Bureau International des Poids et Mesures

Guide to the Realization of the ITS-90

Fixed Points: Influence of Impurities

APPENDIX 4: *Recommended List of Common Impurities for Metallic Fixed-point Materials of the ITS-90*

Consultative Committee for Thermometry
under the auspices of the
International Committee for Weights and Measures

APPENDIX 4

Recommended list of common impurities for metallic fixed-point materials of the ITS-90

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Working Group 1 *Defining fixed points and interpolating instruments* of the Consultative Committee for Thermometry (CCT) has recommended methods for estimating the uncertainties of fixed-point temperatures attributable to chemical impurities [Fellmuth *et al.* 2005]. These methods require chemical analysis of all commonly found impurities in the fixed-point material. The document [Fellmuth *et al.* 2005] states:

> Chemical assays should include, as a minimum, all of the "common" elements that are normally found in a particular fixed-point material. It is the intention of WG1 to prepare Appendices/Addenda for a list of such elements for the respective ITS-90 fixed points.

The present document provides a preliminary list of these common impurities, for each of the metals with fixed-point temperatures defined on the International Temperature Scale of 1990 (ITS-90): mercury, gallium, indium, tin, zinc, aluminum, silver, gold, and copper. For each of these elements, we have collected either chemical assays of various material lots or documentary standards that specify the common impurities found in a particular material.

Tables are given below for each ITS-90 metal, listing the impurities detected or specified in each reference. Different lots of materials may have different impurity profiles, and different assays may be more or less sensitive to individual elements. Thus the recommended list of common impurities, which is also included with each table, is broader than the list of impurities found in any one assay. In deciding which elements should be considered "common," we used the following criteria:

- Volatile or inert elements H, C, N, and O were excluded.
- Impurities observed for only one lot and listed as less than 1 % of the total impurity, listed to be less than the detection limit, or listed as a possible contaminant, were excluded.

The recommended list of common impurities has two uses:

1. The list is a guide in assessing the appropriateness of different chemical assay methods. The assay method or methods chosen should be sensitive to all elements on the list of likely impurities.
2. Chemical assays may give only an upper bound on the concentration of certain impurities. [Fellmuth *et al.* 2005] recommends that if the abundances of these elements are not specifically identified, then half the detection limit should be used as the standard uncertainty. In some cases, the detection limits may be quite high for certain elements that are not likely as an impurity, and inclusion of these

elements in the uncertainty calculation would lead to an unphysically high uncertainty. Including only those elements on the recommended list of common impurities will give a more accurate uncertainty.

In the paragraphs below, we offer several cautions on the appropriate use of these tables.

In many circumstances, volatile or inert impurities (such as carbon, nitrogen, and oxygen) will have impurity concentrations much higher than all other impurities in the as-sold metal. Historically, these elements have been neglected in the calculation of impurity effects[1]. We recommend this course of action as well, but we caution that great care must be taken in the fabrication of fixed-point cells to remove all volatiles in the fabrication process. As one example of an appropriate method, metal shot may be melted into a crucible under high vacuum (followed by freezing under inert gas atmosphere to avoid damage to the crucible).

Some of the ITS-90 metals, particularly mercury, gallium, and indium, are available in such high purity that the overall purity of the metal in a fabricated cell is likely to be determined more by contamination in the fabrication process than by the impurities in the starting material. Although there is no consensus yet on how best to determine the uncertainty of a fixed-point cell in this circumstance, we recommend following the methods outlined in Section 4 of [Fellmuth *et al.* 2005] on validation of fixed-point cells[2].

Finally, the lists of common impurities should be considered preliminary until a larger body of independent assays can be collected. Nonetheless, the present set of tables is a valuable adjunct in the application of [Fellmuth *et al.* 2005].

Last scientific revision was made on 16 September 2008
(CCT Working Document CCT/08-16 reproduced)

Last editorial update: 1 January 2018

References

References for particular elements are listed in the appropriate spreadsheets.

Fellmuth B, Hill K D, Bloembergen P, de Groot M, Hermier Y, Matveyev M, Pokhodun A, Ripple D, Steur P P M, 2005 “Methodologies for the estimation of uncertainties and the correction of fixed-point temperatures attributable to the influence of chemical impurities,” Document CCT/05-08 (BIPM, Sévres, France, 2005). This reference is now replaced by *Guide* Section 2.1 *Influence of impurities.*

[1] Appendix 3 deals with the influence of oxygen, see also Subsection 3.1.
[2] Validation of fixed-point cells is treated in Subsection 7.

