Theodore William Richards Memorial Lecture.

DELIVERED ON APRIL 25TH, 1929.

By SIR HAROLD HARTLEY, M.C., C.B.E., F.R.S.

IT is nearly forty years since the first of these Memorial Lectures was given to the Chemical Society by J. W. Mallet, who came from Virginia to pay a tribute to Jean Servais Stas in a memorable discourse on the determination of the relative masses of the atoms. He appealed to chemists to continue Stas's work and bring it if possible to an even higher pitch of perfection, and he pointed out with much sagacity the principles by which such work must be guided. Little did he realise that the task was already in progress in his adopted country, and that the next stage was so near at hand. We meet to-day to do honour to the memory of Theodore William Richards, whose name will always be remembered with those of Berzelius and Stas—the three great masters of atomic-weight determination. In Richards, Chemistry has lost the founder of a famous school of research, a great experimenter and one whose methods and example have exerted a profound influence on chemical investigations in every country. This Society has special reason to mourn his loss. He was one of our Honorary Fellows, our Faraday Medallist of 1911, and he had a most affectionate and sympathetic regard for this country, and was always eager to welcome English chemists to Harvard.

To give a picture of his endearing personality and to do justice to his massive achievements in research is no easy task. Richards himself was always interested in presenting the growth of a subject, the incidents and accidents that shaped its course, and I will do my best to trace the development of his own scientific career, the decisive factors and influences in his life, in the hope of giving some indication of the debt that Chemistry owes to him, and of conveying to those who did not know him some impression of the man who was so beloved by his pupils, his colleagues, and his friends.*

Theodore Richards was born in Germantown, Pennsylvania, on January 31st, 1868. His father, William Trost Richards, of English, Dutch, and Welsh extraction, was a well-known marine painter.

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* The preparation of this lecture would have been impossible without the assistance of Professor Richards's friends and pupils. I am particularly indebted to Professor Baxter's biography in the Harvard Graduates Magazine, from which I have borrowed freely. In addition I owe much to the help of Professor P. W. Bridgman, Professor J. B. Conant, Professor H. B. Dixon, Mr. Garrod-Thomas, Dr. Lawrence P. Hall, Professor L. J. Henderson, Mr. W. D. Hutchinson, Professor G. N. Lewis, Professor Loring Jackson, Principal H. R. Raikes, and Dr. W. T. Richards.

His mother, Anna Matlack Richards, who came of an old English Quaker family in Philadelphia, was a woman of great cultivation and activity of mind, and a writer of prose and verse.

Richards grew up under the close influence of his two gifted parents, and his rapid progress and the wide interests which he kept throughout his life were due to the stimulating atmosphere of his home and to the devotion of his parents to their children. Each summer was spent by the sea, where the boy watched his father painting and began to sketch at a very early age. When he was six years old the family went to Newport, Rhode Island, so that his father might study the effect of waves breaking upon rocks. This visit was to have a decisive effect on the boy's career, as he there made friends with Professor Josiah Parsons Cooke of Harvard, who showed to his wondering eyes the rings of Saturn through a four-inch telescope, an experience which Richards never forgot. His mother, mistrusting the local schools where the pace was set by the slowest-witted, decided to teach her younger children herself and Richards received from her virtually the whole of his education before going to college. He always spoke with affection and gratitude of his debt to his mother's skilful and sympathetic teaching.

In 1878 the family came to Europe for two years. Most of the time was spent in England, the winters in London and the summers on the Cornish and Dorset coast, where Richards first gained his love of the English countryside. Even as a child he was never happier than when using his fingers, and in 1880 he made a model schooner, the "Yankee," which he sailed with pride across the Round Pond in Kensington Gardens, flying the Stars and Stripes. His first chemical experiments were made with Pharaoh's serpents and coloured flames in Warwick Gardens, Kensington. His next Christmas present was a box of chemicals and apparatus, and so quickly did his interest develop that in 1881 he was allowed to attend some chemical lectures at the University of Pennsylvania. In the same year he printed on a hand-press an edition of his mother's sonnets, which was bound and made copyright, and with the proceeds of its sale he fitted up a small laboratory in his home in Germantown. By this time his earliest dreams of becoming an artist like his father had faded, and he had already set his heart on science. He entered Haverford College in 1882 at the unusually early age of 14, without ever having been to school. Here chemistry and astronomy were his main subjects and but for his defective eyesight * he might have chosen to become an astronomer. In 1885 he graduated as Bachelor of Science at the head of his class, and this success led his parents to send him to Harvard to work under his old Newport friend Professor

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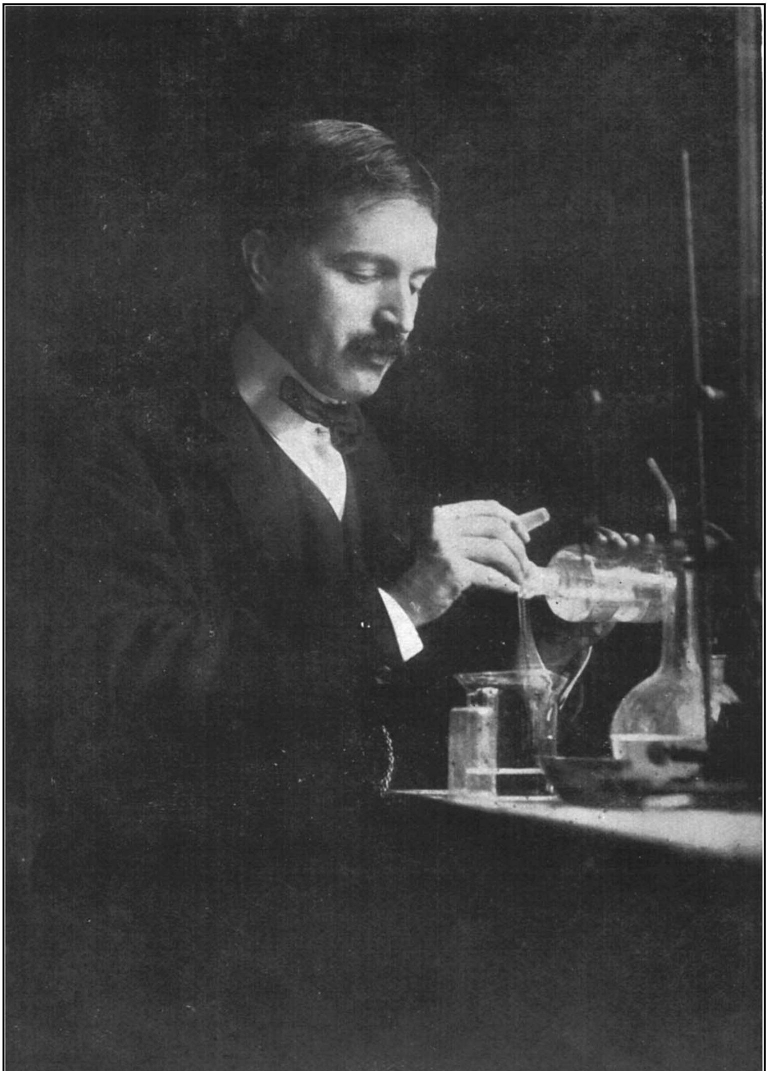
* His left eye was myopic, and his right hypermetropic and astigmatic.



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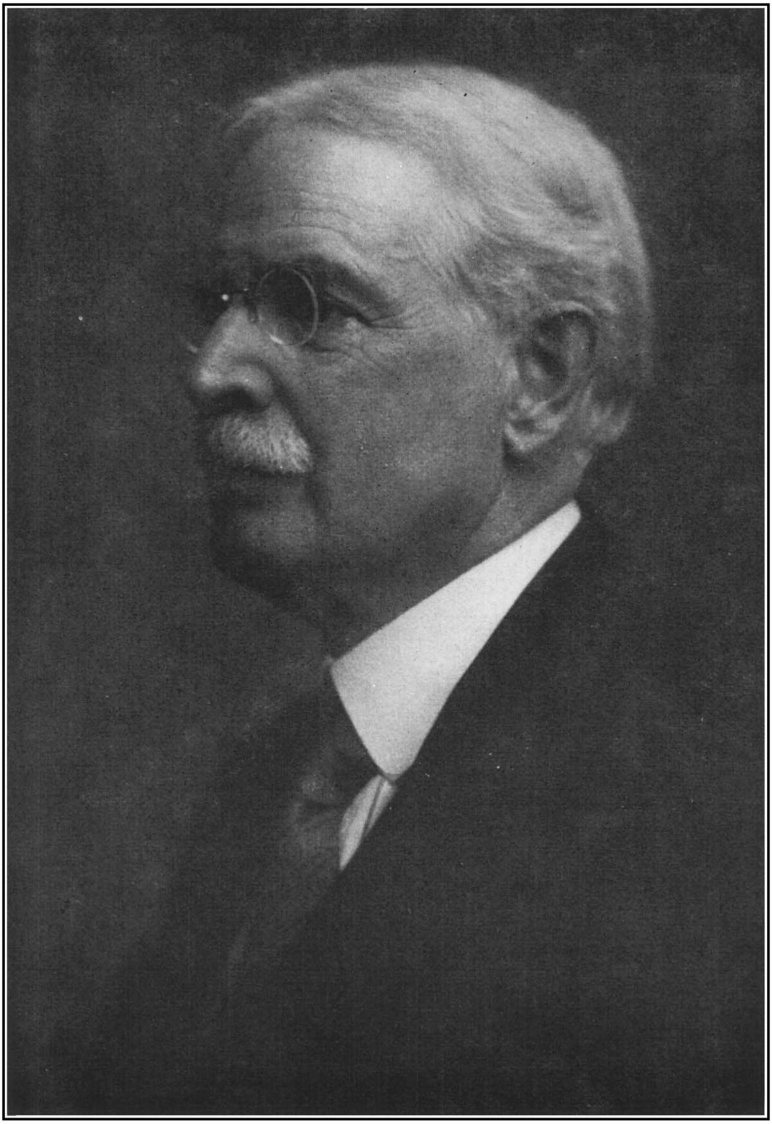

1925.

