VALIDITY OF THE SPECIFIC GRAVITY METHOD FOR THE DETERMINATION OF THE FINENESS OF GOLD OBJECTS

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The determination of the gold content or fineness of gold objects by means of specific gravity measurements is one of the oldest known methods of assay. The account given by Vitruvius of the way by which Archimedes detected the adulteration of the gold in the crown of Hieron of Syracuse shows that the method was known in principle, even if not widely used, before the beginning of the Christian Era. There is evidence from Arab sources that it was used in the Middle Ages, and the accounts of the method given in works on assaying of the sixteenth and seventeenth centuries indicate that it was in common use in early modern times. It is still used occasionally for the determination of the fineness of gold objects which cannot be assayed or analyzed by the usual dry or wet methods. Indeed, the great and unique value of the method is that it makes possible an estimate of the fineness of gold objects, which, because of their great antiquarian or artistic value, cannot be sampled in any way, even for microanalysis. In spite of the long time this method has been in use and in spite of its undoubted special value, no critical estimate of its probable accuracy or limitations, apart from brief statements, appears ever to have been published. There is considerable evidence that various workers have used this method uncritically and attributed to it an unwarranted degree of accuracy. For example, Giesecke (4) determined the specific gravities of a number of ancient electrum coins and then calculated their gold content in two decimal places in percent. It can easily be shown that the method does not warrant expressing results to such an apparent degree of accuracy. The purpose of the present paper is to indicate its probable degree of accuracy and its limitations.

A primary difficulty in the determination of the composition of alloys of gold and silver, or of gold and copper, by specific gravity measurements is that the specific gravities of the pure metals themselves cannot be defined with any high degree of precision. Results of even very careful measurements of this so-called constant have varied considerably in accordance with the mechanical and thermal history of the specimens studied. Mellor (11) has ably summarized the discordant results obtained by different workers. Though the lack of agreement is less when only the most reliable results on massive specimens are considered, and still less when mechanically worked metal is alone considered, this being of more practical significance in connection with the kinds of objects ordinarily assayed by the specific gravity method, there is nevertheless apparently no justification for expressing the specific gravities of the pure metals to more than a single decimal place for the purpose of computing the composition of their alloys. This means that as a basis for determination carried out at or close to 25° C. with reference to the density of water at 4° C. the specific gravity of gold should be taken as 19.3, that of silver as 10.5, and that of copper as 8.9. Hence it follows that for the determination of the composition of gold-silver alloys with a possible range of 0 to 100 percent for either component, there are actually available from the difference between the specific gravities of the two metals only 88 possible units in the scale of measurement, each of these units being a tenth of a unit in specific gravity. On the average, therefore, a little more than one percent is the closest approach that can possibly be attained in respect to the composition of such alloys by this method. Actually if no contraction or expansion occurs on alloying, each tenth of a unit in specific gravity represents a little more than half a percent change in composition near the top of the range in gold content and about two percent change near the bottom of the range. Likewise for gold-copper alloys there are only 104 possible units in the scale of measurement, and on the average slightly less than one percent is the closest possible approach to composition that can be attained, with approximately the same differences at the extremes as with gold-silver alloys if no change in volume occurs on alloying. These differences at the extremes of the ranges necessarily follow from the nature of the ideal proportional relationship between specific gravity and percentage composition by weight of such binary alloys. This relationship may be expressed by the following convenient formula:

$$\% \text{ Gold} = \frac{S_1 S_x - S_1 S_2}{S_1 S_x - S_2 S_x} \cdot 100$$

Where, on the same temperature basis for each,

S_1 is the specific gravity of pure gold.
S_2 is the specific gravity of pure silver or of pure copper.
S_x is the specific gravity of a given alloy.

