TABLE VII.

Substance.	F°_{298}.	Equation.	Substance.	F°_{298}.	Equation.
Diamond	520	5	HCO_3^-	—140140	16
$CO(g)$	—32560	11	CO_3^{--}	—126130	18
$CO_2(g)$	—94360	12	CH_4	—12800	20
H_2CO_3 (aq.)	—148970	14	$COCl_2$	—45380	22

BERKELEY, CAL.

[CONTRIBUTION FROM THE WOLCOTT GIBBS MEMORIAL LABORATORY OF HARVARD UNIVERSITY.]

COMPRESSIBILITIES OF MERCURY, COPPER, LEAD, MOLYBDENUM, TANTALUM, TUNGSTEN AND SILVER BROMIDE.

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The compressibilities of the elements are data of great interest, in common with all the other properties of these fundamental substances. Until recently, however, they received but little attention. Six years ago, for the first time, results for a large number of elements, consistently determined by a new and adequate method, were available.[1] From these results it became clear that compressibilities, like many other properties of the elements, are highly periodic in their nature as referred to the progressively increasing atomic weights. Since that time much interest has been taken in the subject, and Bridgman,[2] at the Jefferson Physical Laboratory at Harvard University, and Grüneisen,[3] at the Physikalisch-technische Reichanstalt in Berlin, have both thrown further light upon it. In the main, these results have confirmed and amplified the earlier Harvard results, but there remain two or three points of difference to be explained, and, moreover, it seemed highly desirable to extend the list of elements. Hence the present investigation was undertaken with both of these aims in view. The method employed was precisely that used in preceding investigations,[4] except that in our most accurate work the piezometer was made of soft steel instead of glass. For the details the reader is referred to earlier publications.

In brief, the method consisted in the determination of the difference between the compressibility of each substance in question and that of mercury, which was itself determined by reference to iron. The linear compressibility of iron has been absolutely determined by Bridgman. The piezometer used in the present investigation consisted of a cylindrical vessel of glass or soft steel filled with mercury, being so arranged that the

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[1] Richards, Stull, Brink and Bonnet, *Pub. Carnegie Inst. Wash.*, No. 76 (1907); *Z. physik. Chem.*, 61, 77, 183 (1908); THIS JOURNAL, 31, 154 (1909).

[2] Bridgman, *Proc. Amer. Acad.*, 47, 347 (1911).

[3] *Ann. phys.*, 25, 825 (1908); 33, 1239 (1910).

[4] See for example THIS JOURNAL, 34, 971 (1912); see also Stähler's "Handbuch der Arbeitsmethoden in der anorganischen Chemie," Vol. III, p. 246 (1912).

only free surface of this liquid metal was exposed in a capillary tube, which made it possible to measure very small changes of volume. The level of the mercury in this capillary tube was determined by a very finely pointed platinum wire, which completed an electrical circuit. Successive weighed drops of mercury were added in this tube, and the relation between the weight of this added mercury and the pressure necessary to compress the system exactly to the attainment of electrical contact was determined in each case. In this way, at first mercury alone was compressed in the piezometer, and the relation of the added mercury to the increasing pressure was found. Subsequently, each other substance in turn was completely immersed in the mercury, and the operation repeated. Obviously, if the immersed substance had the same compressibility of mercury, a curve precisely similar to the first would have been attained, but, as all the substances discussed in this paper had a less compressibility than mercury, the curves were different from that obtained when mercury alone was present, in such a sense that for a given weight of added mercury a greater pressure was necessary than with mercury alone in the piezometer. Diagrams of the two forms of piezometer will help to make the matter clear.

The glass piezometer (Fig. 1) has been described in detail before.[1] Although the steel piezometer was somewhat different in arrangement, the principle is exactly the same. It consisted of a hollow steel cylinder, K, closed at the bottom, which had been turned and bored from a heavy rod of steel. (Figs. 2 and 3.) Upon the top of this was clamped, by a powerful screw, a cover, G, containing the capillary. Below this cover was secured a little pail or capsule, J, to hold mercury, in case a lighter liquid was to be confined in the piezometer itself. This pail or capillary would, of course, be unnecessary if no liquid besides mercury were present. The contact was made by a stout, steel needle, E, with a very finely pointed platinum tip, F; it was secured above in such a way as to be rigid and unchangeable in position, centered below by a light movable bracing of wires, and was insulated from the rest of the apparatus by a thin film of mica, C. This upper portion of the piezometer is shown on a large scale in Fig. 2, since the details are important, and were the outcome of much thought and experiment.