Mercury

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, < 1 % of total impurity or $<10^{-9}$ fraction by weight
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)					
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3a	3b	3c	4
1	Hydrogen	H							
2	Helium	He							
3	Lithium	Li							
4	Beryllium	Be	**C**			-	-	-	
5	Boron	B	**C**				-	X	
6	Carbon	C							
7	Nitrogen	N							
8	Oxygen	O							
9	Fluorine	F							
11	Sodium	Na	**C**	X					
12	Magnesium	Mg	**C**		U				
13	Aluminum	Al	**C**		U	X	-	X	
14	Silicon	Si	**C**		U				
15	Phosphorus	P							
16	Sulfur	S							
17	Chlorine	Cl							
19	Potassium	K							
20	Calcium	Ca	**C**		U				
21	Scandium	Sc							
22	Titanium	Ti							
23	Vanadium	V	**C**			X	-	-	
24	Chromium	Cr	**C**			-	-	-	
25	Manganese	Mn	**C**			-	-	-	-
26	Iron	Fe	**C**		U	X	-	-	
27	Cobalt	Co	**C**			-	-	-	
28	Nickel	Ni	**C**			-	-	-	
29	Copper	Cu	**C**		U	X	-	-	-
30	Zinc	Zn	**C**			-	-	-	-
31	Gallium	Ga							
32	Germanium	Ge							
33	Arsenic	As	**C**			-	-	-	
34	Selenium	Se							-
35	Bromine	Br							
37	Rubidium	Rb							
38	Strontium	Sr							
39	Yttrium	Y							
40	Zirconium	Zr							
41	Niobium	Nb							
42	Molybdenum	Mo							
43	Technitium	Tc							
44	Ruthenium	Ru							
45	Rhodium	Rh							
46	Palladium	Pd							
47	Silver	Ag	**C**			X	-	-	-
48	Cadmium	Cd	**C**			-	-	-	-

Mercury (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below) 1	2	3a	3b	3c	4
49	Indium	In							
50	Tin	Sn							-
51	Antimony	Sb	**C**			-	-	-	
52	Tellurium	Te							
53	Iodine	I							
55	Cesium	Cs							
56	Barium	Ba	**C**			-	-	-	
57	Lanthanum	La							
58	Cerium	Ce							
72	Hafnium	Hf							
73	Tantalum	Ta							
74	Tungsten	W							
75	Rhenium	Re							
76	Osmium	Os							
77	Iridium	Ir							
78	Platinum	Pt							
79	Gold	Au							
80	Mercury	Hg	**M**	M	M	M	M	M	M
81	Thallium	Tl							
82	Lead	Pb	**C**		U	-	-	-	-
83	Bismuth	Bi							
90	Thorium	Th							
92	Uranium	U							

NOTE: Mercury is commonly available at sufficiently high purity that contamination from the cell preparation and cell crucible are likely to dominate the overall cell impurity level.

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh., Moscow, Nauka, 2003, 236 pp.
2. NIST Standard Reference Material 743, Mercury Triple Point (supplier analysis).
3. D. del Campo, V. Chimenti, J. Reyes, J. A. Rodríguez Castrillón. M. Moldovan, and J. I. García Alonso, *Int. J. Thermophys.* **29**, 93-103 (2008); a. as received from supplier and triple distilled, b. vacuum distilled, c. vacuum bi-distilled.
4. LNE, N9 mercury cell (supplier analysis).

Gallium

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)	
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2
1	Hydrogen	H			
2	Helium	He			
3	Lithium	Li			
4	Beryllium	Be			
5	Boron	B			
6	Carbon	C			
7	Nitrogen	N			
8	Oxygen	O			
9	Fluorine	F	**C**	X	
11	Sodium	Na			
12	Magnesium	Mg			
13	Aluminum	Al	**C**	X	X
14	Silicon	Si			
15	Phosphorus	P			
16	Sulfur	S			
17	Chlorine	Cl	**C**		X
19	Potassium	K			
20	Calcium	Ca			
21	Scandium	Sc			
22	Titanium	Ti	**C**		X
23	Vanadium	V	**C**		X
24	Chromium	Cr			
25	Manganese	Mn			
26	Iron	Fe	**C**		X
27	Cobalt	Co			
28	Nickel	Ni	**C**		X
29	Copper	Cu	**C**		X
30	Zinc	Zn			
31	Gallium	Ga	**M**	M	M
32	Germanium	Ge			
33	Arsenic	As	**C**	X	
34	Selenium	Se			
35	Bromine	Br			
37	Rubidium	Rb			
38	Strontium	Sr			
39	Yttrium	Y			
40	Zirconium	Zr			
41	Niobium	Nb			
42	Molybdenum	Mo			
43	Technitium	Tc			
44	Ruthenium	Ru			
45	Rhodium	Rh			
46	Palladium	Pd			
47	Silver	Ag			
48	Cadmium	Cd			

