce CuSO₄ of the necessary purity. Given the potential contamination of the recrystallized CuSO₄ and the purity of the anode copper, CuSO₄ is now generated directly from the anode copper by running a current through a bath filled with dilute ultra-pure sulfuric acid, which yields Th concentrations in the bath not much higher than that found in the anode copper. This method has allowed us to avoid unexpectedly high ²³²Th levels such as those observed here in electroforming bath solutions that have been shown to be a limiting factor in producing ultra-low background copper.

3.2 Using ICP-MS to measure uranium

Similar to the Th assay described, uranium detection in ultra-low background materials is also plagued by the introduction of contamination from a variety of sources. Significant effort has gone into the development of cleaning procedures that aid in reducing and maintaining a low background test environment. [21] The most

straightforward sample preparation method is one which selectively concentrates the analyte of interest. Having the ability to elevate the target species concentration without incorporating contamination into the prepared samples reduces the need to operate at such consistently low background levels. Ion exchange resins have been utilized in an attempt to concentrate ^{238}U from the copper in solution. Dowex 1x8Cl⁻ resin has shown potential towards achieving the target assay detection goals by functionally binding uranium and allowing elution of a variety of other species including copper. When used for low-background copper assay, large volumes of high purity copper solution pass through the exchange column, and uranium is bound by the active sites. Fractionated column stripping can then be used to remove uranium that was entrained in the resin. The fractions are then readied for ICP-MS analysis.

Initial results using the Dowex 1x8Cl⁻ resin indicated that the as-received resin was significantly contaminated with ^{238}U . Resin cleaning techniques were used in an effort to fully remove ^{238}U from the column so that the background concentration remained constant and less than 50 fg/mL. Column stripping was performed by successively alternating the concentration of the stripping eluent (0.1M HCl and 12M HCl). The technique was shown to significantly aid ^{238}U removal. This is likely due to resin swelling and contraction in response to the varying acid concentration that is believed to enhance U mobility. Figure 4 shows the effectiveness of this resin clean-up procedure. Acid was passed through the resin filled column and each bed volume (BV) was fraction collected. Only the results of dilute acid stripping fractions were measured directly and evaluated for ^{238}U contamination. The dilute fractions that are graphed indicate that the concentration of ^{238}U spikes directly following concentrated acid washes, leading to more rapid ^{238}U removal. A final, stabilized concentration of ^{238}U of ~44 fg/mL was achieved following the resin cleaning procedure.

Directly following resin cleaning, ion exchange columns were loaded with a high matrix-copper solution (>1500 ppm). Functionality testing using ^{233}U as a surrogate analyte for ^{238}U was performed in order to identify the lowest achievable detection limits in the case where all background issues (associated with a direct assay of natural ^{238}U) could be neglected. The functionality of the resin was evaluated using ^{233}U tracer material that was spiked to 300 fg/mL. Following loading, the copper solution was rinsed from the column and ^{233}U was stripped and the fraction collected. The total ^{233}U recovery was calculated to average 78.9%. Most importantly, the ion exchange column bed volume containing the highest ^{233}U concentration was used to identify a new detection limit for ^{233}U , which was calculated to be $0.4 \times 10^{-12} \text{ g}^{233}\text{U/g Cu}$ and corresponds to a theoretical detection limit of $\sim 5 \text{ } \mu\text{Bq}^{233}\text{U/kg Cu}$. Repeating the experiment with three times the copper loading further reduced the ^{233}U detection limit to $0.10 \times 10^{-12} \text{ g}^{233}\text{U/g Cu}$. Since the response factors on the ICP-MS instrument for ^{233}U and ^{238}U are nearly identical, this equated to a theoretical detection limit of $\sim 1.3 \text{ } \mu\text{Bq}^{238}\text{U/kg Cu}$. However, the increased copper loading resulted in a reduced tracer recovery of 35%. It is important to consider that this ^{238}U detection limit is solely theoretical. Because the experiment was performed using ^{233}U tracer, many natural ^{238}U contamination issues were eliminated. The key aspect of this effort is that while a direct ^{238}U assay detection limit at this level was not measured, the ^{233}U results indicate there is significant potential to reach target detection limits using this method.

