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SI-traceable monoelemental solutions on the highest level of accuracy: 25 years from the foundation of CCQM to recent advances in the development of measurement methods

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PAPER

Focus on Advances in Metrology in Chemistry and Biology

SI-traceable monoelemental solutions on the highest level of accuracy: 25 years from the foundation of CCQM to recent advances in the development of measurement methods

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The authors would like to dedicate this article to Dr Mike Sargent who led the Working Group on Inorganic Analysis for two decades. His wise and diplomatic leadership was important for the direction the IAWG took and therefore, crucial for the development and constant improvement of the traceability chain in inorganic analysis discussed in this article. Thank you, Mike!

Abstract

Within the *Working Group on Inorganic Analysis (IAWG)* of the *Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM)* international key comparisons and pilot studies related to inorganic analysis are carried to ensure consistency in this field at the highest level. Some of these comparisons deal directly with the preparation and characterization of monoelemental solutions or with topics, closely related. The importance of monoelemental solutions lies in the fact that almost every measurement in inorganic analysis relies on the comparison with either a reference material, or references in form of solutions, usually (mono)elemental solutions. All quantitative measurement approaches, e.g. isotope dilution or standard addition, need an accurate reference solution made from a well characterized reference material, prepared under full gravimetric control. These primary (monoelemental) solutions do not only serve as arbitrary references/calibration solutions, but they also link up measurement results to the International System of units (SI), this way establishing the so-called *metrological traceability to a measurement unit of the SI*. Without such solutions on the highest possible level of accuracy and with the smallest possible associated uncertainties (for e.g. element content and/or impurities), an analysis itself can never be as good as it could be with appropriate reference solutions. This article highlights select key comparisons and pilot studies dealing with monoelemental solution-

related topics within the IAWG from the foundation of CCQM – 25 years ago – up to latest achievements in the field of inorganic analysis.

Keywords: Monoelemental solutions, inorganic analysis, CCQM, IAWG, traceability chain, traceability to the SI

Introduction

The *Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology* (CCQM) is currently one of ten consultative committees of the *International Committee for Weights and Measures* (CIPM). Since the foundation of CCQM in 1993, one of the main responsibilities of the CCQM is "to establish global comparability of measurement results through promoting traceability to the SI" [1]. Traceability to the SI means that the results are metrologically linked to a measurement unit of the SI [2], typically the unit mole or kilogram in case of chemical and biological measurement results, via a so-called traceability chain (see figure 1, adopted from [3]). Even though today the concept of traceability is widely accepted, in the early days, most analytical chemists were unconvinced of the value of issues such as traceability and measurement uncertainty [4, 5]. To establish SI-traceability, in inorganic chemistry, usually a fully characterized solid material with an assigned purity such as a high purity metal or salt serves as the primary realization of the SI unit for amount of substance of the respective element. From the solid material, a primary solution can be derived by dissolving it. The primary (monoelemental) solution can then serve as the calibration solution for secondary solutions, which are used to disseminate SI-traceability to the broader analytical chemistry community. Due to the high costs and efforts to fully characterize the primary material (with the aim to determine its purity and if necessary, its stoichiometry) and to prepare primary solutions thereof, usually a direct dissemination of these materials to the public is not reasonable or even feasible. However, linking secondary and derived calibration solutions to primary solutions via precision measurements, establishes an unbroken traceability chain up to the SI [3]. In order to establish such a traceability chain, *three core capabilities* are needed and should be regularly tested within the comparisons of CCQM-IAWG:

First, the purity of a (preferably high purity) starting material must be determined. An ideal purity of 1 g/g does not exist in real materials. Therefore, either the purity needs to be quantified via a direct approach like e.g. titrimetry or via the determination of every single impurity other than the matrix element. For example, the comparisons CCQM-K72, CCQM-P107 and CCQM-P149,

discussed in detail later on, were especially designed to test the “purity determination” core capability of the participants. The second core capability is the “preparation of a primary reference solution”. Here it is very important to bring the starting materials with their well-known purities into solution under full gravimetric control, while correcting for air buoyancy and evaporation losses, after having chosen an appropriate container material, labware and solvent to avoid contamination of the solution. CCQM-P46 and, just recently, CCQM-K143 tested this capability of the participants directly. Finally, the comparison of two solutions with each other in terms of a high “precision measurement” is the third core capability that is necessary to provide a complete traceability chain. This capability was tested e.g. in the comparisons CCQM-K8, CCQM-K87 and CCQM-P124. However, also comparisons like CCQM-K2, in which the element content of two elements in a real-world matrix, in this case river water, had to be measured, indirectly test some of the core capabilities, because no measurement of a matrix sample can be done without a suitable SI-traceable reference solution. Thereby, at least the precision measurement capability is always tested within such a comparison, and – in some cases – also the ability to prepare a primary solution, or at least to appropriately handle reference solutions provided by other national metrology institutes (NMIs), designated institutes (DIs) or commercial suppliers.