A comparison between the ideal figures as computed by the above formula and the experimental figures obtained by various investigators also shows that

TABLE I

COMPARISON BETWEEN ACTUAL GOLD CONTENT OF GOLD-SILVER ALLOYS AND THEIR GOLD CONTENT AS CALCULATED FROM THEIR SPECIFIC GRAVITIES

Specific Gravity	Gold Content from Specific Gravity	Actual Gold Content	Difference	Literature Reference
	%	%	%	
19.28	99.9	99.7	+0.2	6
19.17	99.2	99.5	−0.3	6
18.08	91.9	91.7	+0.2	8
18.04	91.6	91.6	±0.0	10
17.93	90.9	91.7	−0.8	6
17.54	88.0	88.0	±0.0	10
16.96	83.6	84.3	−0.7	8
16.35	78.5	78.5	±0.0	10
16.03	75.6	75.0	+0.6	8
15.07	66.5	66.7	−0.2	8
14.87	64.6	64.6	±0.0	10
14.24	57.6	58.3	−0.7	8
13.60	50.0	50.0	±0.0	8
13.43	47.9	47.8	+0.1	10
13.00	42.2	41.7	+0.5	8
12.38	33.3	33.3	±0.0	8
12.26	31.5	31.4	+0.1	10
11.78	23.8	25.0	−1.2	8
11.76	23.5	23.4	+0.1	10
11.29	15.3	16.7	−1.4	8

NOTES ON ORIGINAL DATA

REFERENCE 6. The gold content is given in carats and grains, and the specific gravity to three decimal places.

REFERENCE 8. The gold content is given in parts per thousand, and the specific gravity as shown.

REFERENCE 10. The gold content is given by formula, e.g., Ag_4Au, and the specific gravity to three decimal places.

the method is not any more reliable than about one percent even under the best experimental conditions. In Tables I and II are shown comparisons of figures from what appear to be the most careful experiments on record with corresponding ideal figures for gold-silver and gold-copper alloys. In order to show up distinctly the differences between the ideal figures and the experimental figures, the specific gravity of gold for this special purpose was taken as 19.30, that of silver as 10.50, and that of copper as 8.90 when calculating the ideal figures from the measured specific gravities, and the ideal gold content is correspondingly given to the first decimal place. As explained in the footnotes to these tables, most of the experimental figures were obtained by appropriate recalculation of the original published data so as to place all the figures on a uniform basis for the purpose of easy comparison. However, no corrections have been made for the differences in the

TABLE II

COMPARISON BETWEEN ACTUAL GOLD CONTENT OF GOLD-COPPER ALLOYS AND THEIR GOLD CONTENT AS CALCULATED FROM THEIR SPECIFIC GRAVITIES

Specific Gravity	Gold Content from Specific Gravity	Actual Gold Content	Difference	Literature Reference
	%	%	%	
18.84	97.9	98.0	−0.1	13
18.58	96.7	96.9	−0.2	13
18.36	95.6	95.8	−0.2	13
18.12	94.4	94.8	−0.4	13
17.93	93.5	93.9	−0.4	13
17.79	92.7	93.2	−0.5	13
17.57	91.6	92.3	−0.7	13
17.35	90.4	91.7	−1.3	8
17.17	89.4	90.1	−0.7	13
16.81	87.4	88.1	−0.7	13
16.48	85.4	86.1	−0.7	13
15.86	81.5	83.3	−1.8	8
14.74	73.5	75.0	−1.5	8
12.69	55.4	58.3	−2.9	8
10.04	21.0	25.0	−4.0	8

NOTES ON ORIGINAL DATA

REFERENCE 8. The gold content is given in parts per thousand, and the specific gravity as shown.

REFERENCE 13. The gold content is given to two decimal places in percent. Three experimental results are given for the specific gravity of each alloy, and the average of these to four decimal places.

temperatures at which the specific gravities were measured since the lack of uniformity in this respect apparently would not be enough to affect the first decimal place in the calculated percentages of gold. The figures in Table I were all derived from measurements on cast alloys, with the exception of those of the first line, so that there is probably a reasonable degree of uniformity in the physical condition of the gold-silver alloys here compared. From this table it is evident that for gold-silver alloys the agreement between the calculated and the actual percentages of gold is fairly good throughout the whole range of composition. Nevertheless, individual deviations amounting to around one percent are by no means uncommon. From Table II it is evident that for gold-copper alloys the agreement throughout the whole range of composition is not good. In part this may be because the measurements of one of the investigators were made on worked alloys, and the other on cast alloys. However, if the results on the worked alloys are alone considered (Reference 13), individual deviations approaching one percent are still common. A more important cause of the general lack of agreement is that when gold is alloyed with copper a change in total volume occurs, this increasing as the proportion of copper in the alloy increases, so that the ideal formula does not strictly apply. However, even if a correction is made for this change in volume, individual deviations of around one percent still occur, so that here again the method is not consistently reliable to more than about one percent even under the most favorable conditions.