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Cooke. In order to do so he studied Greek with his mother during the summer, and entered as the youngest member of the Senior Class in the autumn. In the following year he received the degree of Bachelor of Arts, *summa cum laude*, with the highest honours in Chemistry.

At Harvard Richards came directly under the influence of Cooke, whose interests were largely in the field now called physical chemistry, partly by inclination, partly perhaps through association with Regnault, with whom he had worked in Paris. Cooke had always been interested in the combining proportions of the elements, and his work on the atomic weight of antimony—the first extended work of the kind in America—had emphasised once more the nearness of many atomic weights to whole numbers if they are referred to oxygen as 16, a regularity which disappears if hydrogen = 1 is taken as the standard. Hence Cooke decided to investigate anew the ratio of oxygen to hydrogen, to see if it was not really 16 : 1 in accordance with Prout's hypothesis, instead of 15·96 : 1, the value found by Dumas in 1842 by weighing the amount of water formed by the reduction of a known weight of cupric oxide. The work begun in 1883 had been delayed by Cooke's bad eyesight, and Richards was chosen to carry on the determinations, which involved the weighing of globes of hydrogen, the passage of the gas over cupric oxide and the weighing of the resulting water. It was a most difficult piece of work for a novice of eighteen years of age to undertake, and its success was an early proof of Richards's exceptional experimental skill.[1] The value found for the atomic weight of oxygen, *viz.*, 15·869 ± 0·0017,* does not differ much from the value accepted to-day (15·875), and it showed that the atomic weight was even further from a whole number than Dumas had supposed. The work was finished in 1888 and its excellence was recognised by the University by the award of the Parker Fellowship which enabled Richards to spend a year in Europe. The winter semester was spent at Göttingen, where he studied analytical chemistry under Jannasch and vapour density determinations under Victor Meyer. A research with Jannasch on the determination of sulphate in the presence of iron gave Richards some experience of the difficulties of precipitating a pure substance from a solution. The spring and summer of 1889 were spent in visiting most of the important laboratories of Germany, Switzerland, France, and England. This plan of spending half a year

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[1] This and other numerical references relate to the short bibliography of selected papers on p. 1968.

* The value in the original paper, 15·953 ± 0·0017, which seemed to support Dumas, was subsequently corrected at Lord Rayleigh's suggestion for the contraction of the globe on evacuation.

abroad in intensive work in one institution, followed by half a year of peripatetic study, he always advocated to students as offering on the whole the greatest good for the time available. It was in this summer that he first met Lord Rayleigh, Sir Henry Roscoe, and other English chemists who were to remain his life-long friends. In the autumn he returned to Harvard as assistant in quantitative analysis, never again to break his connexion with the University except for his visit to Berlin as visiting Professor in 1907. Promotion to an instructorship came in 1891 and to an assistant professorship in 1894. In the following year the death of Cooke made it necessary to find an instructor in physical chemistry, and Richards was sent by the University to spend a semester with Ostwald at Leipzig and Nernst at Göttingen in order to study the developments of the new subject and the methods of teaching it. In 1901 Richards received the rather unusual compliment of a call to a Chair in a European University, when Göttingen invited him to accept a full professorship in Chemistry with only nominal teaching duties. To a man impatient to make more rapid progress in research, and working with a heavy load of teaching in a laboratory that was far from ideal, such an offer was tempting in the extreme. But Harvard, realising the distinction of Richards's work and what a loss he would be to their scientific school, rose to the occasion with the offer of a full professorship coupled with a drastic reduction of the amount of teaching and administrative work that would be expected of him. Many other offers came to Richards, but he remained at Harvard, to which he was attached by so many bonds, and in 1912 on the retirement of Professor Jackson he was appointed to the Erving Professorship of Chemistry (endowed in 1792) which he held until his death.

Richards's main reason for choosing an academic career was the opportunity it offered of pursuing his investigations, and of satisfying the great intellectual wish of his life—" an intense desire to know something more definite about the material and energetic structure of the universe." On his return from Europe in 1889 he resumed the investigation of atomic weights, a field of research which was to occupy a great part of his life, and seldom can an investigator have been better fitted to attack the problem of his choice. This field was chosen " not merely because I felt more competent in that direction than in any other (having already shewn the atomic weight of hydrogen to be distinctly too high and that of copper distinctly too low)*, but also because atomic weights seemed to be one of the primal mysteries of the universe. They are values which no man

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* The work on the atomic weight of copper had been started while he was investigating the hydrogen : oxygen ratio, and two preliminary papers had been published in 1887.

by taking thought can change. They seem to be independent of place and time. They are silent witnesses of the very beginning of the universe, and the half-hidden, half-disclosed symmetry of the periodic system of the elements only enhances one's curiosity about them. Moreover among the many properties possessed by an element, the atomic weight seems one of the most definite and precise. Hence in trying to satisfy a desire which had as its object the discovery of more knowledge concerning the fundamental nature of things, one naturally assigns to the atomic weights an important place."

He returned first to the investigation of copper, a fortunate choice, as the examination of the various methods used by previous workers and the detection of the errors that had affected their results gave him a wide range of experience of the subtle sources of error which may influence work of this kind—the difficulty of avoiding occlusions in precipitates, the impossibility of preparing oxides free from included gases, and the care needed to ensure that all substances are weighed in an anhydrous condition. The work showed, too, the advantage of the Marignac–Stas method of analysing whenever possible the haloid compounds of an element by means of silver precipitation. The research extended over several years and led to a detailed investigation of many compounds of copper which must have given him most valuable experience. It was carried out with the thoroughness which was to become typical of Richards's work. Every cause of variation was tracked to its source, and finally a value of 63·57 * was found as the mean of the results of five different methods, a value which stands unchanged to-day; the older value was 63·3.[2]

The analysis of copper sulphate by means of barium sulphate had revealed an uncertainty in the atomic weight of barium, and this was the element next investigated by means of the analysis of the bromide and chloride, yielding a value of 137·37 for the atomic weight in place of the previous value of 137·0. Convinced by these results of the necessity for the re-determination of these constants, Richards proceeded with the remaining metals of the group in the order strontium, zinc, magnesium, and calcium, and, with the assistance of a number of graduate students who were now associated with him, progress became much more rapid. The work on strontium was notable for producing two new experimental devices, the bottling apparatus and the nephelometer, on which the accuracy attained in modern atomic-weight determination is largely dependent.[3] Richards

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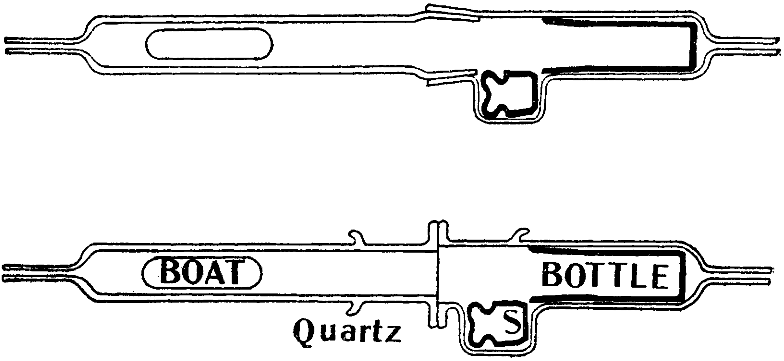
* Since the values of the atomic weights obtained by the analysis of halides are dependent on the value assigned to silver, all the older values quoted are referred to the present accepted value of silver, 107·88.

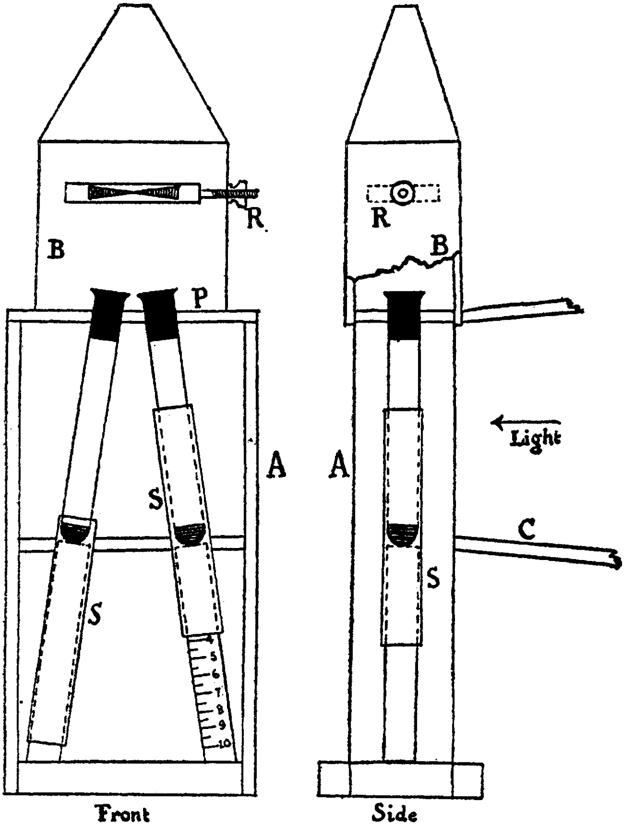
had found that the only safe method of removing the last traces of included or occluded moisture from a substance before weighing it was to fuse it in a dry atmosphere. Strontium bromide when so treated became alkaline owing to loss of hydrogen bromide, and hence it was necessary to fuse it in a stream of this gas, which was then displaced by dry nitrogen, in which the solid was cooled. The transference of the boat or crucible to a weighing bottle through the atmosphere always resulted in the absorption of traces of moisture. Hence a method was devised for carrying out all these operations without exposure to the air. A crude form of this device used with strontium was elaborated in the following year with the assistance of H. G. Parker into the well-known bottling apparatus shown in Fig. 1. " This simple device consists of a quartz ignition tube fitted to a soft-glass tube which has a projection or pocket in one side. A weighing-bottle is placed at the end of the latter tube, and its stopper in the pocket. The boat containing the substance to be dried is heated in the quartz tube, surrounded by an atmosphere consisting of any desired mixture of gases. These gases are displaced, after partial cooling, first by nitrogen, and then by pure dry air, and the boat is pushed past the stopper into the weighing bottle, the stopper being then forced into place, and the substance thus shut up in an entirely dry atmosphere. The weighing-bottle may now be removed, placed in an ordinary desiccator, and weighed at leisure. The substance is really dry, and its weight has definite significance."