The washer, I, sealing the joint between the cylinder and its cover gave much trouble. After various attempts with lacquered lead, copper and organic substances, we finally chose soft iron, and found that, if both surfaces of the ring of soft iron were made somewhat pointed (that is to say, the cross section of the ring made of a very elongated "diamond"-shape), good contact and complete closure were effected. The volume of liquid retained by this device outside of the washer, and not under

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[1] THIS JOURNAL, 34, 975 (1912).

Fig. 1.

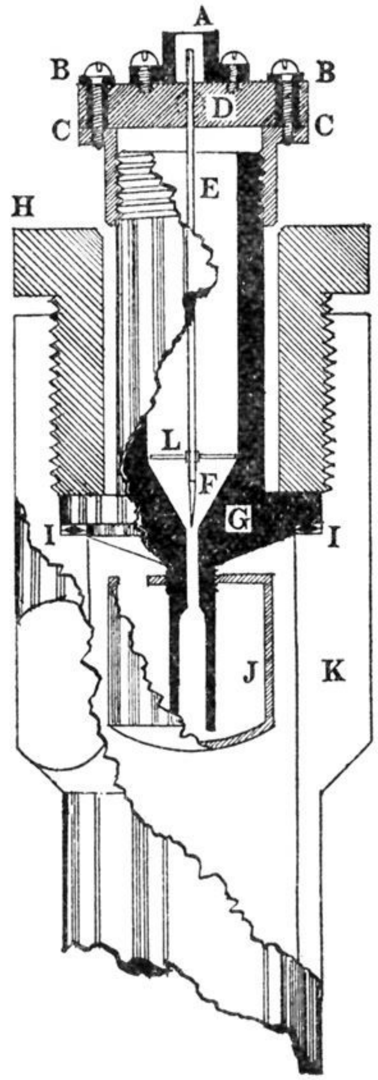

Fig. 2.

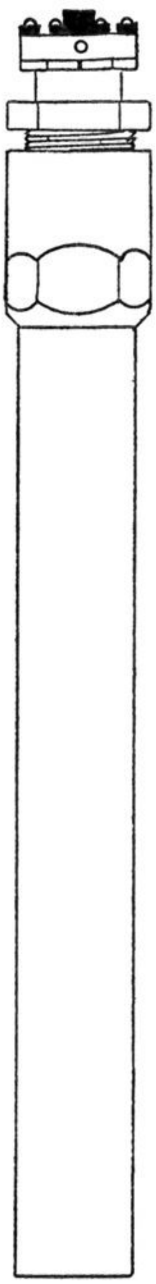

Fig. 3.

Fig. 1.—Glass piezometer.

Fig. 2.—Details of top of steel piezometer.

A, hard rubber cup to hold mercury for making contact.
B, hard rubber bushing to insulate screws.
C, joint with thin plate of insulating mica.
D, set screw to hold needle in position.
E, steel needle.
F, platinum point attached to needle.
G, steel top of piezometer held in place by
H, screw cap, and made mercury-tight by
I, soft iron washer.
J, cup to hold mercury.
K, section of cylinder-wall.
L, guide to hold needle in center.

The whole is of soft Bessemer steel, except the three rubber pieces, A, B, B, the mica plate C, and the platinum point F.

Fig. 3.—Sketch of exterior of steel piezometer when assembled.

quantitative compression was computed, and due allowance was made for it.

The pressure gauge was an absolute one, consisting of a perfectly cylindrical piston or plunger exactly fitting into an equally cylindrical hole just 0.0002 cm. larger in diameter, which communicated with the pressure pump. The apparatus had been made especially with unusual care by the Taft-Pierce Co., of Woonsocket, and had been very carefully studied and verified in all its details in an earlier research carried out by one of us in common with Dr. J. W. Shipley, as yet unpublished. Careful measurement of the piston gave us its area, to which was added half the area of the very thin ring of lubricant around it, and it was weighted with standardized weights by means of an oscillating carriage. For approximate preliminary observation of the pressure, a Bourdon gauge also was attached to the system. The pressure was applied by a Cailletet pump of the usual type, capable of giving 1000 atmospheres, and was transmitted to both of the gauges and the piezometers by castor oil, according to the recommendation of the Earl of Berkeley. The unit of pressure adopted is the megabar (or megabarie), which has been suggested on various sides and has now received international sanction.[1] It is the pressure of a megadyne per square centimeter, and is 1.3% less than an "atmosphere" or 2.0% more than 1 kg./cm^2. The mercury contact was indicated by a delicate galvanometer.