When this method is used for estimating the gold content of actual objects of unknown composition the error may often far exceed one percent for any of various reasons. In the first place the mechanical and thermal history of a given object is often unknown so that it may not be easy to determine whether the object is worked or cast. More serious is the possible presence of foreign inclusions in the metal, and worse yet the possible presence of hidden cavities. Another serious source of error may be a lack of knowledge of the particular metals alloyed with the gold.

TABLE III

MAGNITUDE OF POSSIBLE ERROR WHEN ALLOYING COMPONENT IS UNKNOWN

Observed Specific Gravity	Calculated Gold Content if Silver is Assumed to be the Sole Alloying Component %	Calculated Gold Content if Copper is Assumed to be the Sole Alloying Component %	Difference in Calculated Gold Content %
19.20	99.4	99.6	0.2
19.00	98.1	98.6	0.5
18.80	96.8	97.7	0.9
18.60	95.5	96.8	1.3
18.40	94.2	95.8	1.6
18.20	92.8	94.8	2.0
18.00	91.4	93.8	2.4
17.80	89.9	92.8	2.9
17.60	88.5	91.7	3.2
17.40	87.0	90.7	3.7
17.20	85.4	89.6	4.2
17.00	83.9	88.4	4.5
16.80	82.2	87.3	5.1
16.60	80.6	86.1	5.5
16.40	78.9	84.9	6.0
16.20	77.2	83.6	6.4
16.00	75.4	82.4	7.0

The presence of platinum or other heavy metals of the platinum group, for example, would lead to deceptively high results, though this cannot be considered a common source of error. More commonly, if the gold is alloyed with copper alone and it is assumed that it is alloyed with silver, or vice versa, or more commonly still, if it is alloyed with both in some unknown proportion and the assumption is made that it is alloyed with one or the other only, serious errors may arise in the estimation of the gold content of the metal from the observed specific gravity. The possible extent of this error from this one important source alone is indicated by the differences in the computed ideal results shown in Table III. It will be noted that this source of error is not serious for alloys of very high gold content, but that it becomes increasingly serious with decrease in gold content.

Since a considerable number and variety of natural and artificial gold objects have been assayed or analyzed by standard dry or wet assay methods by previous investigators, who at the same time carefully measured the specific gravity of these objects, the degree of error from all sources likely to be encountered in actual practice may be approximated by an examination of their results. Curiously enough, only thirteen examples could be found where the investigator, himself, had estimated the gold content from the specific gravity and compared the result with the actual content found by analysis or assay. For most of the collected examples shown in Table IV, therefore, the gold content has been computed from

TABLE IV

COMPARISON OF GOLD CONTENT OF VARIOUS NATURAL AND ARTIFICIAL OBJECTS AS ESTIMATED FROM SPECIFIC GRAVITY WITH THEIR GOLD CONTENT AS DETERMINED BY ANALYSIS