FIG. 1.



The nephelometer was devised to overcome certain difficulties which arise from the slight solubility of the silver halides when the atomic weight of an element is determined through its chloride or bromide by finding what weight of the corresponding silver halide is precipitated by silver nitrate, or by finding what volume of a silver nitrate solution is exactly equivalent to the weight of haloid salt taken. The solubility of the silver halides affects the accuracy of both methods, since in the first allowance must be made for the weight of silver halide remaining in solution, and in the second the end-point is difficult to detect since the silver salt in solution will be precipitated by either of its component ions. Richards first used Stas's method of detecting the end-point by seeing when an equal excess of silver or haloid ion produced an equal amount of opalescence observed by transmitted light. Silver bromide is so insoluble that the opalescence is hard to observe accurately, and Richards hit on the idea of comparing the amounts of scattered light from two precipitates. Later, with Wells,[4] this developed into the instrument called the nephelometer shown in Fig. 2. "Its construction is very simple. Two test tubes, near together and

FIG. 2.



slightly inclined toward one another, are arranged so as to be partly or wholly shielded from a bright source of light by sliding shades. The tubes are observed from above through two thin prisms, which bring their images together and produce an appearance resembling that in the familiar half-shadow apparatus. The unknown quantity of dissolved substance is precipitated as a faint opalescence in one tube by means of suitable reagents; and a known amount, treated in exactly the same way, is prepared in the other. Each precipitate reflects the light; the tubes appear faintly luminous. If, then, the shades have to be adjusted at exactly the same height in order that the precipitates may show like tints to the eye, the precipitates may be assumed to be equal. If, on the other hand, the shade over the standard tube must be arranged so as to expose to the light only half as much of this opalescent mixture as the other shade exposes of the other in order to show a like tint, the former precipitate may be assumed to be about twice as plentiful. Accordingly a new standard tube with a known amount is made, about half as concentrated as before, and a new comparison is made. In this way, in a very short time, the amount of suspended precipitate in the unknown tube may be estimated with considerable precision, and therefore the trace of dissolved substance may be determined."

At this point research was interrupted by Richards's second visit to Germany in 1895. This was a decisive episode in his career as it changed his outlook from that of an old-fashioned investigator of atomic weights to that of an enthusiastic if somewhat critical disciple of van't Hoff and Ostwald, and enabled him to bring to bear on his problems all the resources of the new theory of solutions.

The first elements to be tackled on his return were nickel with Cushman and cobalt and iron with Gregory P. Baxter, who was later to be so closely associated with Richards as a colleague at Harvard and to carry out so many admirable atomic-weight determinations on his own account. In each case the existing values of the atomic weights were found to need correction. These investigations were followed quickly by work on calcium, uranium (with Merigold) on account of Becquerel's discovery of its radioactivity and its position as the heaviest element, and cæsium (with Archibald).

Until 1903 all Richards's values for atomic weights were based on Stas's values for the fundamental atomic weights of silver, chlorine, and bromine, and although Richards had improved on Stas's technique in certain respects he had never doubted the accuracy of his values. It is true that discrepancies in the values obtained for barium and other elements from the analysis of their chlorides and bromides might have suggested to him that Stas's values were not impeccable, and it is a tribute to his modesty that he suspected his own work rather than that of his forerunner. The determinations of the atomic weight of nitrogen by both physical and chemical methods had already led Guye and other chemists to suspect Stas's values for that element and also for silver, but Richards was critical of the gas density method owing to the danger of adsorption and the uncertainty of the extrapolation to zero pressure. In 1904 he endeavoured to support Stas's values, and showed that this worker's determinations of the silver : bromine ratio agreed exactly with his own.

But Stas was not infallible and it fell to Richards to establish the errors in his work. The immediate occasion of this was characteristic of the thoroughness of the methods of the Harvard school. Richards was determining the transition temperatures of a number of salt hydrates for use as fixed points in thermometry, among them being sodium bromide with R. C. Wells,[5] and after this salt had been purified with great care, its transition temperature was found to be so definite that it was thought worth while to make a few analyses of its composition. These gave a value for the atomic weight of sodium 0·2% lower than that of Stas, assuming his values for silver and bromine (107·93 and 79·955) to be correct. This discrepancy could not be disregarded, as it indicated either an impurity in the sodium bromide or a flaw in the classical work of Stas. When the first alternative had been pursued in vain, the second was examined with the help of all the physico-chemical knowledge acquired since 1865. The re-determination of the atomic weights of silver, chlorine, and sodium proved conclusively that Stas's work was vitiated by appreciable errors, which were quickly traced and eliminated. In his analysis of sodium chloride Stas dropped the solid salt into silver nitrate solution, causing occlusion of sodium chloride by the precipitate. His sodium chloride contained traces of platinum and silica, his silver traces of oxygen. And finally there was a slight inaccuracy in the end-point of each analysis. In the revision of Stas's values for the fundamental atomic weights a new era of accuracy in analytical methods was inaugurated by Richards and his pupils.

Richards and Wells [6] carried out a masterly series of measurements of the ratios Ag : AgCl, AgCl : NaCl, Ag : NaCl, which confirmed exactly the atomic weight of sodium found from the bromide. But this left Stas's value 107·93 for the atomic weight of silver still in doubt, and this, together with the uncertainty in the value for nitrogen, led to a repetition with G. S. Forbes of Stas's synthesis of silver nitrate from silver.[7] Richards's aim in repeating this work was to exceed in accuracy any chemical work which had ever been published, and to-day we know how well he succeeded. Silver was purified with every precaution, converted into silver nitrate, fused and weighed in a quartz vessel: 100·000 parts of silver in six experiments gave

157·481	157·481	157·481
157·480	157·480	157·480

parts of silver nitrate, and a long series of experiments to examine the purity of the product showed that it contained no dissolved gases, no nitric acid, less than $\frac{1}{2000}$ of 1% of ammonia, and less than $\frac{1}{1000}$ of 1% of water. The corrected weight of silver nitrate was therefore taken as 157·479, a result of great interest as it showed that if the atomic weight of nitrogen had as low a value as 14·01, silver must be 107·88 instead of 107·93 as Stas had supposed. The next step was to establish definitely the value for silver. This was attempted in two ways. In 1907 while Richards was in Berlin as visiting professor, the ratio $NH_4Cl : AgCl$ was determined with Köthner and Tiede [8] and this, together with the previous values found for the ratios $Ag : AgCl$, $Ag : AgNO_3$, gave values for the atomic weights of silver 107·879, chlorine 35·456, and nitrogen 14·008, on the basis of $O = 16$, assuming the value 1·0078 for hydrogen.

A more direct method of attack on the silver : oxygen ratio by means of the decomposition of the oxyhaloid salts such as the chlorates, as used by Stas, was known to be associated with many difficulties and errors, but finally after a long search lithium perchlorate was found to be a suitable substance since it could be formed quantitatively by the action of perchloric acid on lithium chloride. With the help of H. H. Willard [9] the ratios $Ag : LiCl$ and $LiCl : LiClO_4$ were determined, which when combined give a value for silver directly in terms of oxygen. The value found was 107·871, and this Richards always considered more probable than the value 107·88 adopted by the Atomic Weight Commission. And so the question remained in slight uncertainty until 1927–29 when Hönigschmid, who had learned the Harvard technique in 1910 when he was working with Richards on the atomic weight of calcium, redetermined, in Munich, the ratios $Ag : AgCl$ and $Ag : AgNO_3$ with the utmost precision and care. The results are a complete confirmation of the values obtained by Richards twenty years earlier, the agreement being exact to one part in 100,000. Hönigschmid found that the lithium perchlorate ratio could not be determined with equal precision owing to the corrections necessary for loss of lithium chloride in its transference to the quartz vessel and for the presence of unavoidable traces of lithium chloride in the perchlorate. To quote his own words, " Such corrections constitute a defect in an accurate determination which must be eliminated if possible. The investigation in question was carried out in so masterly a way that the limits of accuracy obtainable were actually reached. Even to-day, twenty years later, in spite of all our accumulated experience, we can see no way of improving the method so as to eliminate the corrections." Hönigschmid substituted for it the conversion of barium perchlorate into barium chloride and found a value of 107·879 for silver,[10] which agreed exactly with the values found by Zintl and Meuwsen and Zintl and Goubeau from the study in his laboratory of the ratios $NaNO_3 : NaCl : Ag$ and $KNO_3 : KCl : Ag$. The work of Hönigschmid together with that of Richards appears to settle definitely the values of these fundamental atomic weights and it is noteworthy that the final decision came by the use of Harvard technique in the hands of one of Richards's earlier collaborators.