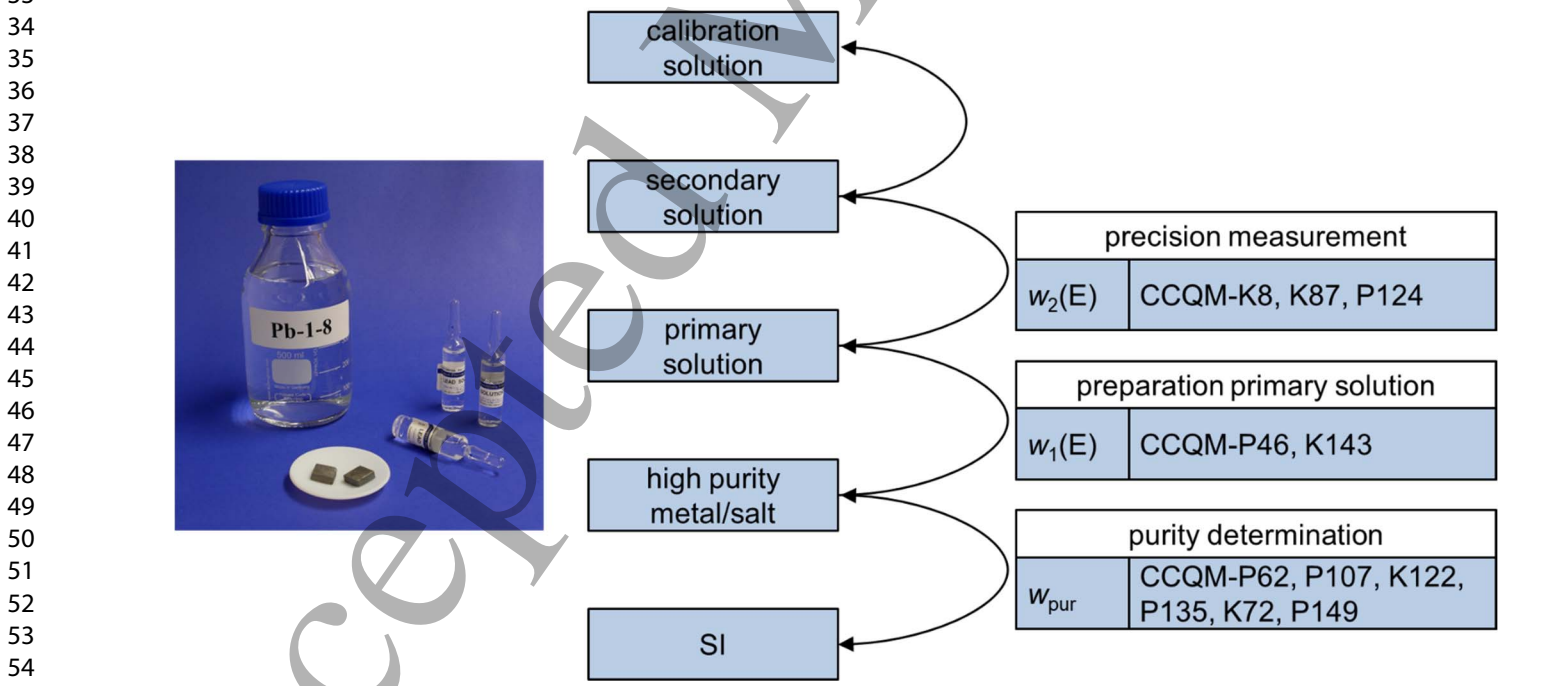


Figure 1: The traceability to the SI of a calibration solution for field laboratory use can be established by a secondary solution which in turn is SI-traceable itself via an unbroken chain of calibration measurements.

25 years of key comparisons and pilot studies organized by CCQM – some examples

CCQM-K2

Shortly after founding the CCQM in 1993, the key comparison CCQM-K2 was initiated at the 4th CCQM meeting in the year 1998. This comparison dealt with the measurement of the element mass fractions $w(E)$ of “Cadmium and Lead in natural water” [6], thereby indirectly testing the participants’ capability to perform precision measurements as already mentioned above. The study was coordinated by the Institute for Reference Materials and Measurements (IRMM, Geel, Belgium) of the Joint Research Centre of the European Commission and was run in parallel with the interlaboratory comparison IMEP-9 (International Measurement Evaluation Programme, round 9, trace elements in water), using the same sample. At this time, river water was considered a “simple” matrix. All participants of CCQM-K2 were asked to use the measurement principle of isotope dilution mass spectrometry (IDMS) [7]. However, the participants were free to design their own IDMS protocols (single, double, or exact matching IDMS, specific spike material, number of aliquots, etc.). In addition, general instructions were provided by the organizers with respect to the minimization of contamination, proper gravimetric handling, possible isotopic interferences and mass discrimination effects [6]. Furthermore, instructions for the calculation of the uncertainty contributions of each parameter of the IDMS equation and the recommended IDMS equation itself were also issued by IRMM in terms of a technical protocol and sent to the participants.

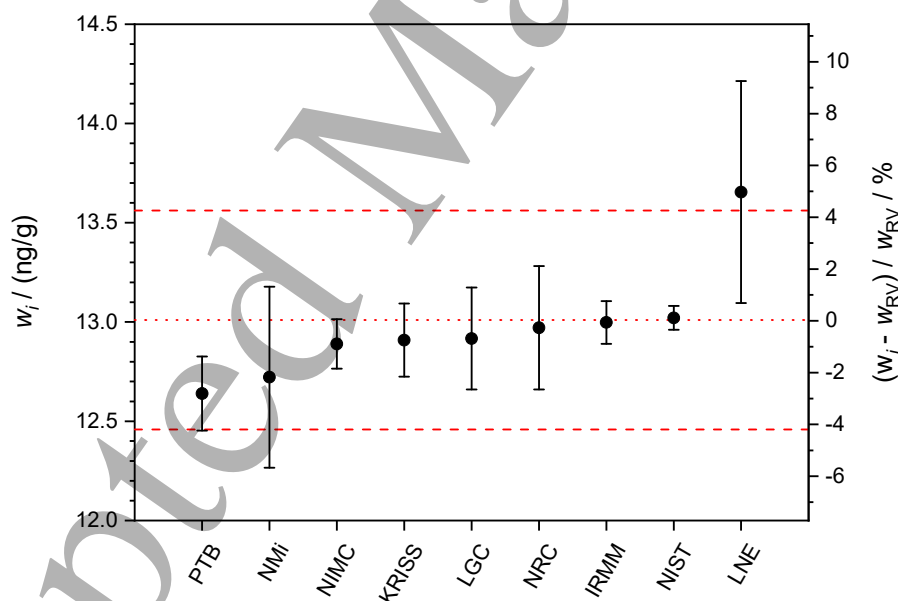
Nevertheless, it was not mandatory to use the provided equations. Nine participants reported results of their IDMS measurements on the cadmium and lead amount content along with the associated uncertainties. The determination of a low element content in a natural matrix sample was successfully demonstrated by all participants of CCQM-K2. For this comparison it was agreed upon that the key comparison reference values (KCRV) were calculated as the arithmetic means of the reported results. All of the participants’ results, for both elements, cadmium and lead, agreed very well, compared to each other and also compared to the resulting KCRV within the limits of the associated uncertainties (figure 2a). This is also nicely reflected in the calculated degrees of equivalence (e.g. for the results of the lead measurements, see figure 2b).