No.	Description	Specific Gravity	Gold Content from Specific Gravity on Given Basis, %			Gold Content by Analysis %	Difference Error on Given Basis, %			Literature Reference
			A	B	C		A	B	C	
1	Nugget	19.10	98.8	99.1	99.0	99.0	−0.2	+0.1	±0.0	14
2	Ancient Ornament	19.10	98.8	99.1	99.0	98.0	+0.8	+1.1	+1.0	15
3	Natural Crystal	18.77	96.6	97.6	97.2	95.4	+1.2	+2.2	+1.8	1
4	Nugget	18.67	96.0	97.1	96.6	94.2	+1.8	+2.9	+2.4	3
5	Ancient Wires	18.59	95.4	96.7	96.2	96.9	−1.5	−0.2	−0.7	9
6	Nugget	18.44	94.4	96.0	95.4	94.4	±0.0	+1.6	+1.0	14
7	Native Grains	18.31	93.6	95.4	94.6	94.7	−1.1	+0.7	−0.1	3
8	Natural Crystal	18.11	92.1	94.4	93.5	92.5	−0.4	+1.9	+1.0	1
9	Ancient Bar	18.05	91.7	94.1	93.1	90.7	+1.0	+3.4	+2.4	16
10	Nugget	17.96	91.1	93.6	92.6	91.4	−0.3	+2.2	+1.2	14
11	Nugget	17.84	90.2	93.0	91.9	93.5	−3.3	−0.5	−1.6	3
12	Nugget	17.59	88.4	91.7	90.3	90.8	−2.4	+0.9	−0.5	14
13	Fragment of Ancient Ornament	17.53	87.9	91.4	89.9	88.6	−0.7	+2.8	+1.3	9
14	Nugget	17.48	87.5	91.1	89.6	89.4	−1.9	+1.7	+0.2	14
15	Nugget	17.40	87.0	90.7	89.1	87.4	−0.4	+3.3	+1.7	14
16	Ancient Plate	17.33	86.4	90.3	88.7	88.7	−2.3	+1.6	±0.0	9
17	Celtic Ring Money	17.26	85.9	89.9	88.2	86.7	−0.8	+3.2	+1.5	9
18	Celtic Ring Money	16.90	83.1	87.8	85.9	85.6	−2.5	+2.2	+0.3	9
19	Nugget	16.87	82.9	87.7	85.7	86.8	−3.9	+0.9	−1.1	14
20	Fragment of Ancient Torque	15.69	72.5	80.3	77.1	71.0	+1.5	+9.3	+6.1	15
21	End of Ancient Bracelet	15.50	70.7	79.0	75.6	75.6	−4.9	+3.4	±0.0	15
22	Fragment of Ancient Torque	15.44	70.2	78.6	75.1	79.5	−9.3	−0.9	−4.4	9
23	Ancient Bosses	15.43	70.1	78.5	75.0	74.7	−4.6	+3.8	+0.3	15
24	Fragment of Ancient Torque	15.38	69.6	78.2	74.6	71.5	−1.9	+6.7	+3.1	9
25	Ancient Coin	15.06	66.4	75.9	72.0	69.0	−2.6	+6.9	+3.0	2
26	Ancient Bar	14.83	64.0	74.2	70.0	66.8	−2.8	+7.4	+3.2	16
27	Ancient Coin	14.35	58.8	70.5	65.6	59.8	−1.0	+10.7	+5.8	7
28	Ancient Coin	14.04	55.3	67.9	62.7	69.7	−14.4	−1.8	−7.0	2
29	Ancient Coin	13.85	53.0	66.3	60.8	59.5	−6.5	+6.8	+1.3	2
30	Ancient Coin	13.66	50.7	64.7	58.9	57.9	−7.2	+6.8	+1.0	5
31	Ancient Coin	13.23	45.3	60.7	54.3	57.3	−12.0	+3.4	−3.0	16
32	Ancient Coin	13.07	43.1	59.2	52.5	51.8	−8.7	+7.4	+0.7	16
33	Ancient Coin	12.19	30.4	50.1	41.9	37.9	−7.5	+12.2	+4.0	2

the specific gravity and compared with the actual gold content for the first time. All previous investigators who calculated the gold content from the observed specific gravity did so on the assumption that the gold was alloyed with silver alone. But it can be shown that this assumption does not provide the best general basis for estimating the gold content of objects in which the nature and proportion of the alloying metal or metals are unknown. It is true that in natural objects of very high gold content, or in objects fashioned from such native gold, silver is often the sole alloying metal, but for such objects of lower gold content copper may also be present in a proportion approaching that of the silver, and sometimes the copper is in higher proportion than the silver. For example, Object No. 5 of Table IV was found by the analyst to contain 2.49% silver and only a trace of copper, whereas Object No. 21 was found to contain 13.03% silver and 11.61% copper, and Object No. 23 to contain 6.22% silver and 19.09% copper. In objects formed from artificial alloys copper is still more likely to be present in high proportion when the gold content is low. It is therefore important to make some allowance for the possible presence of copper in considerable proportion when computing the gold content of objects of low fineness from specific gravity measurements.