Richards's early work had all been done under most trying conditions in Boylston Hall, which had been built in 1858. His own laboratory had been intended for the assistant who gave out all the apparatus and chemicals and it was still lined with cupboards. The door of the draught cupboard had iron sashes which gave a continual rain of iron rust, and he could never feel sure that noxious gases from other parts of the building might not ruin the work of many weeks. On one occasion the ceiling of his laboratory was brought down about his ears by a flood in the room overhead, and constant watchfulness to avoid untoward accidents of this kind was as important for his work as analytical skill. That he was able to carry on such magnificent work under such conditions is a splendid example of the triumph of man over circumstances. Visions of a new laboratory were often in his mind and finally, in 1912, thanks largely to the generosity and interest of Dr. Morris Loeb, the Wolcott Gibbs Memorial Laboratory was planned and erected. In equipment, convenience, freedom from fumes and dirt and from rapid temperature changes it probably excels any other research laboratory in the world, and so for the last fifteen years of his life Richards worked under ideal conditions.

Year by year a constant stream of researches on atomic weights came from Harvard, some directed by Richards and even more by Baxter, and one by one these constants were established with greater precision, but still the solution of the problem of their relationships seemed no nearer. In discussing the discrepancy between the obvious order of the elements cobalt and nickel in the Periodic System and their relative atomic weights, Richards said : " This added to my conviction that the table of the Periodic System represents only in a very crude fashion relationships which are highly complex and subtle. Clearly the nature of these elements is not always capable of being depicted by any such simple sequence of atomic weights and properties as may be ordered by placing the elements in definite pigeon holes."

In 1912 the answer to the riddle came from an entirely different quarter, the consideration of the changes in atomic weight and atomic number accompanying radioactive transformations, which led Russell, Fajans, and Soddy independently to the conception of isotopes. This involved a radical change in the significance of atomic weights, and in the early days of radioactivity there was a certain feeling of doubt as to whether all the care and labour expended on their determination had been justified : the answer to these sceptics came with dramatic force and swiftness. At the moment when the ideas of chemists were undergoing the most revolutionary change since the time of Dalton, it was to Richards's laboratory that Lembert was sent in 1913 by Fajans to ascertain whether uranium lead really differed in atomic weight from ordinary lead, and the rapid acceptance of the new theory rested largely on the result of the crucial experiment made under Richards's supervision,[11] and confirmed by Hönigschmid and Curie. From 1914 until the development of the mass-spectrograph by Aston in 1919, the only conclusive evidence in support of the theory of isotopes was the difference between the atomic weight of ordinary lead and the values found for specimens of radioactive origin.

This work led Richards to a long series of researches on uranium lead. The atomic weights of specimens from a number of sources were determined, leading ultimately to a probable value of 206·02 for the atomic weight of the pure isotope Pb_{206}. Richards was specially interested in the geophysical problems associated with the isotopic leads, and the uranium–lead ratio for the mineral from which the pure isotope Pb_{206} was extracted indicated that it was at least 1,500,000,000 years old, the greatest previous estimate of the kind being of the order of 1,200,000,000 years. A very accurate comparison was made of the properties (atomic volume, melting point, solubility, refractive index, thermoelectric effect) of ordinary and uranium lead, and of certain of their compounds, which showed that the values for both kinds of lead were identical within the limits of experimental error, when reckoned on an atomic or a molecular basis to eliminate the difference in atomic weights.

Even in his earliest work Richards was always alive to the possibility that specimens of an element of different origin might have different atomic weights, but when investigating copper, barium, calcium, sodium, and chlorine identical values were found for specimens from different quarters of the globe. Later, Baxter at Richards's suggestion investigated iron and nickel from meteorites and found atomic weights identical with those for material of terrestrial origin, a result which in the light of our present knowledge of isotopes gives us, as Richards said, " an added realisation of the essential unity of the universe."

In view of the development of the mass-spectrograph for the accurate determination of the mass numbers of isotopes it is pertinent to ask, and it is a question which Richards must often have asked himself, what is the present significance and value of chemical atomic weights? It is true that they represent only the average of the mass numbers of the isotopes present and depend for their interpretation on the help of the mass-spectrograph, but as Richards always maintained, although their significance has altered, an exact knowledge of them is more important than ever, now that we know their real meaning. Until it is possible to calculate the atomic weight of an element from the mass numbers of its isotopes by measuring with sufficient accuracy their relative proportions by means of the intensities of their respective lines in the mass spectrum, chemical methods are our only means of knowing these average atomic weights, which are the constants most frequently required by chemists in quantitative measurements of every kind. Then again, chemical atomic weights are the most direct proof of the identity of specimens of an element from different sources, while variations give us perhaps the most certain clue as to their origin and history. In the recent work of von Hevesy on the isotopes of potassium, the proof that fractionation had been effected and the calculation of the increased concentration of the isotope K_{41} depend on the refinement of Hönigschmid and Goubeau's atomic-weight determinations which revealed with certainty a change from 39·104 to 39·109. Chemical atomic weights too are the only means, apart from internal agreement, of establishing the correctness of the mass numbers found with the mass-spectrograph, thus giving a special importance to accurate determination for elements with only one isotope. Two of Richards's last investigations were on the atomic weights of cæsium,[12] and a specially pure uranium lead,[13] both of which should consist of a simple isotope. For uranium lead Pb_{206} he found a value 206·02, after applying a small correction for the thorium lead present, and this number he believed to be too high, but Aston's recent determination with the mass-spectrograph has given a value of 206·016, so the two are in almost exact agreement. On the other hand Richards found a value 132·81 for cæsium, and Aston 132·93, a discrepancy which points to the existence of a small proportion of a hitherto undetected lighter isotope.

These examples show the force of Richards's contention in his Nobel Lecture (1921): " The subject of atomic weights is thus far from being a completed and closed chapter of Science. The future opens up a prospect of almost endless further investigations . . . let us hope that yet finer means of research and yet deeper chemical knowledge may make possible further improvements.''

Richards investigated either with his own hands or with the aid of his pupils the atomic weights of twenty-five elements. The results of his work together with the older values and those accepted to-day are given in the following table, which is a most striking testimony to his achievement.

Atomic weights determined by Richards and his pupils at Harvard.

Element.	Date of publication.	Previous value.	Harvard value.	Present value.
Hydrogen	1888	1·002	1·0082	1·0078
Lithium	1910	7·03	6·94	6·94
Carbon	1915	12·0	12·005	12·000
Nitrogen	1907	14·04	14·008	14·008
Sodium	1905	23·05	22·995	22·997
Magnesium	1896	24·2	24·32	24·32
Aluminium	1921	27·1	26·96	26·97
Sulphur	1907	32·06	32·07	32·06
Chlorine	1905	35·45	35·458	35·457
Potassium	1907	39·14	39·095	39·104
Calcium	1910	40·00	40·07	40·07
Iron	1900	56·00	55·85	55·84
Nickel	1899	58·5	58·68	58·69
Cobalt	1899	59·1	58·97	58·94
Copper	1886—92	63·3	63·57	63·57
Zinc	1895	65·0	65·37	65·38
Gallium	1923	69·9	69·716	69·72
Bromine	1907	79·95	79·917	79·916
Rubidium	1903	85·5	85·42	85·44
Strontium	1894	87·5	87·62	87·63
Silver	1910	107·93	107·88	107·880
Cæsium	1903—28	132·9	132·81	132·81
Barium	1893	137·0	137·37	137·36
Lead (Uranium)	1915—26	—	206·02	206·02
Uranium	1902	240·2	238·4	238·14

And if we add to these the atomic weights determined independently by Baxter * and those by Hönigschmid † using the Harvard technique, we find that, of the 92 elements, our knowledge of the atomic weights of no less than 55 rests to a large extent on the work of Richards and his former pupils.

When we survey the magnitude of the task, the accuracy with which it has been performed and the progress it represents, we naturally ask what were the principles that guided it and ensured its successful issue. The answer is given by Richards himself in a

* Helium, boron, neon, phosphorus, silicon, argon, titanium, chromium, manganese, iron, cobalt, nickel, germanium, arsenic, bromine, cadmium, tin, iodine, lanthanum, neodymium, praseodymium, lead.

† Beryllium, boron, chlorine, silicon, potassium, scandium, iron, bromine, yttrium, zirconium, silver, antimony, cerium, barium, dysprosium, hafnium, mercury, bismuth, lead, radium, thorium, uranium.

short monograph of fifteen pages on "Methods used in Precise Chemical Investigations,"[14] which merits reading and re-reading by all students of chemistry young and old, for it sets out with masterly clearness and brevity the considerations that should guide the worker in any accurate investigation. "The cause of Richards's success in quantitative measurements," writes Professor Conant, "was his ability to foresee all sorts of sources of error and possible calamities which the average investigator would have overlooked completely. He thus took precautions against many things which less imaginative people would have ignored and reckless people would have been willing to forget optimistically. He was never willing to put aside a possible source of trouble on the ground that good fortune might prevent the possible disaster from descending on his work."

Compare this with Richards's own words: "Every substance must be assumed to be impure, every reaction must be assumed to be incomplete, every method of measurement must be assumed to contain some constant error, until proof to the contrary can be obtained. As little as possible must be taken for granted."

"To sum up the matter in a few words, it may be said that the secret of success in a precise chemical or physico-chemical measurement lies in so choosing the particular substance and process and so checking every operation by parallel experiments that both chemical and physical errors may be avoided as effectually as possible; and this choice often involves much study and above all the application of sound common sense. The precautions must be of a consistent order of refinement. Far more depends upon this intelligent choice of conditions than upon mere mechanical execution of the operations, although that too is important."