Gallium (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below) 1	2
49	Indium	In			
50	Tin	Sn			
51	Antimony	Sb			
52	Tellurium	Te			
53	Iodine	I			
55	Cesium	Cs			
56	Barium	Ba			
57	Lanthanum	La			
58	Cerium	Ce			
72	Hafnium	Hf			
73	Tantalum	Ta			
74	Tungsten	W			
75	Rhenium	Re			
76	Osmium	Os			
77	Iridium	Ir			
78	Platinum	Pt			
79	Gold	Au			
80	Mercury	Hg			
81	Thallium	Tl	**C**		X
82	Lead	Pb	**C**		X
83	Bismuth	Bi			
90	Thorium	Th			
92	Uranium	U			

NOTE: Gallium is commonly available at sufficiently high purity that contamination from the cell preparation and cell crucible are likely to dominate the overall cell impurity level.

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. NIST Standard Reference Material 1751, Gallium Melting-Point Standard.

Indium

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)						
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2a	2b	2c	2d	3	4
1	Hydrogen	H		X						
2	Helium	He								
3	Lithium	Li								
4	Beryllium	Be								
5	Boron	B	**C**	X						
6	Carbon	C				X				
7	Nitrogen	N				X				
8	Oxygen	O				X				
9	Fluorine	F	**C**	X						
11	Sodium	Na	**C**		X					
12	Magnesium	Mg	**C**	X			X	X	-	-
13	Aluminum	Al	**C**	X	X	X				
14	Silicon	Si	**C**	X	X	X			-	
15	Phosphorus	P								
16	Sulfur	S	**C**	X						
17	Chlorine	Cl	**C**	X		X				
19	Potassium	K	**C**	X						
20	Calcium	Ca	**C**						-	-
21	Scandium	Sc								
22	Titanium	Ti								
23	Vanadium	V								
24	Chromium	Cr								
25	Manganese	Mn	**C**	X						
26	Iron	Fe	**C**	X	X		X	X		
27	Cobalt	Co								
28	Nickel	Ni	**C**		X	X				
29	Copper	Cu	**C**	X						
30	Zinc	Zn								
31	Gallium	Ga	**C**			X				
32	Germanium	Ge								
33	Arsenic	As								
34	Selenium	Se								
35	Bromine	Br								
37	Rubidium	Rb								
38	Strontium	Sr								
39	Yttrium	Y								
40	Zirconium	Zr								
41	Niobium	Nb								
42	Molybdenum	Mo								
43	Technitium	Tc								
44	Ruthenium	Ru								
45	Rhodium	Rh								
46	Palladium	Pd								
47	Silver	Ag								
48	Cadmium	Cd		-						

Indium (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below) 1	2a	2b	2c	2d	3	4
49	Indium	In	**M**	M	M	M	M	M	M	M
50	Tin	Sn	**C**		X	X		X	-	
51	Antimony	Sb								
52	Tellurium	Te								
53	Iodine	I								
55	Cesium	Cs								
56	Barium	Ba								
57	Lanthanum	La								
58	Cerium	Ce								
72	Hafnium	Hf								
73	Tantalum	Ta								
74	Tungsten	W								
75	Rhenium	Re								
76	Osmium	Os								
77	Iridium	Ir								
78	Platinum	Pt								
79	Gold	Au								
80	Mercury	Hg								
81	Thallium	Tl	**C**			X				
82	Lead	Pb	**C**	-	X	X	X	X	-	
83	Bismuth	Bi	**C**			X				
90	Thorium	Th								
92	Uranium	U								

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. G. Strouse, "NIST methods of estimating the impurity uncertainty component for ITS-90 fixed-point cells from the Ar TP to the Ag FP," CCT/03-19 (BIPM, France, 2003).
3. P. Steur, private communication, supplier analysis 1993.
4. P. Steur, private communication, supplier analysis 1993.