As shown in Table IV, the gold content of the various objects has been calculated from the observed specific gravities on three different bases in order to find out empirically the best single general basis for such estimations. For Basis A the

TABLE V

ANALYSIS OF DATA OF TABLE IV SHOWING DIFFERENCES IN ACCURACY THAT RESULT FROM THE PARTICULAR BASIS SELECTED FOR COMPUTING FINENESS FROM SPECIFIC GRAVITY

Kind of Difference	Range of Actual Gold Content—%	Basis A	Basis B	Basis C
Proportion of Results Nearer to True Value.	Over 95	60%	20%	20%
	Under 95, over 90	57%	14%	29%
	Under 90, over 85	43%	14%	43%
	Under 85	36%	14%	50%
Average Error	Over 95	+0.4%	+1.2%	+0.9%
	Under 95, over 90	−0.9%	+1.5%	+0.5%
	Under 90, over 85	−1.8%	+2.2%	+0.6%
	Under 85	−6.1%	+5.9%	+1.0%
Greatest Single Error.	Over 95	+1.8%	+2.9%	+2.4%
	Under 95, over 90	−3.3%	+3.4%	+2.4%
	Under 90, over 85	−3.9%	+3.3%	+1.7%
	Under 85	−14.4%	+12.2%	−7.0%

assumption is that the gold was alloyed with silver alone, for Basis B that it was alloyed with copper alone, and for Basis C that it was alloyed with equal proportions of silver and copper, all computations being made according to the ideal mixture formula previously given. A slight uncertainty exists in these calculated results since some of the investigators did not state the temperatures at which the specific gravities were measured, and others measured them at different stated room temperatures. However, as found by test calculations, this lack of uniformity in the specific gravity figures can have little effect on the validity of the conclusions.

The actual figures for the gold content and the difference error on the three different bases are shown in Table IV, and in Table V a comparative summary of the resulting differences in accuracy is given. It will be seen that when the gold content is very high Basis A yields the best results, but that this same basis yields poor results on objects of low gold content. Basis B gives the poorest results when the gold content is high, and results that are nearly as poor as with basis A when the gold content is low. Basis C yields results on objects of very high gold content that are fairly good, and results on objects of lower gold content that are much better than either Basis A or Basis B. It is evident from all these figures that, of the three, Basis C is the best to use for objects of unknown composition.

Of course where the alloying metal is known from qualitative tests to be solely or predominantly silver or copper then Basis A or Basis B should be used. Still closer results on objects of unknown composition and of medium to high gold content might be obtained by selecting as a general basis for computation an ideal alloy having a higher proportion of silver than copper, or by using Basis A for objects of very high specific gravity and Basis C for objects of lower specific gravity, but in view of the approximate nature of the results anyway it is doubtful whether much would be gained by introducing such further refinements. Table VI, computed on Basis C, provides a convenient means for converting the observed specific gravity to percentage of gold when estimating the gold content of objects by this method.

TABLE VI

PRACTICAL CONVERSION TABLE FOR ESTIMATING GOLD CONTENT OF OBJECTS FROM SPECIFIC GRAVITY MEASUREMENTS

Specific Gravity 25°/4°	Gold Content %	Specific Gravity 25°/4°	Gold Content %	Specific Gravity 25°/4°	Gold Content %
19.3	100	16.5	83	13.7	59
19.2	99	16.4	82	13.6	58
19.1	99	16.3	82	13.5	57
19.0	98	16.2	81	13.4	56
18.9	98	16.1	80	13.3	55
18.8	97	16.0	79	13.2	54
18.7	97	15.9	79	13.1	53
18.6	96	15.8	78	13.0	52
18.5	96	15.7	77	12.9	51
18.4	95	15.6	76	12.8	49
18.3	95	15.5	76	12.7	48
18.2	94	15.4	75	12.6	47
18.1	93	15.3	74	12.5	46
18.0	93	15.2	73	12.4	45
17.9	92	15.1	72	12.3	43
17.8	92	15.0	71	12.2	42
17.7	91	14.9	71	12.1	41
17.6	90	14.8	70	12.0	39
17.5	90	14.7	69	11.9	38
17.4	89	14.6	68	11.8	37
17.3	89	14.5	67	11.7	35
17.2	88	14.4	66	11.6	34
17.1	87	14.3	65	11.5	32
17.0	87	14.2	64	11.4	31
16.9	86	14.1	63	11.3	29
16.8	85	14.0	62	11.2	28
16.7	84	13.9	61	11.1	26
16.6	84	13.8	60	11.0	25