Although Richards is best known for his work on atomic weights, which brought him the greatest honours that can fall to a chemist, including the Nobel Prize, it occupied only a fraction of his energies and he had wide interests in other branches of physical chemistry in which he carried out many investigations of outstanding importance. Indeed his success in the field of atomic weights was due largely to the fact that he was not a narrow specialist, his wide experience of other problems supplying the clue to many a difficulty. To follow his interest in other fields we must retrace our steps to the beginning of his scientific career. His first paper, published in 1886, actually dealt with the heat evolved in the precipitation of silver chloride from various metallic chlorides. But his active interest in physical chemistry dates from his visit to Germany in 1895. It was just at this time that the new subject was taking shape in the hands of van't Hoff, Arrhenius, Ostwald, and Nernst. The *Zeitschrift für* *physikalische Chemie* was founded in 1887, and chemists' minds were full of the early triumphs of the new theory of solutions. The explanations it offered of so many obscure points in quantitative chemistry naturally made a great appeal to Richards, and he gladly welcomed the opportunity of visiting the laboratories of Ostwald and Nernst. After his return his field of research was soon enlarged to include investigations in electrochemistry, thermochemistry, and ionic equilibria. G. N. Lewis was his first graduate student in physical chemistry, and with him was begun the study of the electrochemistry and thermochemistry of amalgam cells. It was a fortunate partnership, for Lewis was later to make such important practical and theoretical contributions to our knowledge of electromotive forces.

Not only was this a time of great activity in the laboratory, but Richards was busily speculating on the issues which his recent experiences had raised in his mind. The fruits of his theoretical labours were brought to a focus in four papers [15] on " The Significance of Changing Atomic Volume " published in 1901–4, which are of special interest in outlining the fields of physical chemistry with which he was to be associated most closely for the next twenty-five years.

The starting point in 1899 of Richards's speculations as to the relationship of atomic compressibility to the chemical and physical behaviour of the elements, was the fact that the so-called constant, b, of van der Waals's equation, is really variable under great pressure. This suggested to him that the current view of the molecule and of the atom as hard incompressible particles was incorrect, and he was thus led to think that atoms might undergo volume changes during chemical action as a result of changes in the internal pressure due to their cohesive and chemical attractions for one another. Examination of the facts afforded ample confirmation of this inference. Richards was by nature an experimenter and he almost always attacked problems from an inductive standpoint. " The guiding hypothesis and the mathematical treatment," he says of this inquiry, " were developed from the actual behaviour of matter. For it may be that matter possesses intrinsic potentials which cannot be discovered except by the study of matter itself."

In the first two papers Richards summarised the evidence for changing atomic volume, and showed the close correspondence that exists between the volume changes during chemical combination and the heats of combination of metals with oxygen and the halogens, which led him to think that the heat of reaction represents the work done in the compression of the atoms by the force of chemical affinity, the change in volume being an approximate measure of the pressure resulting from the affinity of the atoms for one another.

The third paper dealt with the relationship of the changes in free energy and total energy accompanying a reaction, a problem which was then attracting so much attention among physical chemists in connexion with the attempts to integrate the Gibbs–Helmholtz equation. Richards attacked it from the point of view of the difference in heat capacity of the reactants and resultants which he thought was associated with the change in volume. A comparison of the experimental data for ten galvanic cells involving a reaction of the type

$$\mathrm{Zn} + \mathrm{CuSO_4} = \mathrm{ZnSO_4} + \mathrm{Cu}$$

showed that the sign and magnitude of the difference between the free and total energy changes are in fact dependent upon the sign and magnitude of the change of the heat capacity during the reaction. This, in conjunction with the Gibbs–Helmholtz and Kirchhoff equations, led him to the further inference that the change of the free energy of a reaction with temperature must have some fundamental connexion with the change of total energy with the temperature, and he showed that for these cells at 18°,

$$dA/dT = -M\,.\,dU/dT,$$

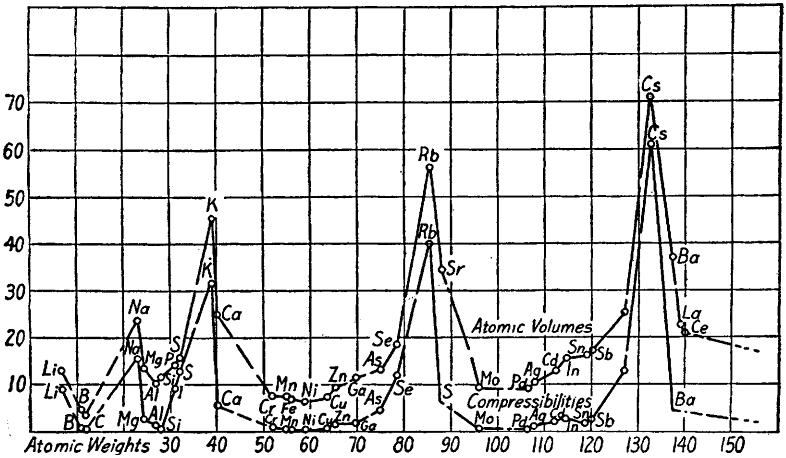
where M had an average value of 2. The diagram of the values showed that the values of A and U must approach one another rapidly as the temperature is lowered, dA/dT and dU/dT in most cases appearing to become zero as the absolute temperature is approached. G. N. Lewis says "the curves presented by Richards very nearly imply the generalisations which were later to be embodied in the third law of thermodynamics." But although it is doubtful whether Richards at the time saw the full implication of his results, the paper was a very suggestive contribution to one of the most vital theoretical issues of the day and attracted much attention, van't Hoff making it the subject of a special memoir.

The last paper of the series discussed the relative effects of the pressures produced by cohesion and chemical affinity, and showed that the agreement between theory and experiment is improved by taking into account the compressibilities of the reacting substances, the change in volume being less with less compressible elements.

After 1900 the theory of compressible atoms was constantly in Richards's thoughts and by means of it he sought to correlate a wide range of phenomena. But the main value of such a theory lies in its stimulus to new experiments. As Richards said, "the saying of Scripture, 'By their fruits ye shall know them,' applies in full force to theories as well as to men," and his theory of compressible atoms gave the impulse to two of the main groups of his researches, those on compressibility and surface tension, and those on thermochemistry.

A new method of determining compressibilities up to 500 atmospheres was worked out in 1904,[16] and by means of it he measured the compressibility of forty elements and many compounds. Richards thus discovered that compressibility was a periodic function of the atomic weight of the elements, closely related to their atomic volume, as is seen in Fig. 3.

FIG. 3.



An examination of the physical properties of a number of liquids showed that in groups of similar substances close relationships exist between their compressibilities, and their densities, surface tensions, boiling points, molecular heats of vaporisation, and coefficients of expansion, all these properties being dependent on the internal pressures exerted by the cohesive forces.

Richards was always striving to put his theory on a mathematical basis, but this was difficult owing to the number of variables involved. He regarded the state of a substance as determined by a balance of pressures due to compressing and distending agencies. For monatomic elements these can be expressed by the equation

$$p + \pi = \pi_p + P_\theta \quad .$$

where p represents external pressure, π the sum of all possible intrinsic compressing effects, π_p the intrinsic distending or repulsive pressure, and P_θ the thermal pressure arising from the kinetic energy of the atoms which is approximately equal to $T\alpha/\beta$, where α and β are the coefficients of expansion and compressibility respectively. A number of attempts were made to evaluate the internal pressure by various methods, one of the main difficulties being that the effect of pressure on compressibility was only known to 500 atmospheres, while it was probable that the internal pressures had much higher values. However, fresh possibilities were opened in 1922 by Bridgman's researches on compressibility up to pressures of 12,000 atmospheres, and during the last year of Richards's life much of his time was devoted to the analysis of Bridgman's results and his own earlier work, and his final estimates of the internal and thermal pressures of isotropic elements are given in the following table :

Estimates of Intrinsic Cohesive Pressures of Several Isotropic Elements together with Approximate Thermal Pressures at 20° *C.*

	Thermal pressure.	Cohesive pressure.
Potassium	2,100	15,300
Sodium	4,000	33,000
Mercury	13,100	41,300
Lead	10,340	72,000
Aluminium	14,000	191,000
Silver	16,120	208,000
Gold	21,800	243,000
Copper	19,390	376,000
Platinum	21,000	465,000
Iron	16,000	587,000
Tungsten	13,400	1,000,000

(The unit of pressure is the megabar, *i.e.*, 0·987 atmosphere.)

The relative magnitudes of the internal pressures correspond satisfactorily with the physical properties of the elements, their volatility, hardness, and elasticity, and in certain cases there is a close agreement between the heat of evaporation calculated from the internal pressure and that found by experiment. There can be little doubt that Richards's values represent the order of magnitude of the internal pressures, and they are confirmed by recent work on the breaking stress of materials, such as Griffith's work with fine glass fibres which indicated a breaking stress of 100,000 atmospheres.

Richards was one of the first to recognise the fundamental importance of this aspect of atomic physics, and his experimental data will be invaluable to future workers in the field. He showed remarkable physical insight in his interpretation of atomic properties in terms of the compressible atom : he foresaw the asymmetric distortion of the atom due to chemical combination, which we now call polarisation, and to-day we use the word deformation to denote some of the effects which Richards had in mind. His theory was a prophetic forecast of the future, and perhaps he hardly realised that his ideas, which were not always regarded with favour in 1900, have now become almost axiomatic. He was not entirely sympathetic to the view that explains chemical affinity solely in terms of electronic forces, and this was typical of a certain conservative tendency in him, which showed itself in other ways—in his attitude towards physical methods of determining atomic weights, in his reluctance to adopt electrical methods of thermometry. And it is perhaps one of the essential characteristics of those who are to bring to completion some long scheme of experimental work : certainly Richards and Berzelius possessed it in common.

We come now to the long series of researches in thermochemistry associated with Richards and the Harvard school, which originated in his interest in the energy changes and the changes in heat capacity accompanying chemical action, and their relation to his theory of compressible atoms. The lack of agreement between the existing thermochemical data quickly convinced him of the need for their revision, and a study of the methods used by Marignac, Thomsen, Berthelot and others showed that they lacked the accuracy and precision which were to Richards essential in any measurements of important constants.* He always had a great respect for the work of his predecessors, and he began by a most careful analysis of the possible errors affecting their results and the best methods of avoiding them.