Tin

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)										
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3	4	5	6	7	8	9	10	11
1	Hydrogen	H												
2	Helium	He												
3	Lithium	Li												
4	Beryllium	Be												
5	Boron	B										-		
6	Carbon	C				X						X		
7	Nitrogen	N				X						X	-	
8	Oxygen	O		X		X						X	-	
9	Fluorine	F												
11	Sodium	Na	**C**	-								-		
12	Magnesium	Mg	**C**					-	U	U	X	-		
13	Aluminum	Al	**C**	X								X	-	
14	Silicon	Si	**C**			X	X		U	X	X	X	-	
15	Phosphorus	P	**C**			X						X	-	
16	Sulfur	S	**C**			X						X	-	X
17	Chlorine	Cl										X	-	
19	Potassium	K												
20	Calcium	Ca	**C**				X							
21	Scandium	Sc												
22	Titanium	Ti	**C**			-						-		
23	Vanadium	V												
24	Chromium	Cr												
25	Manganese	Mn	**C**	-								-		
26	Iron	Fe	**C**		X						X	X		
27	Cobalt	Co	**C**		X									
28	Nickel	Ni	**C**		X									
29	Copper	Cu	**C**	X	X					X		-		X
30	Zinc	Zn										-		
31	Gallium	Ga										-		
32	Germanium	Ge	**C**			X						-		
33	Arsenic	As	**C**		X	X						-		
34	Selenium	Se												
35	Bromine	Br												
37	Rubidium	Rb												
38	Strontium	Sr												
39	Yttrium	Y												
40	Zirconium	Zr												
41	Niobium	Nb												
42	Molybdenum	Mo												
43	Technitium	Tc												
44	Ruthenium	Ru												
45	Rhodium	Rh												
46	Palladium	Pd												
47	Silver	Ag	**C**				X				X			X
48	Cadmium	Cd												

Tin (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below)										
				1	2	3	4	5	6	7	8	9	10	11
49	Indium	In	**C**		X				X	X			X	
50	Tin	Sn	**M**	M	M	M	M	M	M	M	M	M	M	M
51	Antimony	Sb	**C**	-	X						X			
52	Tellurium	Te												
53	Iodine	I												
55	Cesium	Cs												
56	Barium	Ba												
57	Lanthanum	La												
58	Cerium	Ce												
72	Hafnium	Hf												
73	Tantalum	Ta												
74	Tungsten	W												
75	Rhenium	Re												
76	Osmium	Os												
77	Iridium	Ir												
78	Platinum	Pt												
79	Gold	Au		-										
80	Mercury	Hg												
81	Thallium	Tl												
82	Lead	Pb	**C**		X				X	X		X	X	
83	Bismuth	Bi	**C**								X	-		
90	Thorium	Th												
92	Uranium	U												

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. NIST Standard Reference Material 1727, Anode Tin.
3. G. Strouse, private communication, NRC analysis of Firebird Technologies material, nominally 6-9s – 8.
4. NIST Standard Reference Material 741a, Tin Freezing Point Standard (supplier analysis).
5. G. Strouse, supplier analysis, Cominco Electronic Materials, 1988, Lot EM 6878.
6. NBS Standard Reference Material 741, Tin (Freezing Point) (supplier analysis).
7. NBS Standard Reference Material 42G, Tin Secondary Freezing Point Standard.
8. G. Strouse, private communication, supplier analysis Johnson Matthey Lot M1701 (1993).
9. B. Fellmuth and K.D. Hill, *Metrologia* **43** 71-83 (2006).
10. D. Head, private communication.
11. K. Yamazawa, J.V. Widiatmo, and M. Arai, *Intl. J. Thermophys.* **28,** 1941-1956 (2007).

Zinc

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)						
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3	4	5	6	7
1	Hydrogen	H								
2	Helium	He								
3	Lithium	Li			-					
4	Beryllium	Be	**C**		U					
5	Boron	B			-					
6	Carbon	C			U					
7	Nitrogen	N		X	U					
8	Oxygen	O			U					
9	Fluorine	F	**C**		U					
11	Sodium	Na	**C**	-	U	-	U			
12	Magnesium	Mg	**C**		U	-		X		
13	Aluminum	Al	**C**	X	U	-	U			
14	Silicon	Si	**C**	X	U	-		-		
15	Phosphorus	P								
16	Sulfur	S								
17	Chlorine	Cl	**C**	X	U					
19	Potassium	K	**C**		U	-				
20	Calcium	Ca	**C**	X	U	-				
21	Scandium	Sc	**C**			-	-			
22	Titanium	Ti	**C**		U	-				
23	Vanadium	V	**C**			-	-			
24	Chromium	Cr	**C**	X	U	-				X
25	Manganese	Mn	**C**		U	-	-			
26	Iron	Fe	**C**	X	X	X	X	X		X
27	Cobalt	Co	**C**	-		X				
28	Nickel	Ni	**C**		U	X				
29	Copper	Cu	**C**		X	X	X		X	
30	Zinc	Zn	**M**	M	M	M	M	M	M	M
31	Gallium	Ga	**C**			-	-			
32	Germanium	Ge								
33	Arsenic	As	**C**			-	-			
34	Selenium	Se								
35	Bromine	Br								
37	Rubidium	Rb								
38	Strontium	Sr								
39	Yttrium	Y								
40	Zirconium	Zr				-				
41	Niobium	Nb				-				
42	Molybdenum	Mo	**C**			-	-			
43	Technitium	Tc								
44	Ruthenium	Ru				-				
45	Rhodium	Rh	**C**			-	-			
46	Palladium	Pd				-				
47	Silver	Ag	**C**	X	X	X	X		X	
48	Cadmium	Cd	**C**		X	X	X		X	