It is further evident from Tables IV and V that the method is only reliable for objects of high gold content, and that it becomes increasingly less reliable as the gold content decreases until it becomes very unreliable indeed for objects of low gold content. The average error with objects of high gold content approaches one percent, and the error on single determinations may be around two percent, so that even for these the method should be regarded as no more than roughly quantitative. From the large errors likely to occur with objects of low gold content it is evident that for these this method yields only a rough estimate of the true gold content.

On the basis of all the foregoing considerations there is no point, therefore, in attempting to determine the specific gravity of objects to more than the first decimal place for the purpose of estimating their gold content by this method, nor is there any point in expressing the results to more than the nearest whole number in percent. Furthermore, the method should be restricted to objects of a high degree of fineness.

TABLE VII

ESTIMATIONS OF THE FINENESS OF SOME ANCIENT GOLD COINS

No.	Place of issue	Ruler	Approximate Date of Coin	Denomination of Coin	Specific Gravity	Gold Content %
1	Persia	?	4th Cent. B.C.	Daric	19.0	98
2	"	?	4th Cent. B.C.	"	18.9	98
3	Macedon	Philip II	359–336 B.C.	Stater	19.2	99
4	"	Alexander III	323 B.C.	"	19.1	99
5	Carthage	?	277–219 B.C.	"	13.4	56
6	"	?	277–219 B.C.	"	13.3	55
7	Roman Republic	Julius Caesar	46 B.C.	Aureus	19.2	99
8	Roman Empire	Augustus	8 B.C.	"	19.1	99
9	" "	Tiberius	14–15 A.D.	"	19.2	99
10	" "	Tiberius	16–21 A.D.	"	19.2	99
11	" "	Tiberius	21–25 A.D.	"	19.2	99
12	" "	Claudius	49–50 A.D.	"	19.2	99
13	" "	Nero	64–68 A.D.	"	19.2	99
14	" "	Nero	64–68 A.D.	"	19.2	99
15	" "	Vespasian	69–79 A.D.	"	19.1	99
16	" "	Titus	74 A.D.	"	19.1	99
17	" "	Domitian	79 A.D.	"	19.1	99
18	" "	Domitian	84 A.D.	"	19.1	99
19	" "	Trajan	100 A.D.	"	19.2	99
20	" "	Hadrian	117 A.D.	"	19.0	98
21	" "	Hadrian	119–122 A.D.	"	19.1	99
22	" "	Hadrian	134–138 A.D.	"	19.1	99
23	" "	Antoninus Pius	143–144 A.D.	"	19.1	99
24	" "	Antoninus Pius	151–152 A.D.	"	19.2	99
25	" "	Antoninus Pius	156–157 A.D.	"	19.1	99
26	" "	Verus	163–164 A.D.	"	19.1	99
27	" "	Verus	163–164 A.D.	"	19.1	99
28	" "	Verus	163–164 A.D.	"	19.2	99
29	" "	Septimus Severus	193 A.D.	"	19.0	98
30	" "	Macrinus	217–218 A.D.	"	19.1	99
31	" "	Maximianus	286 A.D.	"	19.1	99
32	" "	Maximianus	288–289 A.D.	"	18.7	97
33	" "	Diocletian	287 A.D.	"	19.1	99
34	" "	Diocletian	290–292 A.D.	"	19.0	98
35	" "	Diocletian	296 A.D.	"	19.1	99
36	" "	Diocletian	296 A.D.	"	19.2	99
37	" "	Constantius II	337–361 A.D.	Solidus	18.8	97
38	" "	Constantius II	337–361 A.D.	"	18.4	95
39	" "	Jovian	363–364 A.D.	"	18.3	95
40	" "	Valentinian I	364–375 A.D.	"	19.0	98
41	" "	Valentinian I	364–375 A.D.	"	18.2	94
42	" "	Valens	364–378 A.D.	"	18.5	96
43	" "	Valens	364–378 A.D.	"	18.4	95
44	" "	Gratian	375–383 A.D.	"	19.1	99
45	" "	Theodosius	379–395 A.D.	"	19.0	98
46	" "	Honorius	395–423 A.D.	"	19.0	98
47	" "	Honorius	395–423 A.D.	"	18.7	97
48	" "	Valentinian III	425–455 A.D.	"	18.8	97
49	" "	Valentinian III	425–455 A.D.	"	18.7	97
50	" "	Julius Nepos	474–475 A.D.	Triens	17.8	92