His initial papers all dealt with questions of technique. First came the introduction of the transition temperatures of hydrated salts as new fixed thermometric points to facilitate the standardisation of short-range thermometers without subjecting them to large changes of temperature. The following table shows the systems that were studied at different dates :

System.	Transition temp. on hydrogen scale.	Date.
$Na_2CrO_4,10H_2O-Na_2CrO_4,6H_2O$	19·525°	1911
$Na_2CrO_4,10H_2O-Na_2CrO_4,4H_2O$	19·987°	1911
$Na_2CrO_4,6H_2O-Na_2CrO_4,4H_2O$	25·90°	1911
$Na_2SO_4,10H_2O-Na_2SO_4$	32·383°	1898—1902
$NaBr,2H_2O-NaBr$	50·674°	1906
$MnCl_2,4H_2O-MnCl_2,2H_2O$	58·089°	1907
$SrCl_2,6H_2O-SrCl_2,2H_2O$	61·341°	1918
$SrBr_2,6H_2O-SrBr_2,2H_2O$	88·62°	1918

This was followed in 1905 by work on improved methods of calorimetry with A. B. Lamb, L. J. Henderson, and G. S. Forbes

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* The different values used by different authors for the total heat capacity of a system when calculating the heat of reaction, *e.g.*, the neutralisation of an acid by a base, are an example of the uncertainty of thermochemical measurements at this date. Ostwald and Luther used the sum of the initial capacities, Thomsen often used the capacity of the water alone, Berthelot the heat capacity of an equal volume of water. Richards pointed out that a heat of reaction corresponds to the initial or final temperature according as it is computed from the heat capacities of the resultants or reactants, and that owing to changes in heat capacity during a reaction the method of computation may affect the result considerably.

which led to the introduction of the adiabatic calorimeter, in which the errors due to " the cooling correction " and to thermometer lag are eliminated by surrounding the calorimeter with a jacket, the temperature of which can be kept equal to that of the calorimeter by means of chemical or electrical heating. Calorimeters were constructed embodying this new device, the design of which gave greatly increased accuracy, particularly as regards errors arising from insufficient stirring (which Richards showed to be a constant defect of the older experiments) and from loss of heat by evaporation. With these, a comprehensive study of the thermochemistry of electrolytes was begun with Rowe in 1907, which continued until 1914, although most of the results were not published until 1920—1922.[17] It included the determination of the heats of dilution and the specific heats of solutions of hydrochloric, hydrobromic, hydriodic, and nitric acids and of the chlorides, nitrates, and hydroxides of lithium, sodium, potassium, and cæsium. The specific heats of the more concentrated solutions were found by measuring the rise in temperature of a known quantity of solution caused by the heat given out in the neutralisation of a known quantity of dilute sulphuric acid contained in a platinum vessel submerged in the calorimeter, and comparing it with the rise in temperature of water with precisely the same procedure. The specific heats of the more dilute solutions were found indirectly by means of Kirchhoff's Law (or, as Richards preferred to call it, the Person–Kirchhoff Law, as Person had used it before Kirchhoff) from measurements of the heat of dilution of a solution of known specific heat at two temperatures. The whole research, which involved a vast amount of difficult experimental work, was carried out with the most meticulous accuracy, and it constitutes an invaluable contribution to our thermochemical knowledge. It raised many points of theoretical interest in connexion with the change in heat capacity of the constituents of the solution with dilution, but Richards concluded that while they indicated changes dependent upon the dissociation of the electrolyte, the hydration of ions, and the polymerisation of water, any attempt to explain them would be premature at the moment.

This work was a necessary preliminary to the accurate measurement of the heats of neutralisation of lithium, sodium, and potassium hydroxides with the above-mentioned acids at different dilutions. These values, which are of such great theoretical interest, had already been determined by a number of observers, but their results were not adequate to decide whether the differences between them were due to experimental error or not. Richards and Rowe's results are probably accurate to ± 0·02% and they showed that at the dilutions studied there are definite differences between the heats of neutralisation for each pair of acids and bases, and these differences, although showing some systematic tendencies—the values for potassium hydroxide are greater than for sodium, those for bromides greater than for iodides—also exhibit certain unexplained irregularities. The heats of neutralisation vary with dilution, and by extrapolation from the various series Richards found that the heat of formation of water from its ions at 20° probably lies between 13·69 and 13·62 Calories.

Simultaneously work was in progress on the heats of solution of metals in acids.[18] These are among the most important thermochemical data since the heats of formation of the metallic compounds depend upon them, and owing to the long duration of each experiment the older values were particularly susceptible to errors due to the uncertainty of the cooling correction. The adiabatic method was especially suitable for lengthy determinations of this kind, and by using metals in a fine state of division and dissolving them entirely Richards avoided the errors arising from the withdrawal of the undissolved metal at the conclusion of an experiment. The great difficulties of the investigation were overcome with Richards's usual skill, and very concordant data were obtained for the heats of solution of zinc, aluminium, magnesium, cadmium, and iron.

Another field to be investigated was the thermochemistry of organic compounds. Considerable improvements were effected in the calorimetric bomb in order to secure complete combustion of the compounds under investigation, and the adiabatic method was applied in this case also. Investigations were made of the heats of combustion of the substances proposed for standardising the bomb—sugar, benzoic acid, and naphthalene—and also of a number of isomeric compounds, among them being the octanes and xylenes, to see if accurate thermochemical study would throw light on the differences in their energy content, which were found however to be extremely small.

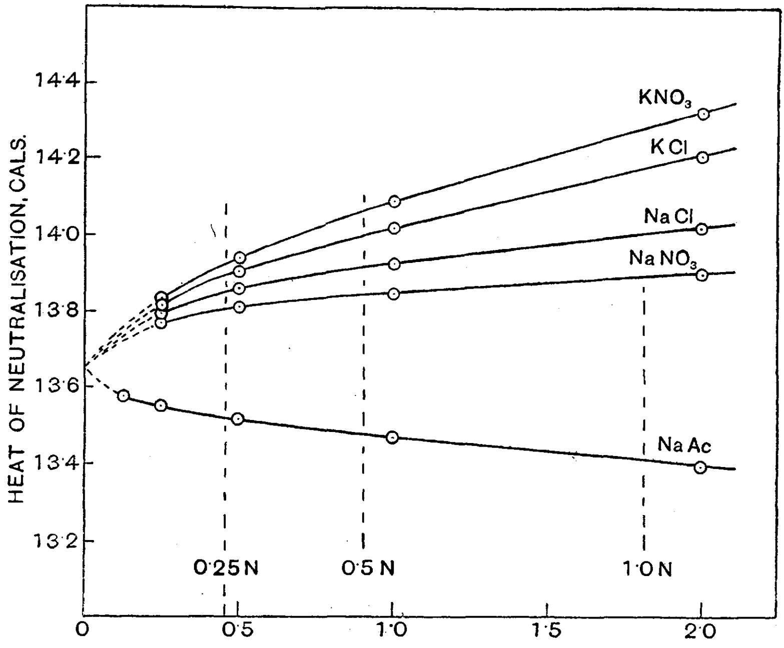
Throughout his pre-war calorimetric work, Richards invariably employed Beckmann thermometers for measuring temperature, and although he recognised certain advantages in electrical thermometry, he clung to the simplicity and directness of his mercury thermometers. In his hands and in those of his co-workers they gave amazingly good results, which are a striking testimony to his skilful experimentation and the accuracy of his calibrations. Only those who have tried to repeat these measurements can really appreciate them. However, after 1922 the study of aqueous solutions was taken up again, using platinum resistance thermometers which increased the thermometric sensitivity ten-fold, and copper–constantan thermocouples or "thermels" for indicating the difference in temperature between the calorimeter and its jacket, thus avoiding the necessity of reading two thermometers simultaneously and facilitating the maintenance of adiabatic conditions. There were also a number of improvements in the design of the calorimeters and in the experimental procedure. For the direct determination of specific heats with Gucker [19] an ingenious modification of the Joule–Pfaundler twin-calorimeter was devised. Two exactly similar calorimeters enclosed in submarine jackets were immersed in a large water-bath, and the difference in temperature of each from the temperature of the bath was measured by a thermel. Similar heating coils were placed in each calorimeter and the same current was sent through both, hence if the liquid in each calorimeter had the same heat capacity the rate of rise in temperature would be the same in both. Many errors were avoided by using one calorimeter as a tare and always placing in it the same volume of water, while in the other water and solution were alternately introduced in such quantities that the rise in temperature was the same in both cases as in the tare : with minor corrections, their heat capacities were therefore inversely proportional to their masses.

A repetition of some of the earlier experiments on specific heats by Richards and Rowe confirmed these very closely, except in the case of sodium hydroxide, the value of which was dependent on the work of earlier observers. This discrepancy was disquieting as it affected the values for the heats of neutralisation and a further investigation with L. P. Hall confirmed the high value found by Gucker, and incidentally the value of the specific heat of $KOH + 100H_2O$ was found directly to be 0·9567, while Richards and Rowe had found 0·9568 directly and 0·9567 indirectly ten years previously, so that the accuracy of the earlier work was upheld. A further study of the heats of dilution of sodium hydroxide made possible the recalculation of the values for the heats of neutralisation of sodium hydroxide. The value of the heat of formation of water from its ions was finally fixed as 13·65 Cals. by determining the heat of neutralisation of acetic acid by sodium hydroxide which decreases with concentration, while those of strong acids increase, so that the value found from the joint extrapolation shown in Fig. 4 is much more accurate.