The substances studied were copper, iron, lead, mercury, molybdenum, tantalum, tungsten and silver bromide. The bar of copper was of pure commercial electrolytic material, and had been thoroughly hammered and turned. The iron had been several times hammered, in order that the pores which sometimes exist in iron should have been closed, and likewise annealed and turned to regular shape. It had been smelted by the American Rolling Mill Co., and contained 0.05% of impurity. The molybdenum, tantalum and tungsten were also each in a very compact condition. They were loaned through the kindness of Dr. W. R. Whitney of the General Electric Company, and were doubtless of high degree of purity. The silver bromide had been prepared in this laboratory, and was the same as that used five years ago by one of us with the collaboration of Grinnell Jones.[2] The mercury was carefully purified by orthodox methods.

The chief measurements were made as nearly as possible over the range from 100 to 500 megabars, the weight of added mercury, w, and the pressure, p, being carefully observed. These data were corrected, as indicated below, precisely to the pressure range just mentioned. In each case the

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[1] *Rapport Internat. Cong. Phys.*, Paris, 1, 100 (1900); see also Richards and Stull, *Loc. cit.*, 1903; Guillaume, "Les récent progres des Syst. Métrique," Paris, 1907.

[2] Richards and Jones, THIS JOURNAL, 31, 158 (1909).

half-way point, at 300 megabars, was taken also, but since these values are only of subordinate interest, they are merely averaged and summarized in the tables below, at the end of each series. They not only verified our work over the larger range, but also served the useful purpose of determining approximately the changing pitch of the curve, dw/dp, over the whole length—an outcome which made it possible to correct each initial reading exactly to 100 megabars, and each final reading exactly to 500 megabars. Evidently the average pitch, dw/dp, over the whole range is (except with very compressible substances) about that of the tangent to the curve in the middle (at 300 megabars). The average pitch over the first half corresponds closely to that of the tangent at 200 megabars, and that over the second half corresponds closely to that of the tangent at 400 megabars. The pitch at either the beginning or the end of the curve, therefore, is found by respectively adding to or subtracting from the mean value of dw/dp over the whole range, the difference between the pitches of the first and second halves of the curve, because this difference corresponds to the change in dw/dp caused by a change of pressure of 200 megabars. This method is not very exact, because its basic assumption that dw/dp varies linearly with the pressure is not quite true; but it is near enough to correct small divergences at either end of the scale as accurately as the experimental results warrant. In the case of compressible substances like water, the pitch of the curve at each end must be experimentally determined; such determinations are recorded in some cases below. The temperature was always exactly 20.00° (±0.002°) maintained by a very accurate thermostat.

The results were all calculated for exactly the range 100–500 megabars, according to the following equation:

$$\beta = \frac{(w - w' - mK)D}{5429.0\,W} + \beta',$$

in which w is the weight of mercury added in the special case, and w' that added when mercury alone is present; m the additional weight of mercury needed for the range 100–500 megabars when one gram of another liquid is substituted for an equal volume of mercury, and K the weight of the other liquid; W the weight of substance and D its density; β and β' represent the compressibility sought and that of mercury, respectively.

The first step toward this, as well as towards any other work with such a piezometer, is the compression of the instrument filled with pure mercury, of which it contained 767.0 g., under atmospheric pressure. The following table recounts a series of such compressions—it shows that under 500 megabars pressure it contains about 768.3 g., the gain for 400 megabars being recorded accurately in the table below:

TABLE I.—THE COMPRESSION OF MERCURY IN STEEL.