In order to be able to assess the spread of the results reported by the participants, the following quantity was defined as the difference between the largest and the smallest degree of equivalence related to the according reference value (RV) of those values fulfilling the criterion $0 \leq |d_i|/U(d_i) \leq 1$ [8, 9]:

$$\Delta \left(\frac{d_i}{w_{RV}} \right) = \left(\frac{d_i}{w_{RV}} \right)_{\max} - \left(\frac{d_i}{w_{RV}} \right)_{\min}$$

According to this definition, the spread of the relative degrees of equivalence of the participants' results for lead as depicted on the righthand axis in figure 2b shows that there is still almost 10 % spread within the results, while “the reason for the large differences in the magnitudes of the reported uncertainties was still unclear” [6] (figure 2a). The results for cadmium showed similar variations of the associated uncertainties like those of lead. Overall, lead is regarded to be more challenging than cadmium for two reasons: The cadmium content in the sample was slightly higher than the one of lead, and the possible variation of the isotopic pattern of lead could introduce additional sources of uncertainty.

Triggered by this not entirely satisfactory result of CCQM-K2 and as a consequence of further discussions within the IAWG, it was decided to have a closer look at the very basis of all those measurements: the primary reference solutions.



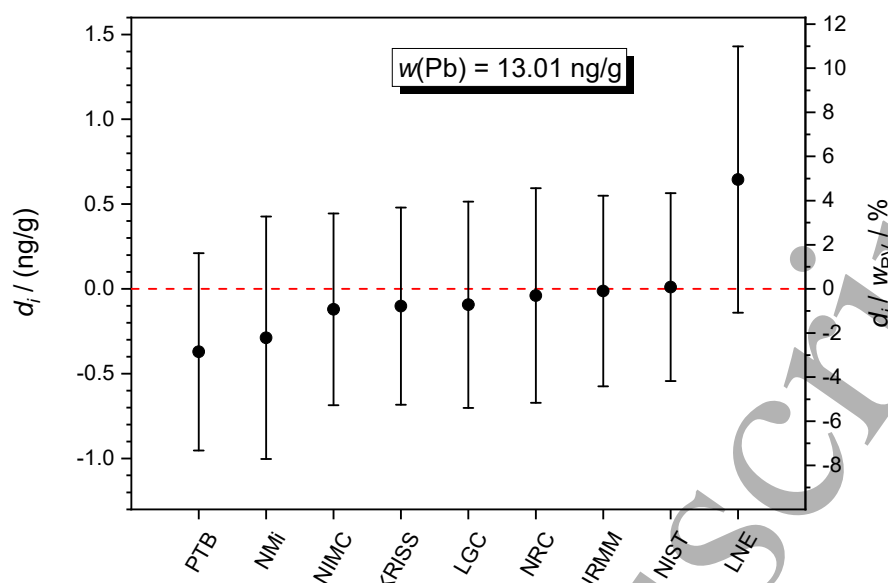


Figure 2a: CCQM-K2 (1998): Lead mass fractions w_i in a natural river water sample as reported by the participants. Error bars indicate expanded uncertainties ($k = 2$). Dotted red line shows the KCRV, dashed red lines the expanded uncertainty associated with the KCRV. Even though all participants were asked to use IDMS, the uncertainties reported varied in a range of nearly one order of magnitude, probably reflecting different experimental designs as well as different approaches for estimating the uncertainty.

Figure 2b: CCQM-K2: Degrees of equivalence d_i of the determined element mass fraction of lead. Expanded uncertainties are plotted with $k = 2$. Although all results agree nicely with the KCRV within the limits of their uncertainties, the spread of the relative degrees of equivalence in terms of $\Delta (d_i / w_{RV})$ as indicated on the righthand axis is almost 10 %, and therefore higher than expected and desirable. Figures 2a and 2b are adopted from [6]. The relative degree of equivalence was included for a better comparison with other CCQM studies. Compared to figure 2a, the individual uncertainties associated with the degrees of equivalences are more even because they are dominated by the relatively large uncertainty associated with the KCRV.

CCQM-K8

Thus, it did not come as a surprise that in 1999, CCQM-K8 “Monoelemental calibration solutions of Al, Cu, Fe and Mg”, hosted by the Federal Laboratories for Materials Testing and Research (EMPA) and the Bureau National de Métrologie - Laboratoire National d’Essais (BNM-LNE), started the tedious but indispensable work on elemental calibration solutions with the preparation of solutions of four different elements, namely aluminum, copper, iron, and magnesium [10]. The four

elements in this key comparison were chosen to represent a broad variety of elements with different fundamental functions. Aluminum represented a monoisotopic, economically important element. Copper and iron were chosen as representatives of transition metal elements, the former with relevance in environmental analysis, the latter with relevance in clinical chemistry. Alkaline earth metals were represented by magnesium. Monoelemental solutions of each of the four elements were gravimetrically prepared from carefully selected (certified) primary materials by EMPA and LNE and sent to the participants. This was the first direct key comparison within the CCQM-IAWG concerned with the determination of the element content in a monoelemental solution. It was already clear from the very beginning that for such purposes like the determination of the element mass fraction $w(E)$ in different matrices, the accurate preparation and handling of monoelemental reference solutions would be the key point for the metrologically sound inorganic analysis. This holds true independent of the applied measurement method. The outcome of CCQM-K2 further underpinned these facts.

In CCQM-K8 the participants were not only free to choose their calibration basis but also free to select the applied measurement method for the determination of the element content in the monoelemental solutions provided by EMPA and LNE. Thus, the applied methods included primary methods like titrimetry, coulometry, gravimetry and IDMS next to the non-primary method of inductively coupled plasma optical emission spectrometry (ICP-OES). The monoelemental solutions were prepared at a nominal mass fraction of 1 mg/g. A relative combined uncertainty of 0.5 % of the participants' results was set as the target. With these requirements, CCQM-K8 was designed to prove the participants' capability to measure pure monoelemental solutions with sufficient accuracy and precision whilst at the same time comparing different measurement techniques/methods at this highest level of accuracy [10]. Each participant was expected to report results for at least three out of four monoelemental solutions. Results for aluminum, copper, and magnesium were reported by all of the 13, results for iron by 12 participants.