Richards published over sixty thermochemical papers dealing with many subjects in addition to those already mentioned, such as the latent heat of evaporation of water, and the heats of dilution of amalgams and the heats of solution of metals in mercury, which had a special interest in connexion with his long series of researches on the electromotive force of amalgam cells. It is impossible in a brief summary to do justice to the value of his work in this most exacting field. He was the pioneer of modern precision calorimetry and for thirty years he sought continuously to increase the accuracy of experimental methods, and the exactness with which thermochemical data are defined.

The remaining field of Richards's investigations was electrochemistry, in which his interests centred on Faraday's laws of electrolysis, and the accuracy of the voltameter, or as he preferred to call it the coulometer, and on the study of electromotive forces, particularly of amalgam cells. In determining the atomic weight of copper he had compared the amounts of silver and of copper deposited by the same current and a difference between the value obtained in this way and by various chemical methods led him to investigate the accuracy of the copper and silver coulometers. When he had traced the main source of the discrepancy to the solution of copper in copper sulphate to form a cuprous ion, he turned his attention to the deposition of silver and with Collins and Heimrod he devised a very simple and accurate silver coulometer which has been much used in exact investigations. Its main feature was a porous pot surrounding the silver anode to prevent the anode solution and sludge from reaching the cathode.

Fig. 4.



Mols. of acid per 100 *mols. of water.*

In 1902 he carried out an investigation with Stull[20] to test Faraday's law over a wide range of temperatures and solvents by comparing the amounts of silver deposited from an aqueous solution of silver nitrate at 25° and from silver nitrate dissolved in a mixture of fused potassium and sodium nitrates at 250°. The weight of the deposits agreed to one part in 20,000 parts, thus showing "that Faraday's Law is not a mere approximation, but is rather to be ranked among the most precise and general of the laws of nature."

Amalgams had been a favourite subject with Richards ever since he was at Leipzig. He saw in them great possibilities since they are solutions free from the complications arising from electrolytic dissociation, and yet admitting of a much more varied investigation than other solutions of non-electrolytes. He hoped to get from them knowledge of the general theory of solutions which was inaccessible in other ways. His investigations of the electromotive forces of amalgam concentration cells, and of their thermochemistry and other properties extended over thirty years: no doubt the accuracy with which the electromotive forces could be measured made a special appeal to him. The study of zinc and cadmium amalgams, begun with G. N. Lewis in 1897, was continued with G. S. Forbes, and the accuracy of the measurements was greatly increased, the electromotive forces being measured to 10^{-5} volt. The heat of dilution of the amalgams was found directly and compared with that calculated from the Gibbs–Helmholtz equation. In 1905 came the study of thallium, indium, tin, zinc, cadmium, lead, copper, and lithium amalgams with Hunt Wilson and Garrod Thomas, an accuracy of 10^{-6} volt being obtained.[21] Thallium amalgams received special attention on account of the large solubility of thallium in mercury, and a most detailed thermochemical investigation was made with Daniels and with Smyth. Sodium amalgams were studied with Conant and cadmium with Frevert and Teeter. All these researches showed that amalgams were far from possessing the properties of ideal solutions. At great dilutions the electromotive force of a concentration cell can be calculated from the simple formula

$$E = RT/nF . \log_e C_1/C_2$$

but the values diverge rapidly with increasing concentration, those for sodium, thallium, indium, and cadmium being too great, and for zinc, lead, and tin too small. These results together with the heats of dilution make it clear that considerable affinities exist between the mercury and metallic atoms, probably hydrargyration and association both being concerned. Richards's work is a most valuable contribution to our knowledge of amalgams; many new and useful facts were established, but it left the puzzling nature of these systems still an unsolved problem.

The impelling forces of Richards's life were his desire to win a deeper understanding of Nature's secrets and his belief that such understanding would come from a more exact knowledge of her fundamental constants and laws. All his efforts were centred on the determination of these constants—atomic weights, compressibilities, surface tensions, densities, energy changes, thermochemical data—and the testing of accepted generalisations such as Faraday's laws and the constancy of atomic weight. He was always seeking discrepancies which might suggest some lack of uniformity, some unsuspected irregularity, " some crack," as he said, " into which you could drive a wedge so as to go deeper into things, and approach nearer to the truth." It is remarkable how few among his many papers were unproductive of results of lasting value, and how little effort was expended on data of use only for proving or disproving some ephemeral hypothesis. His work constitutes a coherent attack on the constants of nature, and he would return again and again to some measurement to check his earlier results and make their value more secure by some new refinement.

Richards was first and foremost an experimentalist. He had very remarkable hands that could do many things well, an exact co-ordination of hand and eye, and the artist's joy in perfection of accomplishment. And to these were joined " an infinite capacity for taking pains, an uncompromising attitude towards the possibilities of hidden errors, a determination to be certain that no precaution had been overlooked, and an extraordinary persistence in the patient repetition of exacting and laborious experiments." When planning a research every detail of the measurements was subjected to a most careful scrutiny, almost every contingency was foreseen, and as a result Richards's investigations proceeded with unusual smoothness. His methods were never unnecessarily elaborate, he disliked complicated apparatus and preferred to get a result if possible by simple means. In the choice of method and the design of apparatus he showed remarkable physical intuition and mechanical ingenuity, and he was equally gifted as regards the pure chemistry of his investigations. Like Berzelius he had a wonderful instinct for choosing the right substance and method for his purpose, and his wide knowledge and his discerning mind seldom failed to overcome the many chemical problems which his work presented. No chemist had ever taken such care that his materials should be as pure as possible, or had subjected his methods of purification to such rigid examination, and this gives to all his results an additional assurance of validity. His simple ways of overcoming difficulties—

the bottling apparatus, the nephelometer, the use of two resistance boxes as a potentiometer, his method of standardising weights, the use of the centrifuge for separating the mother-liquor in recrystallisations—have all become common practice in other laboratories, and it is impossible to over-estimate the saving of time and the increase in accuracy that have resulted from their adoption.

But despite his experimental skill, when one looks back at Richards's massive contribution to chemical science—nearly three hundred communications, many of them involving many months of labour—the question inevitably arises, How was it possible for one man to accomplish so much ? The answer is that Richards was by nature and temperament a great teacher and a leader, with the keenest personal interest in the young men around him and the gift of imparting to them his own enthusiasm and his own standard of attainment.

Richards's teaching experience began as an assistant when he was a graduate student. From 1889 to 1902 he taught quantitative analysis at Harvard. He was a most conscientious teacher and demanded of his students the utmost accuracy both in experiment and in thinking. He was one of the first to insist on the importance of understanding the principles underlying quantitative work, at a time when the new theories were beginning to throw light on the empirical system of quantitative analysis. In 1895 he began to give the lectures on physical chemistry with which he was associated until his death. As the advanced course was taken mainly by graduate students, Richards gave in addition the elementary course in order to keep in touch with the undergraduates. He realised the stimulus which a teacher can receive from presenting to competent but immature students the elements of a great subject. He enjoyed tracing the history of the main principles of his science and the successive discoveries on which they depended, and to the very end he clung with interest and pride to his course on " Elementary, Theoretical, and Physical Chemistry, including the Historical Development of Chemical Theory."

Richards was an admirable lecturer with an exceptionally clear and pleasant voice that compelled attention. His simple logical way of presenting a subject seemed to rob it of its difficulties, and many a student owed to him his first real insight into the principles of chemistry. They learnt from him too the thrill of discovery, and his vividly sketched picture of the unsolved problems was to them " a challenge to join the ranks." Richards knew how to get the best out of young men. They felt his interest in them, and his innate kindness, which often took a practical form. They went to him with their troubles, they did their best to live up to his standards, and when he went round the laboratory a look of disappointment from him was more effective than anger or sarcasm. But with all his kindness Richards was a shrewd judge of men and of their work, and quick to detect any lapse from that uncompromising integrity which he looked for in an investigator. Anyone who tried to bluff him quickly became aware of a sterner side to his character.

Richards was a most meticulous and inspiring director of research. He usually spent some time every day with each of his students, seeing the progress of their work, insisting upon the utmost purity of the substances they used, and if their results were not reproducible he would spare no pains to ascertain the source of trouble. Even the most persistent difficulties yielded to his skilful diagnosis, including the almost supernatural vagaries of a delicate galvanometer which he traced to the movements of a man in an adjoining room with a large bunch of keys in his pocket.

As years went by, more and more graduate students came to him and their supervision left less and less time for his own experiments, so that in the last twenty years he did little with his own hands. But he had the most remarkable gift for devising methods that his students could carry out almost as well as he could himself. In this he differed from some of the great experimenters, whose success has depended on their individual technique and who left no school to follow them. Richards's skill was no less than theirs, but his methods made accuracy as far as possible independent of the human element. Under his leadership his laboratory became one of the most active centres of research, with a wide range of investigations in progress all controlled by his well-ordered mind, and picked students came eagerly from many countries to learn the methods of exact experiment that will always be associated with the Harvard school. I was fortunate enough to spend a fortnight in that stimulating atmosphere in 1902, and even that short time was enough to give me a fresh impulse and a new standard of precision, which I like to think have not been altogether without effect. I always look back with gratitude to Richards's kindness to an unknown beginner and to the encouragement and help that came in each of his letters.

From Richards's laboratory went out a constant stream of men trained in his methods and imbued with his ideals, and there is no better tribute to his memory than the list of his pupils who are now handing on the traditions of the Harvard school in many countries and in many fields of research :—Gregory Baxter at Harvard and Otto Hönigschmid at Munich, the two leaders to-day in atomic weight research in the new world and the old, G. N. Lewis in California, E. H. Archibald in Vancouver, R. C. Wells in Washington,

A. B. Lamb, L. J. Henderson, G. S. Forbes, and Grinnell Jones at Harvard, Arthur Staehler at Berlin, J. Howard Mathews and Farrington Daniels at Wisconsin, H. H. Willard at Michigan, Frederick Barry at Columbia, H. Krepelka at Prague, J. B. Conant and Norris Hall at Harvard, and lastly his son, William T. Richards, at Princeton.