As an example of the proper application of this method and its utility where other methods are not applicable, there are shown in Table VII results obtained by the writer on a group of 50 ancient gold coins. With one exception, these coins were all from the numismatic collection of the Princeton University Library, and the writer hereby acknowledges his indebtedness to Professor S. H. Weber, former Curator of Special Collections of that library, for his kindness in loaning these rare and valuable coins for the purpose of obtaining the results here recorded. The one exceptional coin, No. 2 in Table VII, was found during the excavation of the ancient Agora at Athens, Greece, and was examined by the writer at that site. The specific gravity of these coins was determined by the method of Archimedes, the coins being suspended from the arm of an analytical balance by means of a very fine platinum wire and weighed first in air and then in distilled water at 25°C. The gold content was found from the specific gravity by the use of the data now shown in Table VI.

From Table VII it will be seen that, with two exceptions, these coins were found to contain over 90% gold, and the great majority over 95% gold. Two coins, Nos. 5 and 6 in the table, were found by this method to contain only 56% and 55% gold, respectively, and in accordance with the previous discussion these two figures must be regarded as mere approximations that may be 5% or so from the truth. Nevertheless, these results are useful as showing the much lower fineness of these two coins as contrasted with all the others in this group. It is likely that all the other results are not more than 1% or 2% off from the true values. The fact that results on duplicate coins of the same ruler generally agree well with each other is an indication, at least, that the figures are essentially correct. An independent, though indirect and random, check on the essential correctness of the very high results for the gold content of the Roman coins is given by some figures published by Rauch (12) on the percentages of gold in a few Roman coins as obtained by fire assay. He reports that a coin of Nero contained 99.3% gold, which is close to the two results of 99% here obtained on coins of this same ruler. For a coin of Titus he gives 99.6% which is in fair agreement with the 99% found here. On a coin of Verus he gives 99.0% which agrees with the three results of 99% here obtained on coins of this emperor. It appears likely, therefore, that a considerable degree of confidence may be placed on the very high results shown in Table VII for the gold content of the Roman coins.

The uniformly very high gold content of the coins in the long series of Roman Imperial coins from Augustus to Diocletian, extending over a period of some three centuries, is remarkable. Since only occasional small specimens of native gold of such a high degree of fineness have been found in any part of the world, the occurrence of any ancient deposit of gold of this quality large enough to furnish directly the gold required for this extensive Roman coinage seems very improbable. It is much more probable that the gold which entered into these coins came from a number of different sources at different times, and that such gold was not only of a lower degree of fineness in general, but that it also differed considerably in gold content. The inescapable conclusion seems to be that the Romans knew and applied a highly efficient process for the purification of the native gold that entered into their coinage, and that they were also able consistently to produce purified metal of a very high degree of fineness. The slightly lower average gold content and the less uniform gold content of the Roman coins of the fourth and fifth centuries may be an indication of some loss in technical knowledge and skill, though this decrease in quality may be economic in origin. In general, these experimental results are of significance for the history of metallurgy as indicating the high degree of knowledge and skill in the metallurgy of gold extant in Roman times. The few similar high results for the gold content of the coins of ancient Persia and of Macedon may be an indication of the much earlier existence of a similar degree of metallurgical knowledge and skill.

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