Range. Megabars.	Hg added.	Hg cor. 100–500 megabars.	Other data necessary.
97.5 — 500.3	1.0477	1.0384	W = 767.0
109.0 — 503.9	1.0247	1.0382	
109.0 — 499.1	1.0123	1.0383	D = 13.546
108.9 — 500.2	1.0158	1.0388	
100.0 — 300.0	(0.5227)		
	W = 1.0384		

This table shows, in the third column, the remarkable consistency of the method under favorable conditions. It shows also that a range of 400 megabars corresponds to the added weight of 1.0384 g. of mercury when the piezometer contained 767.0 g.—a compression of about 0.135%. Substituting in the above formula (where for this special case w', m, and K are zero) we find that $\beta' = \beta + 3.378 \times 10^{-6}$. This represents the difference between the compressibility of mercury and the soft steel of the piezometer. It is subject to two slight possibilities of error, as follows: first, the possible existence of minute holes or cracks in the steel, into which high pressure might force mercury; and, secondly, the possible slight change of form of the meniscus under pressure. If with Bridgman[1] we assume the compressibility of this steel to be 0.588×10^{-6} at 20°, the compressibility of mercury is shown by our experiments to be 3.966×10^{-6} over the range 100–500 megabars in question—a value which is probably the maximum.

Another method of using the piezometer fortunately gives us the means of entirely avoiding the second of the above-mentioned difficulties, and causes the first to affect the result in an opposite sense. This method is to immerse a somewhat rounded bar of pure iron into the piezometer, making a new series of determinations of the relation of increasing mercury to increasing pressure and calculating the results from the difference between the outcome of the two series of experiments. According to this procedure all defects in the piezometer are eliminated, occurring in both series. Results of a second series of experiments thus planned are given in Table II; a bar of soft, pure iron already described, was placed in the piezometer, displacing 20.015 cc. of the mercury; and the same determinations were made again. The preliminary trials, which served to acquaint the experimenters with the method and to determine the amount of mercury to be added in each case, are omitted, as in the table above. With exceptions of this sort, all the results in all the following tables were consecutive.

It appears from the first table that the amount of mercury added between 100 and 500 megabars, when mercury alone was present, was 1.0384, but from the second table that this amount was only 0.6758 when the

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[1] Bridgman, *Proc. Am. Acad.*, 47, 366, 367 (1911).

TABLE II.—PURE IRON UNDER MERCURY IN STEEL.

Pressure range. Megabars.	Wt. mercury added.	Wt. mercury cor. to 100–500 megabars.	Other data necessary.	$(\beta - \beta) \times 10^8$.
146.4 — 503.6	0.6000	0.6736	$m = 0$	—334
182.2 — 500.0	0.5357	0.6768	$w = 1.0384$	
98.5 — 499.2	0.6782	0.6770	$W = 157.095$	
62.4 — 503.2	0.7430	0.6734	$D = 7.849$	
503.6 — 206.6	0.5014	0.6773		
499.2 — 143.9	0.5997	0.6764		
100.0 — 300.0	(0.3399)			
	Average,	$= w = 0.6758$		

bar of iron was immersed in the mercury—the difference between being 0.3626. This weight of added mercury occupied a volume of 0.02667 cc. at the highest pressure concerned, a volume which corresponds to the difference between the compression of 20.015 cc. of iron and exactly the same bulk of mercury, due to the addition of 400 megabars pressure. From this it is easy to calculate that the compressibility of mercury over this range must be 0.00000334 plus that of the pure iron.

Now Bridgman has determined, with great care, the compressibility of soft steel ("Bessemer screw-stock") under high pressures, and found that this compressibility is not appreciably affected by increasing pressure up to 10,000 atmospheres, as, indeed, one would expect because of the great internal pressure of the substance. His values in terms of the kg./cm^2. standard were 0.000000583 at 10° and 0.000000601 at 50°,[1] or 0.000000588 at 20°. In a recent investigation of Grüneisen, two different specimens of iron (having the densities 7.83 and 7.82, respectively) gave values between 0.000000585 and 0.000000633, determined by an indirect method depending upon the theory of elasticity.[2] In view of these facts, it seems to be fairly safe to assume (especially because the compressibility even of soft steel is probably slightly less than that of iron) that the compressibility of this latter metal at 20° is very near 0.00000060, if the pressure is registered in kilograms per square centimeter.[3] Calculated in terms of the megabar standard, this becomes 0.00000061; and if this value is added to the difference between the compressibilities of mercury and iron (namely, 0.00000334), we find that the average compressibility of mercury over the range between 100 and 500 megabars

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[1] Bridgman, *Proc. Amer. Acad.*, 47, 366, 367 (1911).

[2] Grüneisen, *Ann. phys.*, 33, 1257 (1910).