In 1896 Richards married Miss Miriam Stuart Thayer, daughter of Professor Thayer of the Harvard Divinity School. In her he found a wife who sympathised wholeheartedly with his devotion to research, and she did all in her power to help and encourage his work. Of their three children, the eldest, Grace Thayer, is the wife of Professor James B. Conant of Harvard, William Theodore inherited his father's scientific tastes and is Assistant Professor of Chemistry at Princeton, and the youngest, Greenough Thayer, is a student of architecture.

The current of Richards's life after his marriage ran smoothly and tranquilly and there are few events to chronicle except his journeys to Europe and the many honours that came to him. In 1907 he spent six months in Berlin as Exchange Professor, where he was the guest of Emil Fischer. He gave a course of lectures on the theory and practice of accurate physico-chemical measurements and carried out a number of investigations with graduate students. In his inaugural lecture he discussed the relations of imagination and experiment in scientific progress. The subject gave ample scope to his breadth of outlook and his wide reading and it was a most polished and suggestive discourse. On the occasion of his lecture on atomic weights to the German Chemical Society the President, Graebe, spoke of the effect of his work on Europe : " The light which formerly radiated from Europe to America is now brilliantly reflected back again."

In 1908 he gave the Lowell Lectures, in 1910 he received the Davy Medal of the Royal Society, followed in 1911 by the award of the Faraday Medal, the greatest honour our Society can bestow. He came to England with his family to give the Faraday Lecture in June of that year on " The Fundamental Properties of the Elements," [22] and the recollection of the charm of that lecture, its modesty, its simplicity, its clearness, and its optimism are still fresh in the minds of many of us. It was most appropriate that on that occasion the vote of thanks to Richards was proposed by Odling, the only survivor of the conference on atomic weights held at Karlsruhe in 1860, when some of the views expressed about atomic weights were so vague that Odling won approval by his vigorous insistence on the fact that an element could only have one atomic weight. Richards was particularly pleased, too, with Professor H. B. Dixon's happy allusion to him as having fulfilled Canning's prophecy : " I look to the new world to redress the balance of the old."

The summer was spent in England revisiting his old haunts, seeing old friends and making many new ones, and he returned to America with honorary degrees from Oxford, Cambridge, and Manchester. In 1912 he received the Willard Gibbs Medal, in 1914 he was President of the American Chemical Society and in November 1915 came the news of the greatest honour of his career, the award of the Nobel Prize in Chemistry. The voyage across the Atlantic was attended with special dangers in 1916 so the Nobel lecture was postponed to more peaceful times. In 1922 he set out with his two sons to Sweden to deliver it, but the critical illness of his elder boy kept him in Paris throughout the summer, when he received the Le Blanc and Lavoisier Medals. In 1925 Richards had the unusual honour paid him of the foundation at Harvard of a Professorship in Chemistry named after him by Thomas W. Lamont in memory of his brother Hammond Lamont, who had been Richards's class-mate and close friend.

During his last years much time was spent in putting the theory of compressible atoms into a mathematical form, and he made good progress in the analysis of Bridgman's results. A number of papers were written giving a comprehensive account of his views. But experimental work never ceased : the Wolcott Gibbs laboratory was full of keen graduate students and the quality of his researches was as fine as ever. Notable among them were determinations of the atomic weights of gallium, cæsium, and various uranium leads. The final group of papers on thermochemistry published posthumously was a fitting conclusion to his labours on account both of their perfection of technique and of their confirmation of his earlier work. In 1927 his mind was as active and clear as ever but his physical strength was beginning to weaken. On March 9th, 1928, he gave his final lecture, three days later he left his laboratory for the last time, and he died on April 2nd at the age of sixty.

" I want to go down with my colours flying," he said in those last weeks, and his wish was granted.

To his English colleagues Richards's death came as a sad loss. For many years he had been such a link between the chemists of the two countries, and we here appreciated to the full his distinction and his many lovable qualities—his perfect modesty and simplicity, his courtesy, his kindness and unselfishness, his good company and his humour, and his affection for his friends. But for the intimate details of his personality I will quote two tributes from his Harvard colleagues with whom his life was passed.

" The distinguished and characteristic precision of Richards' experimental work was not merely dictated by the need of accuracy for the sake of trustworthy scientific results; it was inspired by his inner honesty and by his joy in perfect workmanship. The man's noble ideal of character and the artist in him conspired to bring to full fruition his vigorous and broadly developed mind. Of singular modesty and devoted to his very happy home, his friendliness and charm made his society highly prized, and he moved in a large circle, admired and beloved. His friendships ran through many countries, and his varied interests brought him into contact with a wide range of people. His colleagues recall with deep gratitude the unstinted help he knew how to give and his peculiar gift of instilling new courage at critical moments of baffling difficulty. His strength, never robust, was for years scrupulously conserved for his work, and he often longed for a greater physical power to carry into execution the plans of investigation which thronged his mind.

" Capable of strong feeling and strict judgment, he described the guiding principles of his life as ' kindliness and common-sense '; we may add that these modest qualities were served by genius. The moral conditions of successful scientific work—' the overwhelming importance,' as he put it, ' of perfect sincerity and truth ' —were never absent from his mind, and of them he was himself, in all ways, the very embodiment. Modest, lovable, competent in business, interested in games, possessing a trained knowledge of music and a critical appreciation of art, patient with obstacles, unsparing in painstaking labor, he gave himself to his carefully ordered tasks with joy of life and work and thought." [23]

Professor Baxter writes of him : " Genial and social in his inclinations and with a whimsical sense of humour, Richards was a welcome addition to any gathering, for his interests included practically every form of human activity, especially art and music. His artistic inheritance might well have been developed as his vocation. As a youngster he planned to follow in his father's footsteps, and always obtained enjoyment from exercising his ability to sketch and paint. One of the most interesting sights in the Gibbs Laboratory was a marine picture which was the joint production of father and son. He was particularly warm-hearted and generous towards his friends. No trouble was too much for him to take in their interests and no pleasure greater than his at their success. To me the thirty-five years of close association with Richards as his pupil, colleague, and friend will always be one of the greatest privileges of my life."

" Although never an athlete in a strict sense, he was fond of various outdoor sports. He was especially interested in yachting, and for many years as a young man spent a portion of his summers on his cruising yawl. At one time he was a good tennis player and was one of the earlier devotees of golf in America. The latter pastime he never gave up."

"It would be hard to decide which was the greater, his devotion to his family, to the University or to science, but it is certain that no one could have been more forgetful of self in the interest of any one of them. His creed with relation to the last one of the three has been left in his own words, and is typical of his desire to give faithful service :

"'First and foremost I should emphasise the overwhelming importance of perfect sincerity and truth; one must purge oneself of the very human tendency to look only at the favourable aspects of his work, and be ever on the look-out for self-deception (which may be quite unintentional). Next, one should never be content with a conventional experimental method or scientific point of view; one should be open-minded as to the possibility that the procedure or hypothesis may be incomplete. Each step should be questioned, and each possibility of improvement realised. And then, patience, patience! Only by unremitting, persistent labor can a lasting outcome be reached.'"

Berzelius, when asked to choose an inscription for a medal to be struck in his honour, chose a balance and the words *pondere et numero:* Richards had the Harvard crest and the single word *veritas* carved over the door of his laboratory. What more fitting epitaph than these three words for one whose life was spent in the quest of truth through the measurement of Nature's forces?

ex pondere et numero veritas.

Bibliography.

[1] Cooke and Richards, *Amer. Chem. J.*, 1888, **10**, 81.
[2] Richards, *Chem. News*, 1892, **65**, 236, 244, 260, 265, 281, 293, 302.
[3] Richards, *ibid.*, 1895, **72**, 18, 29, 41, 54, 72.
[4] Richards and Wells, *Amer. Chem. J.*, 1904, **31**, 235.
[5] Richards and Wells, *Z. physikal. Chem.*, 1906, **56**, 348.
[6] Richards and Wells, *J. Amer. Chem. Soc.*, 1905, **27**, 459.
[7] Richards and Forbes, *ibid.*, 1907, **29**, 808.
[8] Richards, Köthner, and Tiede, *ibid.*, 1909, **31**, 6.
[9] Richards and Willard, *ibid.*, 1910, **32**, 4.
[10] Hönigschmid and Sachtleben, *Z. anorg. Chem.*, 1929, **178**, 1.
[11] Richards and Lembert, *J. Amer. Chem. Soc.*, 1914, **36**, 1329.
[12] Richards and Françon, *ibid.*, 1928, **50**, 2162.
[13] Richards and Hall, *ibid.*, 1926, **48**, 704.
[14] Richards, *Carnegie Inst. Washington, Pub.*, 1910, **125**, 95.
[15] Richards, *Z. physikal. Chem.*, 1902, **40**, 169, 597; **42**, 129; 1904, **49**, 15.
[16] Richards and Stull, *J. Amer. Chem. Soc.*, 1904, **26**, 399.
[17] Richards and Rowe, *ibid.*, 1921, **43**, 770; 1922, **44**, 684.

[18] Richards and Thorvaldson, *J. Amer. Chem. Soc.*, 1922, **44**, 1081.

[19] Richards and Gucker, *ibid.*, 1925, **47**, 1876.

[20] Richards and Stull, *Z. physikal. Chem.*, 1903, **42**, 621.

[21] Richards and Wilson; Richards and Garrod-Thomas, *Z. physikal. Chem.* 1910, **72**, 129, 165.

[22] Richards (Faraday Lecture), J., 1911, **99**, 1201.

[23] C. P. Baxter, J. H. Ropes, and T. Lyman, *Harvard University Gazette*, Nov. 1928.