Zinc (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below) 1	2	3	4	5	6	7
49	Indium	In	**C**	X		-	-			
50	Tin	Sn	**C**		X	-	-			
51	Antimony	Sb	**C**			X	U			
52	Tellurium	Te								
53	Iodine	I								
55	Cesium	Cs								
56	Barium	Ba								
57	Lanthanum	La								
58	Cerium	Ce								
72	Hafnium	Hf								
73	Tantalum	Ta								
74	Tungsten	W	**C**			X	-			
75	Rhenium	Re								
76	Osmium	Os								
77	Iridium	Ir				-				
78	Platinum	Pt				-				
79	Gold	Au	**C**			-	-			
80	Mercury	Hg				-				
81	Thallium	Tl	**C**			X	U			
82	Lead	Pb	**C**			X	X	X		X
83	Bismuth	Bi				-				
90	Thorium	Th								
92	Uranium	U								

NOTE: to calculate "-", neglect Cl for refer. 1, which was dominant, but possibly volatile.

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. NIST Standard Reference Material 682, High-Purity Zinc.
3. NIST Standard Reference Material 728, Intermediate Purity Zinc.
4. NIST Standard Reference Material 683, Zinc Metal.
5. G. Strouse, private communication, supplier analysis for Cominco Electronic Materials, 1987, Lot EM 6351.
6. G. Strouse, private communication, supplier analysis for Johnson Matthey, 1993, Lot M2039.
7. J. V. Widiatmo, private communication, supplier analysis.

Aluminum

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)												
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3a	3b	3c	4	5	6	7	8	9	10	11	12
1	Hydrogen	H															
2	Helium	He															
3	Lithium	Li	**C**						S	S	S						
4	Beryllium	Be	**C**						S	S	S						
5	Boron	B	**C**		-				S	S	S		-				
6	Carbon	C			X								X	X	X		
7	Nitrogen	N			X								X	X	X		
8	Oxygen	O			X								X	X	X		
9	Fluorine	F															
11	Sodium	Na	**C**		-			X	S	S	S			-	-		
12	Magnesium	Mg	**C**	X	X	U			S	S	S	-	X			-	
13	Aluminum	Al	**M**	M	M	M	M	M	M	M	M	M	M	M	M	M	M
14	Silicon	Si	**C**	-	X	X	X		S	S	S	-	-	-	-	-	
15	Phosphorus	P	**C**		-				S		S		-	-			
16	Sulfur	S	**C**		-								-	-		-	
17	Chlorine	Cl	**C**		X								-	-		-	
19	Potassium	K	**C**		-				S		S						
20	Calcium	Ca	**C**	-		X	X		S	S	S	-					
21	Scandium	Sc	**C**	X	X									-	-	-	-
22	Titanium	Ti	**C**	-	X			U	S	S	S		-	-	-	-	
23	Vanadium	V	**C**		X				S	S	S		-	-	-	-	
24	Chromium	Cr	**C**	X	X	X		U	S	S	S		-	-	-	-	-
25	Manganese	Mn	**C**	X	X	X	X	U	S	S	S	-	-	-	-	-	
26	Iron	Fe	**C**	X	X	X	X	X	S	S	S		-	-		-	O
27	Cobalt	Co	**C**	-	-					S							-
28	Nickel	Ni	**C**	X	-			U	S	S	S		-	-			
29	Copper	Cu	**C**	X	X	X		U	S	S	S	-	-	-			
30	Zinc	Zn	**C**	X	X			X	S	S	S						-
31	Gallium	Ga	**C**	X				U		S						-	
32	Germanium	Ge															
33	Arsenic	As	**C**	X					S		S						
34	Selenium	Se	**C**	X	-												
35	Bromine	Br			-												
37	Rubidium	Rb												-			
38	Strontium	Sr	**C**							S							
39	Yttrium	Y															
40	Zirconium	Zr	**C**		-				S	S	S			-		-	
41	Niobium	Nb			-												
42	Molybdenum	Mo														-	
43	Technitium	Tc															
44	Ruthenium	Ru															
45	Rhodium	Rh															
46	Palladium	Pd															
47	Silver	Ag	**C**								S	-		-			
48	Cadmium	Cd	**C**	-						S				X			