[3] The early determinations of this value published by one of us in conjunction with F. N. Brink (*Pub. Carnegie Inst. Wash.*, 76, 45 (1907)) made no pretensions to great accuracy. On page 52, in conclusion, the following statement is made: "Hence these results are to be considered merely as preliminary ones, worthy of publication because they exemplify the working of an efficient arrangement of apparatus, as well as because they confirm essentially the work of others on this subject." They yielded a result for iron distinctly lower than the results of Bridgman and Grüneisen. For suggestions as to the cause of the error, see pages 48–49 of the original paper; also Bridgman, *Ibid.*, p. 368.

is 0.00000395. This may be looked upon as the minimum value; and the average 0.00000396 of this and the maximum value (0.000003966) previously mentioned may be taken, with very slight probability of error, as the true compressibility of mercury. On the kg./cm^2. basis, this becomes 0.00000388, and on the "atmosphere" basis, 0.00000401. This is especially interesting and important because no other determination of modern accuracy over this pressure range seems to have been made. Bridgman's results at high pressure are admirable; but his method is not satisfactory at low pressure, and his results below 1000 atmospheres were merely extrapolated. It is interesting to note, nevertheless, that our result is in fairly close agreement with the results of Bridgman for mercury as extrapolated to our pressures. At 22° Bridgman found the change in volume between one and two thousand metric atmospheres to be 0.00377; for the third thousand, 0.00364; for the fourth thousand, 0.00353; for the fifth thousand, 0.00337; for the sixth thousand, 0.00324, as the mean of two series of determinations. Bridgman carried the work to higher pressures, but these do not concern us. The decrease in the compressibility for a thousand metric atmospheres is seen to be on the average nearly 0.00000013. Extrapolating to 300 atmospheres, the value becomes 0.00000391 per metric atmosphere, and correcting this to 20° (from Bridgman's figures at 0°) and then to the megabar standard, we obtain the value 0.00000398 for the compressibility of mercury, which is perhaps as near as could be expected (considering the extrapolation) to our value 0.00000396. Therefore, this latter value will be assumed in the rest of the present paper as the true average value over the range from 100–500 megabars.

Before proceeding to the determinations of the compressibilities of the several metals, a table should be given recording the constant for the glass piezometer, which was used in some cases. The glass piezometer, while it gives accurate results if quickly compressed and always read after exactly the same length of time (as soon as the heat of compression has been dissipated) shows marked hysteresis when the pressure is long continued. The determinations given below are all made under the same conditions, and the hysteresis-effects will be discussed in another connection later. The glass apparatus contained 385.28 g. of mercury.

TABLE III.—MERCURY IN GLASS.

Range. Megabars.	Hg added.	Hg cor. 100–500 megabars.	Other data necessary.
99.0 — 503.7	0.2498	0.2470	
110.2 — 509.8	0.2478	0.2481	
102.7 — 503.5	0.2474	0.2471	
503.7 — 150.4	0.2171	0.2459	W = 385.28
509.8 — 90.6	0.2580	0.2462	D = 13.546
100.0 — 300.0	(0.1256)		

Average = w = 0.2469

The difference between the compressibility of mercury and glass over the range from 100–500 megabars is 1.60, as calculated from the above results. Therefore, the compressibility of the glass must have been 2.35×10^{-6}. This is about the usual compressibility of soft glass.

It was necessary also in some cases, in order to prevent the substance from being attacked by the mercury, to surround the former with water—an expedient possible in both forms of piezometer, as may readily be seen. For this purpose it was needful to know exactly the difference between the compression of a gram of water and an equal bulk of mercury over the range 100–500 megabars; this was found to correspond to 0.2069 g. of added mercury, since 55.08 g. of water required 11.395 g. of added mercury, as a mean of many trials.

After these preliminaries, tables giving the data for the several other solid substances are now to be given.

Table IV.—Observations and Data Concerning the Compressibility of Various Solids.

Substance and conditions.	Pressure range. Megabars.	Weight mercury added. Grams.	Wt. mercury cor. to 100–500 megabars. Grams.	Other data necessary.	$(\beta - \beta') \times 10^8$.
Copper under water and mercury in glass	102.3–508.6	1.3463	1.3256	K = 6.971	
	508.6–103.2	1.3657	1.3268	m = 0.2069	—318
	100.0–300.0	(0.6837)	....	w' = 0.2469	
				W = 187.368	
				D = 8.894	
		Average = w =	1.3262		

Table V.