4.0 Summary of progress in copper assay and purity

Gradual improvements in assay sensitivity to U- and Th-chain species and the levels of copper contamination are documented in Table 3. The Reeves 3 copper described in this work was electroformed with a substantially higher copper growth rate such that surface electroforming was deemed fast enough to avoid serious cosmic-ray production of ^{60}Co .

The high growth rate produced many physical imperfections in the copper, some of which required almost daily machining to remove from parts as they grew, others which caused serious real or virtual leaks which required repair. The measurement reported in [15] assumed all the thorium observable from decay products was due to the copper, which is a bit conservative. Thus, while the Reeves 3 copper may not be as much as 10 times higher in thorium, the only production advantage it offers is speed which is greatly offset by the cost of almost constant machining, repairing, and poorer mechanical properties. Further, Hoppe 1 copper can be further improved with better starting materials.

The comparative impact of the background reductions in Table 3 is shown for a notional 1-kg Ge detector in Table 4 which includes a 0.5-kg cryostat around it, and a ~5-cm copper shield of 33 kg mass, as shown in figure 5. This mass includes the small parts required for detector readout placed directly beneath a 1 cm copper shield below the detector. The Th copper contamination of the ‘Reeves 3’ and current best copper ‘Hoppe 1’ are compared. This calculation assumes that the bulk shielding outside this inner copper is sufficiently pure to make no significant contribution through ~5 cm of copper shield.

The efficiencies for producing counts per each keV at 2 MeV in a HPGe detector were estimated with an EGS4-based simulation [22], and the masses of parts were drawn from previous PNNL designs. Where estimates of the IGEX-era [23] specific activity of Th in materials exist, they were used. Examples of ‘IGEX-Era’ and ‘Best Known’ published Th specific activities are included in Table 5. The remaining values were estimates.

If it is accepted that Th is representative of all the important contaminants, a system built today of the best known materials would have a factor of ~10 fewer raw

background counts than prior efforts. By rebuilding all components from a very small palette of known-good materials (meeting today's purity goals) another factor-of-2 reduction would be obtainable. Table 4 shows that even with improvements in all non-copper parts to the best available materials, reductions in copper activity have removed copper from being the leading contributor of net counts, leaving small parts, electronic parts, and cables as the next purity challenge to be addressed.

If this hypothetical factor of twenty is considered in light of Figure 1, it is conceivable that materials background reductions might cut in half the distance between the 'Homestake' system and the normalized underground muon intensity. Stated another way, materials purity limitations would still be dominant over cosmic-ray-induced backgrounds by about a factor of ten.

To make additional reductions in background, it will be necessary to formulate various plastics and other materials from clean starting materials, using phase changes and other chemical strategies to separate primordial K, U and Th from the finished material. Of course, other strategies exist for reducing background in the data acquired from the measurement system, such as pulse-shape analysis, coincidence analysis, and so forth, but it is preferable, where possible, to eliminate sources of radioactivity rather than rely on data rejection techniques.

5.0 Conclusions

While work continues toward better purity and assay capabilities, there are several useful conclusions at this time for ultra-low background detector experiments. First, the starting copper anode material (Outo Kumpu) was measured to have $0.9 \pm 0.3 \text{ } \mu\text{Bq/kg}$ ^{232}Th . Based on the limited sampling this copper should be satisfactory as starting anode material for experiments that employ electroformed copper in the foreseeable future. And although its current form as small 2.5 cm (1") diameter nuggets make it difficult to

work with, for example as a shield, it could be used for less critical low-background uses if the ^{60}Co in-growth after manufacturing can be controlled by limiting the above-ground exposure time.

Second, a thorium rejection ratio of over two orders magnitude was observed in the production of the ‘Hoppe 1’ copper, which corroborates previous results. This should be adequate considering CuSO_4 can now be produced with far less Th than was used to electroform copper in this work. Suitable ultra-high-purity CuSO_4 can be made using the starting anode material and high-purity acid. If the bath then contains an equivalent of 10 $\mu\text{Bq/kg}$, for example, copper may be produced with levels of Th that will not impact the next generation of ultra-low-background detectors.