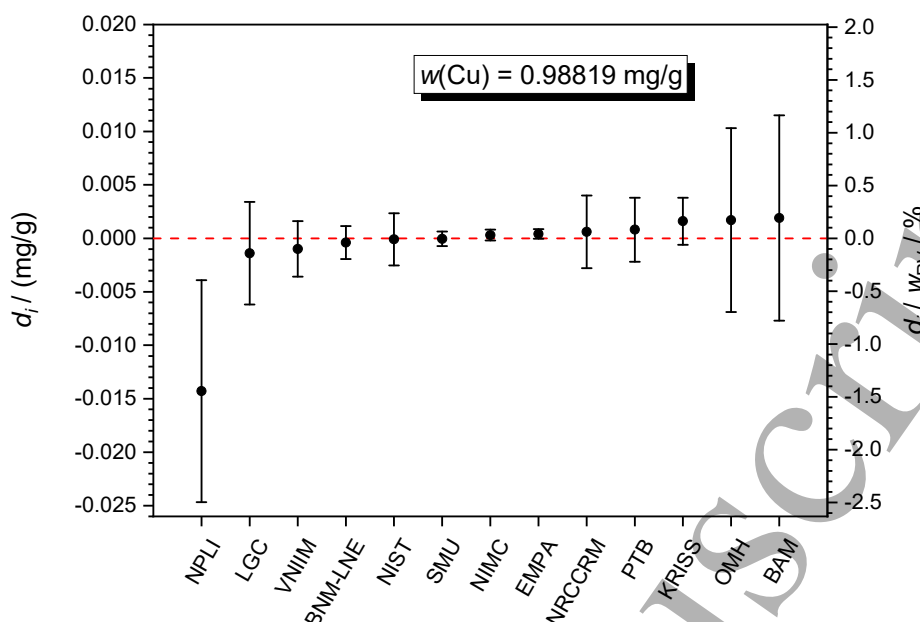


Figure 3: CCQM-K8 (1999): Degrees of equivalence d_i of the determined element mass fraction of copper in a mono-elemental solution in the 1 mg/g mass fraction range. Expanded uncertainties are plotted with $k = 2$. Compared to CCQM-K2, the spread of the relative degrees of equivalence in terms of $\Delta(d_i / w_{RV})$ as indicated on the righthand axis is already much smaller, resulting in only 0.4 % (or 1.4 % including the one result, that does not match the KCRV within the limits of its expanded uncertainty). Figure 3 is adapted from [10].

Figure 3 exemplarily shows the improvements of the participants' measurement capabilities. Although different measurement methods were applied, the spread $\Delta(d_i / w_{RV}) = 0.4 \%$ of the participants' reported results for the mass fraction of the nominal 1 mg/g copper solution is approximately one order of magnitude smaller compared to the results of CCQM-K2 depicted in figure 2b. The results reported for Al, Mg, and Fe showed a slightly larger spread but of the same order of magnitude like those of Cu. The visible variation of the associated uncertainties (figure 3) reflected different methods applied and experimental designs as well as different approaches to the estimation of the uncertainty.

Despite the overall improved results in CCQM-K8, of course the element content of the tested samples is higher than the one of lead in CCQM-K2 before, but considering that the results were determined with several completely different measurement techniques, this can still be regarded as a real improvement. Furthermore, the growing number of participants underlines the importance of conducting such comparisons.

CCQM-K87 and CCQM-P124

After more than a decade, in 2010, CCQM-K87 “Monoelemental calibration solutions of Cr, Co and Pb”, coordinated by PTB, was again set up to test the precision measurement capabilities of the participants by measuring 1 mg/g solutions of cobalt, chromium and lead, and at the same time to indirectly assess the participants ability to prepare their own monoelemental reference solutions [11]. In parallel, “CCQM-P124 was organized to give less experienced institutes as well as industrial laboratories also the opportunity to participate and prove their ability to perform high precision measurements” [11]. Furthermore, well established institutes may take the chance to test alternative techniques in a pilot study. Fortunately, the number of participants in the key comparison heavily increased to 19, plus another 6 in the parallel pilot study, when compared to 13 participants in CCQM-K8, indicating the awareness of the NMIs/DIs of the importance of these comparisons and the need for international comparability of measurement results. As in CCQM-K8 the participants were free to choose their preferred measurement technique.

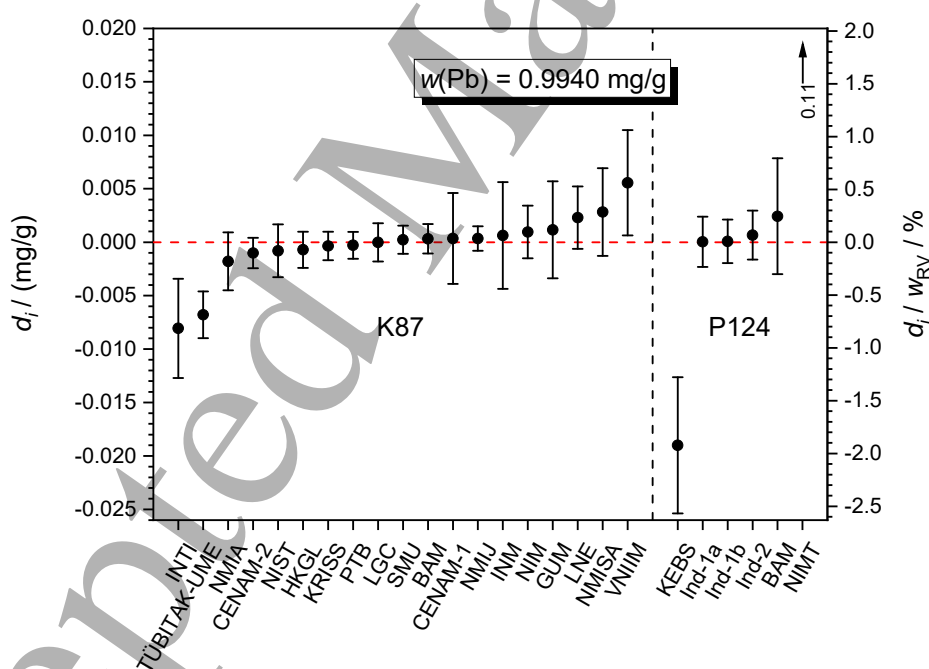


Figure 4: CCQM-K87/CCQM-P124 (2010): Degrees of equivalence d_i of the determined element mass fraction of lead in the 1 mg/g mass fraction range in a monoelemental solution. Expanded uncertainties are plotted with $k = 2$. Most results agree nicely with the KCRV within the limits of their uncertainties. The spread of the relative degrees of equivalence in terms of $\Delta (d_i / w_{RV})$ as indicated on the righthand axis is approximately 0.5 % for the CCQM-K87 participants' results that agree with the KCRV, and 1.4 % for all reported results. Figure 4 is adapted from [11].