Aluminum (continued)

	Impurity		Common	Reference (see below)												
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3a	3b	3c	4	5	6	7	8	9	10	11	12
49	Indium	In	**C**		X									-			
50	Tin	Sn	**C**						S	S	S						
51	Antimony	Sb	**C**								S			-			
52	Tellurium	Te	**C**	-	-									-			
53	Iodine	I															
55	Cesium	Cs	**C**						S		S						
56	Barium	Ba															
57	Lanthanum	La	**C**														X
58	Cerium	Ce	**C**						S		S						X
72	Hafnium	Hf															
73	Tantalum	Ta	**C**	X													
74	Tungsten	W	**C**	-	-											-	O
75	Rhenium	Re			-												
76	Osmium	Os															
77	Iridium	Ir															
78	Platinum	Pt			-												
79	Gold	Au	**C**						S		S						
80	Mercury	Hg	**C**											X			-
81	Thallium	Tl												-			
82	Lead	Pb	**C**							S							
83	Bismuth	Bi	**C**							S							
90	Thorium	Th	**C**		-				S		S						
92	Uranium	U	**C**		-				S		S						

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. M. Arai, private communication.
3. G. T. Furukawa, *J. Res. NBS* **78A**, 477-495 (1974); a. Batch 1558 (Supplier - spectrochemical analysis), b. Batch 2571 (Supplier - spectrochemical analysis), c. Batch 2571 (NBS - Mass spectrometric analysis)
4. "Standard Test Method for Trace Metallic Impurities in Electronic Grade Aluminum by High Mass-Resolution Glow-Discharge Mass Spectrometer," ASTM F 1593-97 (West Conshohocken, PA, USA, ASTM, 1997).
5. "Standard Specification for Pure Aluminum (Unalloyed) Source Material for Vacuum Coating Applications," ASTM F 1594-95 (West Conshohocken, PA, USA, ASTM, 1995).
6. "Standard Specification for Pure Aluminum (Unalloyed) Source Material for Thin Film Applications," ASTM F 1513-94 (West Conshohocken, PA, USA, ASTM, 1994).
7. P. Steur, private communication, supplier analysis 1993.
8. D. Head, private communication.
9. D. Head, private communication.
10. P. Steur, private communication, National Research Council, Canada analysis on INRiM sample.
11. P. Steur, private communication, supplier analysis on INRiM sample.
12. P. Steur, private communication, NAA on INRiM sample (Fe and W probably due to sample taking).

Silver

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)										
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3	4a	4b	5	6	7a	7b	7c	8
1	Hydrogen	H												
2	Helium	He												
3	Lithium	Li												
4	Beryllium	Be												-
5	Boron	B												
6	Carbon	C												
7	Nitrogen	N												
8	Oxygen	O		X										
9	Fluorine	F												
11	Sodium	Na	**C**								X		X	
12	Magnesium	Mg	**C**	X	X	X	X	X			X	X	X	-
13	Aluminum	Al	**C**				X				X		X	
14	Silicon	Si	**C**		X	X				-	X		X	-
15	Phosphorus	P	**C**	X								X		-
16	Sulfur	S	**C**	X								X	X	
17	Chlorine	Cl	**C**									X	X	
19	Potassium	K												
20	Calcium	Ca	**C**			X					X		X	
21	Scandium	Sc												
22	Titanium	Ti	**C**										X	
23	Vanadium	V	**C**	X									X	
24	Chromium	Cr	**C**				X	X			X	X	X	
25	Manganese	Mn	**C**	X						-		X	X	-
26	Iron	Fe	**C**		X	X	X	X	S	-	X	X	X	
27	Cobalt	Co	**C**								X	X	X	
28	Nickel	Ni	**C**	X				X			X	X	X	
29	Copper	Cu	**C**			X			S	-	X	X	X	
30	Zinc	Zn	**C**	X							X	X	X	
31	Gallium	Ga												
32	Germanium	Ge												
33	Arsenic	As												-
34	Selenium	Se	**C**						S			X	X	
35	Bromine	Br												
37	Rubidium	Rb												
38	Strontium	Sr												
39	Yttrium	Y												
40	Zirconium	Zr												
41	Niobium	Nb												
42	Molybdenum	Mo												
43	Technitium	Tc												
44	Ruthenium	Ru												
45	Rhodium	Rh	**C**								X			
46	Palladium	Pd	**C**						S					
47	Silver	Ag	**M**	M	M	M	M	M	M	M	M	M	M	M
48	Cadmium	Cd	**C**								X			-

Silver (continued)