Third, these purification successes suggest other materials in the cryostat, such as cables, electrical components, and small plastic parts, will be the next area of concern for further background reduction. Fortunately, HPGe detectors can be assembled using only a very small palette of materials, such that efforts can focus on improving the purity of a small number of non-copper items.

The implications of the current best known materials for applications of ultra-low background measurements are significant. If a background counting rate of 0.04 counts /keV-kg-year at 2 MeV using a realistic HPGe detector resolution is applied for a 1-kg detector operated for two weeks, it would give an average of 0.012 counts in an 8 keV region of interest (ROI), and only about one more order of magnitude for lower energies. One might consider that this low level of background is not warranted for sample counting, since several counts in the ROI will be required to confidently identify an isotope’s presence. However, the next generation of HPGe systems will employ many germanium crystals in large arrays. This is driven by the low detection efficiency of a single 1-kg detector for 2 MeV gamma rays, currently only a few percent at best.

Thus it is not unreasonable to expect 10-20 kg of HPGe detectors to be employed in future systems to provide greater detection efficiency to complement low backgrounds. This would result in a background rate still less than one count in the ROI for the above example, but perhaps 25% total efficiency for a 2 MeV gamma ray, and much greater efficiency for lower energy gamma rays.

Thus, the use of the best known materials today, including the improved copper reported here, would enable a new generation of measurement systems with efficiencies rivaling the largest NaI(Tl) sample counters, yet with negligible background signals arising either from cosmic rays (depth and veto), detector, or shielding.

Acknowledgements

The authors would like to acknowledge the United States Department of Energy, NNSA Office of Research and Engineering (NA-22), and the Office of Nuclear Physics in the DOE Office of Science for their support of this work. Pacific Northwest National Laboratory is managed by Battelle Memorial Institute under contract DE-AC05-76RLO1830. Further, the authors wish to gratefully acknowledge the scientific leadership of our deceased colleague, Ronald L. Brodzinski, who with humor and resolution inspired us to confidently approach the unknown again and again.

Figures

Fig. 1: Comparative integrated counting rates similar to [5] from 40-2700 keV for several PNNL systems: located at PNNL (329 18-C); under Lower Monumental Dam (LOMO, 75 mwe) near Richland, WA; in the Soudan mine near Soudan, MN; and at the 4850 foot level of the Homestake mine, near Lead, SD. An arbitrarily scaled muon fluence curve is shown for reference, computed as in Heisinger *et al.* [24].

Fig. 2: Notional diagram of the electroplating process shows the movement of copper ions across a H_2SO_4 / CuSO_4 bath under the influence of a low-voltage. A filtration cartridge for particulates is also seeded with BaSO_4 for the purpose of scavenging Ra from the solution.

Fig. 3: The ICP-MS procedure uses a conditioning (load) solution (1), a sample solution at the same pH (2), and then an eluting solution (3) into valve (a). After the sample has passed through the column, the wash solution strips the Th from the exchange resin and through valve (b) to produce a concentrated pulse into the ICP-MS. A mass 229 tracer indicates the timing of the mass 232 pulse.

Fig.4 Dowex 1x8Cl- resin stripping and clean-up effectiveness is shown. Only the results of dilute acid washes are plotted. Several bed volumes (BV) of concentrated HCl were used as an intermediate column strip between the graphs shown. The number of concentrated HCl washes can be identified as skipped bed volumes on the x-axis. The elevated concentration of ^{238}U spike in the center graph indicates the concentrated wash was necessary for adequate column stripping. The graph on the far right shows a final stabilized background of <20 CPS (instrument response of counts per second) or <50ppq ^{238}U was achieved.

Fig. 5. A notional 1-kg HPGe detector system for Monte Carlo simulation, with a close-fitting, 1-mm-thick copper vacuum jacket, a 1-cm copper slab below to provide

some shielding from necessary electronics, a cable and small parts package just below, and a 5-cm copper shield outside.