The molar mass of the lead samples used in this study did not match the respective IUPAC value [12]. Therefore, in addition to the determination of the lead mass fraction itself, the participants of CCQM-K87 were asked to determine the molar mass of the sample, in order to use it to correct their resulting lead mass fractions, if possible. Thus, the measurement of the lead sample can be considered a more demanding task than the measurement of the copper solutions in the previous comparison CCQM-K8. Still, the spread of the relative degrees of equivalence $\Delta(d_i / w_{RV})$ of the reported results whose uncertainties overlap with $d = 0$ is very similar to that of CCQM-K8, with 0.5 % (see figure 4). In summary, the outcome of CCQM-K87 indicates that a large number of NMIs/DIs around the world are able to produce comparable results and thereby are able to realize this part of the traceability chain and create the link to the SI.

CCQM-P46

The unpublished pilot study CCQM-P46 hosted by NIST in 2004, dealt with the preparation of monoelemental solutions of copper, magnesium, and rhodium with a well-known mass fraction between 1 and 10 mg/g which were then compared against each other at NIST. The participants were responsible for choosing and/or characterizing a starting material. The technical protocol only defined a target range for the element mass fraction, but no further instructions concerning any air buoyancy correction or evaporation correction were issued. The participants used their own bottles and packaging materials. In case of copper, NIST determined a spread of the ratio of the measured and the claimed mass fractions of 0.8 %. In case of rhodium and magnesium, the spread was even larger. This pilot study is another example of the actuality of the topic and that it is still far from being trivial to prepare primary monoelemental solutions for every element without difficulties. Rhodium was a big challenge mostly due to its “resistance” to be brought into solution quantitatively, while characterizing a suitable magnesium starting material turned out to be more difficult than expected due to the presence of a significant amount of non-metallic impurities.

CCQM-K143 and CCQM-P181

The central importance of the accurate preparation and use of monoelemental solutions is consequently reflected in the recurrent conduct of (key) comparisons, like for example in the ongoing comparison CCQM-K143/CCQM-P181 “Copper calibration solutions”, which is hosted by NIST, with measurement support from PTB. The comparison was initially set up in 2015 and the first results were discussed in October 2018 during the CCQM meeting. The comparison dealt with

the accurate preparation of 10 g/kg copper solutions from high purity copper materials, which could be freely chosen by the participants.

The results of CCQM-K143 presented at the meeting in Ottawa (October 2018) and in the follow-up meeting in Paris (April 2019) indicated that the participants were very capable to prepare their own monoelemental solutions with a defined element mass fraction and appropriate uncertainty, suitable for the use as primary calibration standards. Therefore, the second core capability – the preparation of a primary monoelemental solution – can be regarded as realizable by the participating institutes, at least for those elements, that are stable in solution and not considered to be too difficult to dissolve. In contrast to e.g. rhodium, copper is regarded to be one of the more easy-to-handle elements.

Even though the results of CCQM-P46 were never made public, the comparison between CCQM-P46 and CCQM-K143 revealed another important aspect: The bottling, sealing of the bottles and proper shipping is at least of the same importance as the preparation and the measurements. While in CCQM-P46 the preparation and packaging of the samples was completely left in the hands of the participants, in CCQM-K143 NIST issued a relatively strict but tried and tested protocol for the preparation and packaging. NIST also provided all participants with standardized bottles and tools e.g. like a torque wrench for closing the bottles in a reproduceable and comparable manner as well as an insulated return box. All these measures resulted in a largely improved outcome: CCQM-K143 showed a spread of the ratio of the measured and the claimed mass fractions of copper of approximately 0.2 %, four times smaller than what was achieved in CCQM-P46.

CCQM-P62, CCQM-P107, CCQM-K72, CCQM-P107.1, and CCQM-P149

A series of comparisons was initiated to test the first core capability related to the traceability chain, namely the determination of the purity of a specific material in order to become a fully characterized primary material, necessary to prepare primary monoelemental solutions. It is noteworthy that – despite the high relevance of the very first step of the traceability chain – four pilot studies but only one key comparison focussing on the purity of a metal were organized. Reasons for this could be the enormous efforts necessary to fully characterize the purity of a metal but also the fact that comparisons carried out on real-world samples always indirectly test the quality of the references used. This in turn caused a lengthy discussion about the urgency of purity determinations within the IAWG.

The first pilot study dealing with the purity determination of a metal was CCQM-P62 “Purity of Ni with respect to six defined metallic impurities” in 2004, coordinated by BAM [13]. In this study, the mass fractions of the major impurities Ag, Al, Cu, Fe, Pb, and Zn ranging from 0.1 mg/kg to 5.0 mg/kg had to be determined within the nickel matrix. Additionally, the participants were asked to calculate and report the sum of the six mass fractions as a rough estimate of the purity. Therefore, direct approaches for the measurement of the purity of nickel were not applicable in this case. However, the total number of impurity-elements was restricted to six in order to limit the effort, but at the same time yield a reasonable value for the purity. The reported sums of the impurities ranged from 3.1 mg/kg to 25.4 mg/kg, which would equate to a 5N and 4N material, respectively. This outcome and the small number of only 6 participants, reporting 7 independent results, however, indicated that “further efforts needed to be taken” [13]. In 2007, CCQM-P62 was followed up by the technically less demanding pilot study CCQM-P107 “Purity of Zinc with respect to six metallic analytes” [14], again coordinated by BAM. The element zinc was chosen as the matrix because it is considered to be a comparatively easy matrix, especially for mass spectrometry, but of high industrial and clinical relevance. Here, the impurity-elements with comparable mass fractions were Ag, Bi, Cd, Cr, Ni, and Tl. The results of CCQM-P107 were much better compared to the earlier study CCQM-P62. While in CCQM-P62 the results differed by a factor of 8, in CCQM-P107 the spread was less than 30 % [15]. Thus, the IAWG decided to finally conduct a corresponding key comparison and parallel pilot study coordinated again by BAM in 2012: CCQM-K72/P107.1 “Purity of zinc with respect to six defined metallic analytes”. This time, Ag, Al, Cd, Cr, Ni, and Tl had to be determined [15]. The reported sums of impurities showed a spread of less than 19 % indicating that the NMIs/DIs have made a big step forward. The number of nine participants in the key comparison and two more in the pilot study, however, was still far from being satisfactory taking into account that the characterization of the starting material is the very first step necessary to establish a traceability chain and that the uncertainty associated with the purity is the limiting contribution to the entire traceability chain.