Copper under water and mercury in glass	520.9– 99.2	1.4345	1.3656	K = 7.190	
	99.2–517.2	1.4237	1.3652	m = 0.2069	—321
	102.4–499.6	1.3565	1.3677	w' = 0.2469	
	95.5–503.4	1.3936	1.3670	W = 187.368	
	517.2–102.4	1.4121	1.3648	D = 8.894	
	100.0–300.0	(0.7082)	....		
		Average = w =	1.3661		

Table VI.

Lead under water and mercury in steel	111.3–501.6	4.3278	4.4441	K = 18.059	
	107.8–500.0	4.3487	4.4402	m = 0.2069	—161
	102.3–501.5	4.4357	4.4468	w' = 1.0369[1]	
	100.9–500.0	4.4348	4.4450	W = 426.67	
	100.7–500.8	4.4409	4.4423	D = 11.298	
	100.0–300.0	(2.2807)	....		
	89.9–107.8	(0.2105)	....		
		Average = w =	4.4437		

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[1] Before this experiment (which was chronologically the last made with the steel piezometer) the volume of the instrument had been somewhat diminished by turning off the shoulder receiving the washer, in order to make better contact.

Table VII.

Substance and conditions.	Pressure range. Megabars.	Weight mercury added. Grams.	Wt. mercury cor. to 100–500 megabars. Grams.	Other data necessary.	$(\beta - \beta') \times 10^8$.
Molybdenum under mercury in steel	126.7–500.0	0.8927	0.9436	$m = 0$	
	99.2–500.2	0.9464	0.9441	$w' = 1.0384$	—349
	100.6–501.1	0.9451	0.9440	$W = 50.971$	
	100.0–300.0	(0.4753)	....	$D = 10.228$	
	Average	= w =	0.9439		

Table VIII.

Tantalum under mercury in steel	105.4–502.9	0.9965	1.0028	$m = 0$	
	119.0–500.7	0.9573	1.0039	$w' = 1.0384$	—345
	102.7–504.9	1.0094	1.0041	$W = 30.889$	
	(100.0–300.0)	(0.5051)	....	$D = 16.667$	
	Average	= w =	1.0036		

Table IX.

Tungsten under mercury in steel	104.5–499.8	0.9300	0.9412	$m = 0$	
	104.4–502.3	0.9362	0.9415	$w' = 1.0384$	—368
	95.6–500.4	0.9551	0.9439	$W = 91.676$	
	107.3–505.0	0.9387	0.9444	$D = 19.231$	
	108.5–506.0	0.9382	0.9444		
	100.2–501.2	0.9465	0.9445		
	100.0–300.0	(0.4746)	....		
	Average	= w =	0.9433		

Table X.

Tantalum with tungsten under mercury in steel	98.2–499.5	0.9128	0.9101	$K = 91.676$	
	119.2–501.1	0.8665	0.9092	$m = -0.0010385$	—336
	101.1–499.7	0.9038	0.9073	$w' = 1.0384$	
	101.1–501.9	0.9127	0.9110	$W = 30.889$	
	100.0–300.0	(0.4575)	....	$D = 16.667$	
	Average	= w =	0.9094		

Table XI.

Silver bromide under water and mercury in glass	103.0–494.9	2.1581	2.2032	$K = 10.037$	
	494.9–111.4	2.1082	2.1990	$m = 0.2069$	—126
	102.7–500.7	2.1908	2.2027	$w' = 0.2469$	
	500.7– 98.8	2.2123	2.2022	$W = 115.965$	
	....	(1.1313)	....	$D = 6.473$	
	Average	= w =	2.2018		

Table XII.

Silver bromide under water and mercury in glass	511.2– 91.9	2.2509	2.1476	$K = 9.770$	
	99.4–510.7	2.2053	2.1480	$m = 0.2069$	—125
	99.9–499.4	2.1460	2.1492	$w' = 0.2469$	
	103.9–499.6	2.1214	2.1459	$W = 117.896$	
	499.4–103.9	2.1199	2.1445	$D = 6.473$	
	510.7– 99.9	2.2015	2.1441		
	100.0–300.0	1.1031	....		
	Average	= w =	2.1465		

The data in the preceding tables yielded upon suitable calculation the following results, which represent the averages of all the determinations in each case. It should perhaps be noted that the two values for $\beta - \beta'$ for tantalum, -3.45×10^{-6} and -3.36×10^{-6} are the most widely discrepant of all the values. This was doubtless because so small a quantity of tantalum was used—less than 2 cc. The first (more directly found) value may be given twice the weight of the second. In the case of copper on the other hand, where two entirely separate sets of observations were made, the values for $\beta - \beta'$ were, respectively, 3.18×10^{-6} and 3.21×10^{-6}. In both cases study of the data will show that this agreement is as good as could reasonably be expected, considering the quantities of materials used and the extremely minute values to be measured.