Tables

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Ave	Std
Column 1	67.2	10.4	2.0	0.7	0.7	1.7	1.1	1.0	0.46
Column 2	22.3	8.2	1.3	0.7	0.1	0.6	0.6	0.5	0.27
Column 3	26.6	7.8	1.7	0.5	0.6	0.6	0.5	0.6	0.05
Column 4	32.1	6.9	1.2	0.4	0.4	0.7	0.5	0.5	0.15
Column 5	36.0	7.8	1.5	0.5	0.3	0.6	0.7	0.5	0.17
Column 6	21.3	7.6	1.6	0.3	0.5	0.3	0.6	0.4	0.13
Column 7	34.5	6.2	2.1	0.8	0.4	0.5	0.6	0.6	0.17
Ave	34.3	7.8	1.6	0.6	0.4	0.7	0.7	0.6	0.2
Std Dev	15.6	1.3	0.3	0.2	0.2	0.4	0.2	0.2	0.13
% Std Dev	45.5%	16.7%	20.6%	32.5%	46.1%	62.9%	30.0%	34.9%	65.5%

Table 1: ^{232}Th normalized to $\mu\text{Bq/kg}$ Cu from blanks using TRU resin demonstrating the progressive reduction of background.

	Blanks (Ave)	Starting copper	Electroformed copper
Column 1	1.0	1.7	1.6
Column 2	0.5	1.6	1.2
Column 3	0.6	1.4	0.9
Column 4	0.5	1.5	2.0
Column 5	0.5	1.8	1.5
Column 6	0.4	1.0	1.3
Column 7	0.6	1.3	0.9
Ave	0.6	1.5	1.3
Std Dev	0.2	0.2	0.4
% Std Dev	35%	17%	30%

Table 2: Quantity of ^{232}Th in $\mu\text{Bq/kg}$ Cu from analysis using TRU resin sample preparation.

Year	Reference / copper Type	^{232}Th	^{238}U
1985	[18]	^{208}Tl	^{214}Bi
	Commercial OFHC 1	<5000	<13333
	Commercial OFHC 2	<500	<833
1993	[19]	^{226}Ra	^{228}Ra
	Reeves 2 (IGEX)	3300	
	Reeves 1 (PNNL-USC)	350	250
1995	[15]	^{226}Ra	^{228}Th
	Reeves 3 (improved IGEX)	<25	9*
2006	[16]		^{232}Th
	Reeves 4		~ 5
	(blank sensitivity)		2 to 4
This work			^{232}Th
	Outo Kumpu		0.9 ± 0.3
	Hoppe 1		0.7 ± 0.5
	(blank sensitivity)		0.6 ± 0.2

Table 3: Increasing assay capability and improving copper contamination levels in $\mu\text{Bq/kg}$. Here blank values have been subtracted from current results, with error bars derived from Table 2. *All activity was attributed to copper. Otherwise, this should be a limit, i.e., less than 9 $\mu\text{Bq/kg}$.

Location	Mass kg	Efficiency per keV	IGEX-Era Levels		Current Era Levels		Today's Purity Goals	
			Activity $\mu\text{Bq/kg}$	BKG Rate 1/keV-kg- y	Activity $\mu\text{Bq/kg}$	BKG Rate 1/ keV-kg- y	Activity $\mu\text{Bq/kg}$	BKG Rate 1/ keV-kg- y
Cu inner shield	32.8	6.9E-06	10	0.07	0.7	0.005	0.1	0.001
Cu cryostat	0.450	6.7E-05	10	0.01	0.7	0.001	0.1	0.000
cable	0.005	3.5E-05	36000	0.20	2000	0.011	500	0.003
electronics	0.003	3.5E-05	13000	0.04	2400	0.008	1000	0.003
small parts	0.020	3.5E-05	5000	0.11	500	0.011	500	0.011
			total	0.43	total	0.036	total	0.018

Table 4. Comparison of copper contamination reduction to backgrounds from other materials. Background signal suppression from pulse-shape analysis or other signal analysis is not considered.

IGEX cable [25]	36 mBq/kg
SNO NCD cable [26]	2 mBq/kg
BOREXINO nylon rod [22]	<0.5 mBq/kg
EXO TPC circuit material [27]	2.4 mBq/kg

Table 5. Some published values for the radioactive concentration of other materials used in ultra-low background detectors.

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