Finally, the pilot study CCQM-P149 “Purity determination of zinc to be used as primary standard for zinc determination”, conducted by BAM in 2013, was intended to prove the ability to quantify the total purity of a zinc material [16], in contrast to the previous studies where only a very limited number of impurity-elements were determined. The zinc material used in CCQM-P149 was the same as in CCQM-K72. This time, for the total purity determination “either a direct metal assay of the Zn mass fraction was undertaken by EDTA titrimetry, or an indirect approach was used wherein all impurities, or at least the major ones, were determined and their sum subtracted from the ideal purity of 100 %, or 1 kg/kg” [16]. The participants were not only free to choose their methods

applied, but they were also allowed to contract external laboratories for the determination of one or more impurities contributing to the total purity reported. Figure 5 summarizes the outcome of this very successful pilot study. Almost all of the reported measurement results are consistent with the reference value within the limits of their uncertainties. Those which do not agree with the RV, only missed it due to their rather small uncertainties. Nevertheless, it can be stated that the overall performance of the participants was really good, which can be seen more clearly when considering that the spread of results is only 0.05 % as $\Delta(d_i / w_{RV})$. Although it is uncommon to calculate d_i in a pilot study, for the reason of comparability with the selected key comparisons, they are provided in figure 5 for the reported results of CCQM-P149. Again, an improvement by another order of magnitude compared to the results of CCQM-K2 has been achieved in this pilot study and the number of participants in this technically highly sophisticated study underlines once more the importance and relevance of conducting such comparisons within CCQM.

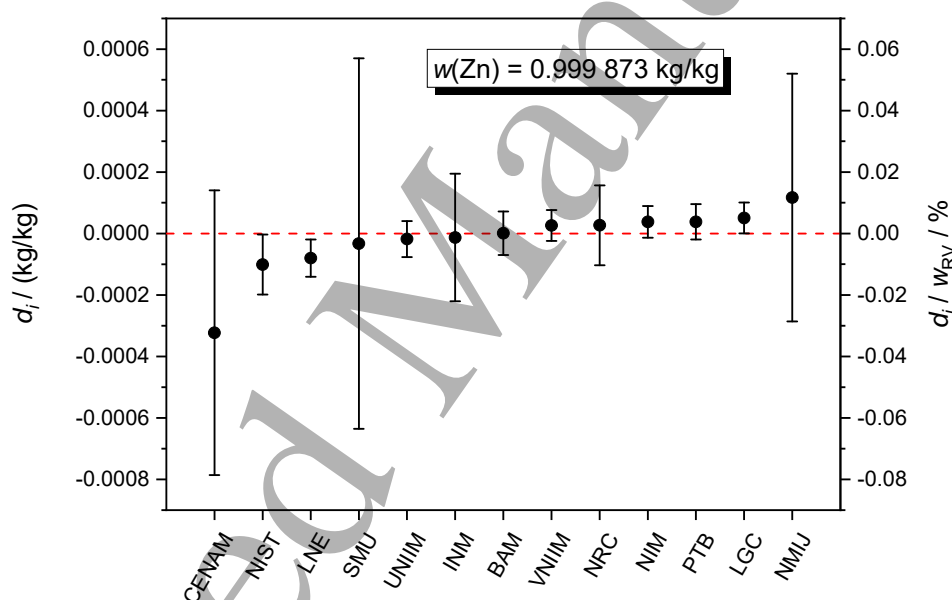


Figure 5: CCQM-P149 (2013): Degrees of equivalence d_i of the determined mass fraction of zinc in a high purity zinc sample – here equal to the total purity. Expanded uncertainties are plotted with $k = 2$. Most of the reported 13 results agree nicely with the RV within the limits of their uncertainties. Those results not matching the RV, just missed it due to very small expanded uncertainties, but were nevertheless very close to the RV. The spread of the relative degrees of equivalence in terms of $\Delta(d_i / w_{RV})$ as indicated on the righthand axis is approximately 0.05 %. Figure 5 is adapted from [16]. Even though uncommon in pilot studies, d_i are used to assess the results.

Furthermore, in the course of this pilot study, a “roadmap” was established and published covering the basic principles of how to fully characterize a high purity material [17]. In the future, this

roadmap will give laboratories, especially NMIs/DIs, advice on how to transform common materials into primary materials and thereby deliver the first link of the traceability chain to the SI.

CCQM-P135, CCQM-P135.1, and CCQM-K122

In several cases it is nearly impossible or at least too difficult to start the preparation of the primary monoelemental solution from a pure metal. This concerns e.g. most of the alkali and alkaline earth metals. Therefore, select monoelemental solutions are preferably prepared from salts with a defined stoichiometry. For this reason, a series of comparisons for anionic impurities in salts, intended to be used to prepare monoelemental reference solutions of e.g. sodium and potassium, were hosted by PTB. In 2012, it started with the pilot study CCQM-P135 “Anionic impurities in salts (NaCl)”. Therein, participants could register for the determination of the mass fraction of the anions bromide, sulfate and nitrate in solid sodium chloride. The intention of CCQM-P135 was to improve and to verify the measurement capabilities of the NMIs for the determination of anionic impurities with a mass fraction of $0.1 \mu\text{g/g} < w(\text{A}) < 30 \mu\text{g/g}$ in a salt matrix and it was a joint comparison of the IAWG together with the Working Group on Electrochemical Analysis (EAWG) [18]. Three anionic analytes in the lower and sub- $\mu\text{g/g}$ level were chosen, namely bromide, sulfate and nitrate. Figure 6 presents the results for the bromide mass fraction in a NaCl matrix. Nine NMIs reported a total of 11 measurement results. Most results agree well with the reference value within the limits of their uncertainties, independent of the applied measurement method. Using $|d_i|/U(d_i) \leq 1$ as the criterion of satisfactory or acceptable equivalence, approximately 80 % of the bromide results were at least satisfactory. Most of the participants used ion chromatography either with an electrical conductivity or a UV detector but also results measured with gas chromatography coupled to mass spectrometry and inductively coupled plasma quadrupole mass spectrometry have been reported. Independent of the applied method, it can easily be seen that the spread of the results of approximately 27 % for the mass fraction of bromide is huge compared to the previous examples of CCQM key comparisons and pilot studies.