	Impurity		Common	Reference (see below)										
Atomic No.	Name	Symbol	Impurity	1	2	3	4a	4b	5	6	7a	7b	7c	8
49	Indium	In												
50	Tin	Sn	**C**									X	X	
51	Antimony	Sb	**C**									X	X	-
52	Tellurium	Te	**C**						S					-
53	Iodine	I												
55	Cesium	Cs												
56	Barium	Ba												
57	Lanthanum	La												
58	Cerium	Ce												
72	Hafnium	Hf												
73	Tantalum	Ta												
74	Tungsten	W												
75	Rhenium	Re												
76	Osmium	Os												
77	Iridium	Ir	**C**								X			
78	Platinum	Pt	**C**								X		X	
79	Gold	Au	**C**								X			-
80	Mercury	Hg												-
81	Thallium	Tl												-
82	Lead	Pb	**C**			X			S		X		X	-
83	Bismuth	Bi	**C**						S		X		X	
90	Thorium	Th												
92	Uranium	U												

NOTE: to calculate "-", neglect Cl for refer. 1, which was dominant, but possibly volatile.

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. NIST Standard Reference Material 1746, Silver (Freezing Point); Johnson Matthey Lot M1282 (1991) (supplier analysis).
3. T.P. Jones and J. Tapping , "A Photoelectric Pyrometer Temperature Scale Below 1064.43 °C and its Use to Measure the Silver Point," in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6 (AIP, New York, 1982) pp. 169-174.
4. M. Ohtsuka and R.E. Bedford, "Measurement of the Thermodynamic Temperature Interval between the Freezing Points of Silver and Copper," in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6 (AIP, New York, 1982) pp. 175-180.
5. "Standard Specification for Refined Silver," ASTM Standard B 413-97a (West Conshohocken, PA, USA, ASTM, 1997).
6. P. Steur, private communication of supplier analysis 1991/3.
7. J.V. Widiatmo, K. Harada, K. Yamazawa, M. Arai, *Intl. J. Thermophys.* **29**, 158-170 (2008).
8. P. Steur, private communication of supplier analysis.

Gold

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
K	Known contaminant
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)		
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3
1	Hydrogen	H				
2	Helium	He				
3	Lithium	Li				
4	Beryllium	Be				
5	Boron	B		-		
6	Carbon	C			O	
7	Nitrogen	N			O	
8	Oxygen	O			X	
9	Fluorine	F			O	
11	Sodium	Na			O	
12	Magnesium	Mg	**C**	X	O	K
13	Aluminum	Al			O	
14	Silicon	Si	**C**	X	O	
15	Phosphorus	P				
16	Sulfur	S	**C**	X	O	
17	Chlorine	Cl	**C**	X	O	
19	Potassium	K			O	
20	Calcium	Ca			O	
21	Scandium	Sc				
22	Titanium	Ti	**C**	X		K
23	Vanadium	V	**C**	-	O	
24	Chromium	Cr	**C**	X	O	K
25	Manganese	Mn	**C**	X		K
26	Iron	Fe	**C**	X	X	K
27	Cobalt	Co				
28	Nickel	Ni	**C**	X	O	K
29	Copper	Cu	**C**	X	X	K
30	Zinc	Zn	**C**	X	O	K
31	Gallium	Ga	**C**	X		
32	Germanium	Ge				
33	Arsenic	As	**C**			K
34	Selenium	Se			O	
35	Bromine	Br				
37	Rubidium	Rb				
38	Strontium	Sr			O	
39	Yttrium	Y				
40	Zirconium	Zr				
41	Niobium	Nb	**C**	X	O	
42	Molybdenum	Mo				
43	Technitium	Tc				
44	Ruthenium	Ru				
45	Rhodium	Rh				
46	Palladium	Pd	**C**			K
47	Silver	Ag	**C**	X	X	K
48	Cadmium	Cd				

Gold (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below) 1	2	3
49	Indium	In	**C**		X	
50	Tin	Sn	**C**	-	O	K
51	Antimony	Sb				
52	Tellurium	Te				
53	Iodine	I				
55	Cesium	Cs				
56	Barium	Ba			O	
57	Lanthanum	La				
58	Cerium	Ce				
72	Hafnium	Hf				
73	Tantalum	Ta				
74	Tungsten	W				
75	Rhenium	Re				
76	Osmium	Os				
77	Iridium	Ir				
78	Platinum	Pt				
79	Gold	Au	**M**	M	M	M
80	Mercury	Hg				
81	Thallium	Tl				
82	Lead	Pb	**C**	X		K
83	Bismuth	Bi	**C**	-		K
90	Thorium	Th				
92	Uranium	U				

NOTE 1: To calculate "-", neglect O for ref. 2, which was dominant, but possibly volatile.