Attention is called to the extremely small value of the compressibility of tungsten—the smallest, perhaps, of any substance which has thus far been measured.

FINAL RESULTS.

Temperature = 20.0°.

Calculated upon the megabar standard.

Substance.	$(\beta - \beta) \times 10^6$.	Compressibility $\times 10^6$. (Average over range 100–500 megabars.)
Copper	—3.20	0.76
Iron (standard)	—3.35	(0.61)
Lead	—1.61	2.35
Mercury	0	3.96
Molybdenum	—3.49	0.47
Tantalum	—3.42	0.54
Tungsten	—3.68	0.28
Silver bromide	—1.26	2.70

It will be seen that the values given in the first column of figures agree quite as closely as could be expected with the values given for $\beta - \beta'$ by the early Harvard work. Thus the old value for copper was —3.25;[1] that for iron —3.385; that for lead (only a single experiment) —1.55; and that for silver bromide —1.20, all reduced to the megabar standard. The reason why the compressibilities formerly computed from these values differed considerably from those in the last column above is simply because β' was taken as 3.79×10^{-6} in the old work (the best value then available), whereas in the present work it is taken as 3.96×10^{-6}—a difference of 0.00000017, which must be added to all the old values in order to make them correspond to the present knowledge concerning mercury. A more extensive discussion of this connection will be given in another place.

It is interesting to note also that the values given above are in excellent accord with the results of Grüneisen, as indicated in the papers already mentioned. His average value for copper is 0.74 to 0.78; for iron 0.59

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[1] *Pub. Carnegie Inst. Wash.*, **76,** 44 (1907).

to 0.64; for lead (which is too soft to give good results by his method), 2.0 to 3.2. Thus in each case our values lie between his extremes. The other substances were not studied by him, and there are two among them (namely, tantalum and tungsten) which have never before had their compressibilities determined, so far as we know. It is especially satisfactory to have the apparent inconsistencies of the earlier results adequately explained and removed.[1]

We are greatly indebted to the Carnegie Institution of Washington for generous support in this investigation.

Summary.

This paper describes careful determinations involving the compressibilities of eight substances, of which two had apparently never been studied before, namely, tantalum and tungsten. The method which has been used for over ten years by one of the authors was modified by the construction of the piezometer of steel instead of glass. This change has the advantage of avoiding the hysteresis of glass under high pressure. The results show, however, that the method of manipulation used in the earlier work had overcome this difficulty and that the earlier results were quite as satisfactory and accurate as they were supposed to be at the time. The difference in the final values of the compressibilities is due chiefly to the change in the assumed compressibility of mercury, which is now referred to a better new absolute value for iron (0.00000061) rather than to earlier less accurate work. The compressibility of the various substances, at 20° (expressed in the megabar standard, multiplied by a million) were found as follows: Copper 0.76, lead 2.35, mercury 3.96, molybdenum 0.47, tantalum 0.54, tungsten 0.28, silver bromide 2.70. In each case the range of pressure was between 100 and 500 megabars. The outcome is as consistent as could be expected with the work of Bridgman and Grüneisen, and previous discrepancies are explained. Especial attention is called to the very small compressibility of tungsten.

CAMBRIDGE, MASS.

[CONTRIBUTION FROM THE GEOPHYSICAL LABORATORY OF THE CARNEGIE INSTITUTION.]

THE MEASUREMENT OF THE FREEZING-POINT DEPRESSION OF DILUTE SOLUTIONS.

BY LEASON H. ADAMS.

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The present paper is a description of a method of determining the freezing-point depression of dilute solutions, by the use of which one is enabled to observe the equilibrium temperature with an uncertainty

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[1] Attention is called to the interesting compilation by W. Schut entitled "Piëzochemie der Gecondenseerde Systemen" (Utrecht, 1912) when some of these matters are discussed.