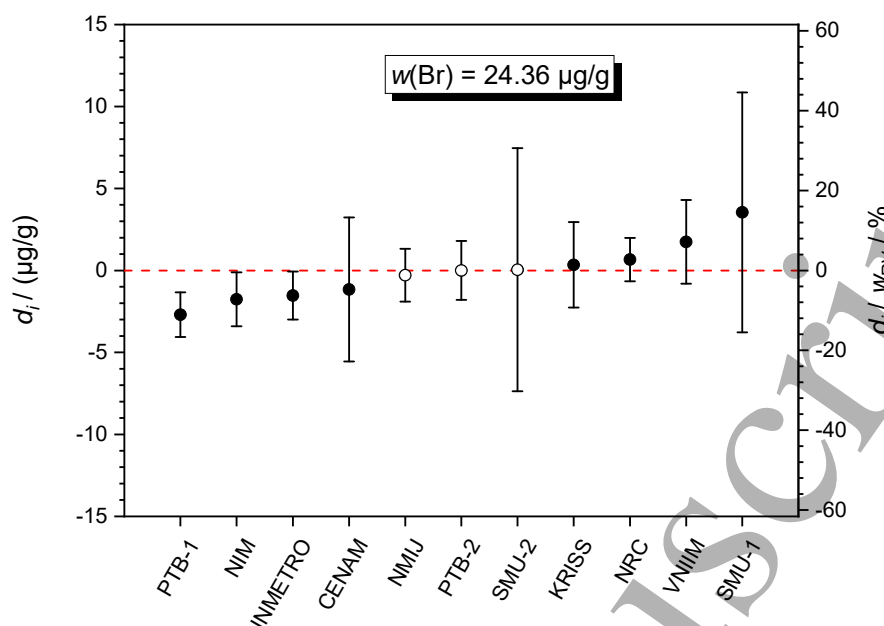


Figure 6: CCQM-P135 (2012): Degrees of equivalence d_i of the determined element mass fraction of bromide in the 24 $\mu\text{g/g}$ mass fraction range within a solid NaCl salt matrix. Expanded uncertainties are plotted with $k = 2$. Open circles denote ion chromatography (IC) measurements with an optical ultraviolet (UV) detector. Most results agree well with the reference value within the limits of their uncertainties, independent of the applied measurement method. The spread in terms of $\Delta(d_i / w_{RV})$ as indicated on the righthand axis is approximately 27 % for the CCQM-P135 participants' results. Figure 6 is adapted from [18]. Even though uncommon in pilot studies, d_i are used to assess the results.

Still, the majority of the participants' results looks promising in terms of good agreement with the derived KCRV as well as with each other, and "taking into account the extremely difficult matrix and the relatively low trace contents of the analyte anions, the demonstrated performance of virtually all participants was satisfactory or at least appropriate" [18]. As a consequence, it was decided to have the follow-up key comparison CCQM-K122 together with the parallel pilot study CCQM-P135.1. The bromide content in CCQM-K122 was nearly one order of magnitude smaller and again, approximately 80 % of the results were satisfactory, showing a clear improvement of the participants' performance [19].

Within these studies related to a salt matrix, also the element mass fraction of lead within the sodium chloride matrix had to be determined in CCQM-K122 as shown in figure 7. A total number of only 8 participants reported their results for the lead mass fraction. Almost all measurement results are in good agreement with the KCRV within the limits of their expanded uncertainties. Even results of participants who joined the comparisons for the first time can be considered

satisfactory, given the difficulty of the high matrix load and the low analyte concentration. The concentration in this comparison was similar to the concentration level of lead as in CCQM-K2, but of course the matrix with an extremely high salt content of 15 % NaCl raises much more difficulties than the river water matrix in CCQM-K2. Despite those difficulties, the spread of the reported measurement results for the lead mass fraction in CCQM-K122 is already approximately 6 times smaller than compared to the lead example in CCQM-K2. Still, it would be highly appreciable to further lower the spread between the participants' results and at the same time to increase the number of participants.

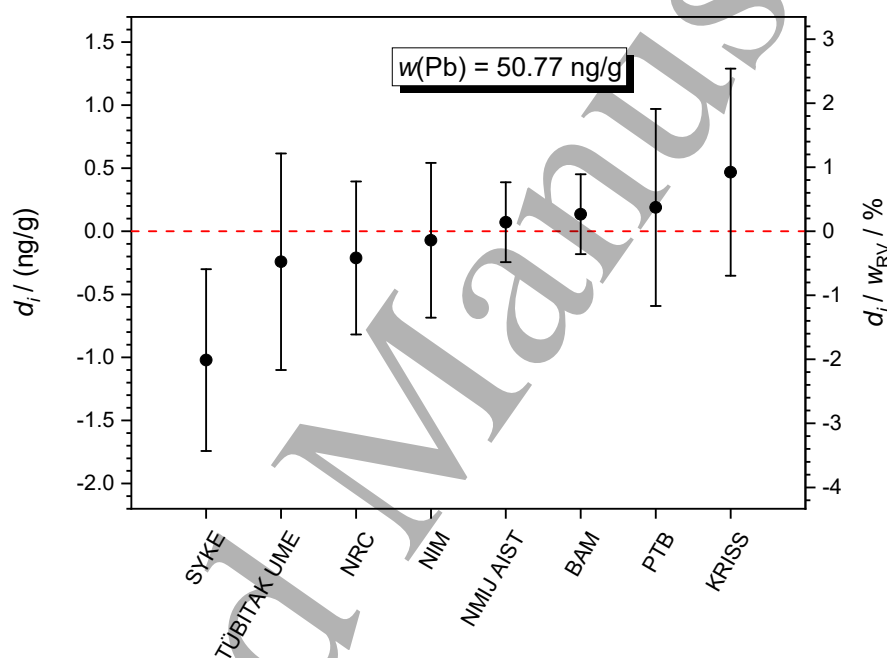


Figure 7: CCQM-K122 (2014): Degrees of equivalence d_i of the determined element mass fraction of lead in the 50 ng/g mass fraction range within a 15 % NaCl solution. Expanded uncertainties are plotted with $k = 2$. All but one of the reported results agree with the KCRV within the limits of their expanded uncertainties. The spread of the relative degrees of equivalence in terms of $\Delta (d_i / w_{RV})$ as indicated on the righthand axis is approximately 1.4 % for the CCQM-K122 participants results being consistent with the KCRV, and 2.9 % considering all of the 8 reported results. Figure 7 is adapted from [19].