NOTE 2: Ref. 2 identifies other elements, but suggests the sample was contaminated in some cases)

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. NIST Standard Reference Material 685, High-Purity Gold.
3. Royal Canadian Mint Reference Materials 8050, 8051, 8052; “Standard Specification for Refined Gold,” ASTM Standard B562-95 (West Conshohocken, PA, USA, ASTM, 1995).

Copper

M	Matrix element
X	Significant impurity detected
-	Impurity detected above det. limit, less than 1 % of total impurity
S	Specified elements for assay
O	Element identified, but possibly a contaminant
U	Only upper concentration limit given
C	Identified as common impurity

	Impurity		Common	Reference (see below)					
Atomic No.	**Name**	**Symbol**	**Impurity**	1	2	3	4a	4b	5
1	Hydrogen	H							
2	Helium	He							
3	Lithium	Li							
4	Beryllium	Be							
5	Boron	B		-					
6	Carbon	C							
7	Nitrogen	N		X					
8	Oxygen	O			X	U			S
9	Fluorine	F	**C**	X					
11	Sodium	Na							
12	Magnesium	Mg	**C**	X		U	X	X	
13	Aluminum	Al	**C**	X		U	X	X	
14	Silicon	Si	**C**	X		U	X	X	
15	Phosphorus	P	**C**	X					S
16	Sulfur	S	**C**	X	X	X			S
17	Chlorine	Cl	**C**	X					
19	Potassium	K							
20	Calcium	Ca							
21	Scandium	Sc							
22	Titanium	Ti	**C**	X					
23	Vanadium	V							
24	Chromium	Cr	**C**	X		U	X	X	
25	Manganese	Mn	**C**			-			S
26	Iron	Fe	**C**		X	X	X	X	S
27	Cobalt	Co	**C**			U			
28	Nickel	Ni	**C**	X	-	X		X	S
29	Copper	Cu	**M**	M	M	M	M	M	
30	Zinc	Zn	**C**		-	U			S
31	Gallium	Ga							
32	Germanium	Ge							
33	Arsenic	As	**C**	X	-	X			S
34	Selenium	Se	**C**			X			S
35	Bromine	Br							
37	Rubidium	Rb							
38	Strontium	Sr							
39	Yttrium	Y							
40	Zirconium	Zr							
41	Niobium	Nb							
42	Molybdenum	Mo							
43	Technitium	Tc							
44	Ruthenium	Ru							
45	Rhodium	Rh							
46	Palladium	Pd							
47	Silver	Ag	**C**		X	X			S
48	Cadmium	Cd	**C**	X		U			S

Copper (continued)

Atomic No.	Impurity Name	Symbol	Common Impurity	Reference (see below) 1	2	3	4a	4b	5
49	Indium	In	**C**	X					
50	Tin	Sn	**C**		-	-			S
51	Antimony	Sb	**C**		-	X			S
52	Tellurium	Te	**C**			X			S
53	Iodine	I							
55	Cesium	Cs							
56	Barium	Ba							
57	Lanthanum	La							
58	Cerium	Ce							
72	Hafnium	Hf							
73	Tantalum	Ta							
74	Tungsten	W							
75	Rhenium	Re							
76	Osmium	Os							
77	Iridium	Ir							
78	Platinum	Pt							
79	Gold	Au	**C**	X		-			
80	Mercury	Hg							
81	Thallium	Tl							
82	Lead	Pb	**C**		-	X			S
83	Bismuth	Bi	**C**		-	X			S
90	Thorium	Th							
92	Uranium	U							

NOTE: to calculate "-", neglect O for refer. 2 & 3, which was dominant, but possibly volatile.

1. *Collection Exhibition of Special-Purity Substances*, G. G. Devyatykh, Yu.A. Karpov, L.I. Osipova, Ed. by G.G. Devyatykh. (Moscow, Nauka, 2003) 236 pp.
2. NIST Standard Reference Material 885, Refined Copper.
3. T.P. Jones and J. Tapping , "A Photoelectric Pyrometer Temperature Scale Below 1064.43 °C and its Use to Measure the Silver Point," in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6 (AIP, New York, 1982) pp. 169-174.
4. M. Ohtsuka and R.E. Bedford, "Measurement of the Thermodynamic Temperature Interval between the Freezing Points of Silver and Copper," in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6 (AIP, New York, 1982) pp. 175-180.
5. "Standard Specification for Oxygen-Free Electrolytic Copper—Refinery Shapes," ASTM Standard B 170-99 (West Conshohocken, PA, USA, ASTM, 1999).