Examples of approaches to disseminate the concept of traceability to the SI to field measurements

One could question if it is necessary to put so much effort into the preparation of reference solutions or if the need for high accuracy monoelemental solutions is only an academic end itself. The answer is: It clearly is not! It finds its way into the real (analytical chemistry) world outside of academia.

Starting in the year 2000, in Germany, PTB, BAM and Merck KGaA initiated a joint project for the establishment of a traceability system for inorganic analysis based on highly accurate monoelemental solutions, indicating the (commercial) importance of reliable monoelemental solutions as the very basis of all inorganic measurements. Within this approach, BAM characterized ten high purity reference materials with respect to all possible impurities – with the purity defined as $w_{\text{pur}}(\text{E}) = 1 \text{ g/g} - \sum w_{\text{imp},i}$ – with up to 91 elemental impurities taken into account with an overall relative expanded uncertainty of $U_{\text{rel}}(w_{\text{pur}}(\text{E})) \leq 0.01 \%$ [3]. From these reference materials, PTB gravimetrically prepared reference solutions with $U_{\text{rel}}(w(\text{E})) \leq 0.05 \%$. Finally, Merck produced commercially available solutions with $U_{\text{rel}}(w(\text{E})) \leq 0.3 \%$.

The solid materials, which were characterized within the joint project, are forming primary standards for elemental analysis and help to make SI-traceable calibration standards available to a larger number of users outside the metrology community.

The importance of completely characterized high purity metals which serve as the realization of the SI unit has also been recognized by the European Commission. This is clearly expressed by funding the project EMRP-SIB09 “Primary standards for challenging elements” [20-22] through the European Metrology Research Programme (EMRP). In the framework of this programme, European NMIs/DIs put further effort into the development and improvement of methodologies applicable for the characterization and establishment of traceability to the SI of materials, e.g. using instrumental neutron activation analysis (INAA) to link monoelemental solutions to the SI [23]. Further technical improvements have been achieved for the measurement of non-metallic impurities and in the development of pulsed ion sources for glow discharge mass spectrometry. Based on the original idea of CCQM-P46, the difficult dissolution of rhodium metal was part of the joint project and eventually, a microwave assisted method was developed to successfully dissolve rhodium and prepare monoelemental solutions from a high purity metal [24]. Also inspired by the difficulties encountered in the magnesium solutions in CCQM-P46, the characterization of a magnesium reference material with respect to non-metallic impurities and its isotopic composition [25-27] was substantially improved.

Another, more recent, example is the latest project initiated by the European Directorate for the Quality of Medicines and HealthCare (EDQM), PTB, BAM, and JRC (Joint Research Center, Geel, Belgium). Within this project, monoelemental reference standards with an element mass fraction traceable to the SI were produced for several toxic elements such as lead and mercury. In 2018, the European Pharmacopoeia (Ph. Eur.) implemented an international guideline, the ICH Q3D guideline¹, for the analysis of elemental impurities in medicinal/pharmaceutical products. The standards which were developed in the course of the project are especially intended to be used in conjunction with the corresponding chapters and monographs of the Ph. Eur. During the development of a high accuracy measurement method for 1 g/kg mercury solutions, a novel inductively coupled plasma optical emission spectrometry (ICP-OES) method has been established that allows for the comparison of two mercury solutions with each other with an outstandingly small relative expanded uncertainty of $U_{\text{rel}}(w(\text{Hg})) = 0.16 \%$ [28]. In case of mercury, such small uncertainties would otherwise only be achievable by applying isotope dilution multicollector inductively coupled plasma mass spectrometry (ID-MC-ICP-MS). However, the MS measurements would require more dilution steps than the OES method to prepare a reasonable working solution when starting from $w(\text{Hg}) = 1 \text{ g/kg}$. Therefore, the newly developed method is not only time-saving but it also reduces the risk of a larger measurement uncertainty due to the additional dilution steps. The latter being especially crucial in case of mercury due to unwanted interactions of mercury with the walls of the containers and labware used as well as possible contaminations due to the ubiquitous appearance of mercury in the (laboratory-) environment.

In summary, these three examples underpin the importance of SI-traceable monoelemental solutions for practical use outside the metrology community. They also clearly demonstrate the strong need for further improvements of the applied methods and instruments in order to meet the permanently rising demands of the customers.

Footnote

¹ ICH Q3D: The International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use, Guideline for Elemental Impurities Q3D

Conclusion and Outlook

The technical progress demonstrated in all these CCQM key comparisons and pilot studies discussed, directly impacting the dissemination of the metrological concepts, would not have been possible at all without the ongoing efforts – and sometimes lively and controversial discussions – within the metrological community over 25 years of joint research in the field of high accuracy monoelemental solutions.

CCQM-K2 started with the determination of less demanding elements in a simple matrix measured using a single method applied by all participants. Compared to this first example, CCQM-P149 demonstrated an improvement of 3 orders of magnitude in terms of the spread $\Delta (d_i / w_{\text{med}})$ of the results reported. In general, huge improvements of all three necessary core capabilities for the establishment of a complete traceability chain all the way to the SI unit have been made throughout the last 25 years. Even though more demanding elements were under investigation, and also the matrix became more challenging – ranging from very simple monoelemental solutions to very difficult high salt content samples – the improvements are clearly visible. Nevertheless, this is just the beginning of further developments!

For example, the difficult work on the determination of the mass fractions of non-metallic impurities and their corresponding uncertainties is one of the topics which needs to be addressed by the CCQM in future comparisons in order to further improve the characterization of high purity primary materials as the basis for the preparation of primary monoelemental solutions. Taking into account the necessary low uncertainty associated with the purity of the primary materials ($U_{\text{rel}}(w_{\text{pur}}) \leq 0.01 \%$), the resulting huge amount of work, that needs to be invested to fully characterize such a primary material, can in future obviously only be managed by a joint cooperation of as many NMIs/DIs as possible. Fortunately, CCQM already offers the perfect platform for exactly this challenge. The “Roadmap for the purity determination of pure metallic elements” [17] developed in the framework of the IAWG can be considered a tangible evidence.

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