OBITUARY NOTICE.

WILLIAM ARTHUR BONE.*

1871—1938

WILLIAM ARTHUR BONE, the distinguished fuel technologist and chemist, was essentially a product of heredity and environment. His character, work, politics, friendships and religion were all in the nature of loyalties to his ancestry and upbringing and indissolubly intertwined, so that his evolution as a man and as a scientist bears the aspect of inevitability.

By birth and upbringing, Bone was a north countryman and inherited the pride of his race. He was born at Stockton-on-Tees in 1871, the eldest child of Christopher and Mary Elizabeth Bone, both of whom appear to have handed on to their son a goodly heritage. Christopher Bone was a tea merchant and a prominent citizen of the town, taking an active part in its social and political welfare, and being generally respected for his forcefulness, sincerity, fearlessness and independence of thought, speech, and action. He was public-spirited to a degree, a born fighter for what he considered right and just, who, despite a magnificent physique, overtaxed his strength and died early. Mary Elizabeth Bone, to whom indirectly, as will presently be seen, William Arthur owed his choice of career, was of an equally lively intelligence and nature and shared her husband's interests. Both were ardent Liberals and whole-hearted Wesleyans. We can trace nothing negative in their mental make-up. Looking still further back into the family history to the respective parents of Christopher and Mary Elizabeth, one finds the same reality of outlook and lively interest in and feeling for life. It was this characteristic of positiveness that, handed down in generous measure to their grandson, was the dominating contribution to his greatness. In an age when mental and moral structure is rarely uncorroded by fear in one or other of its many manifestations, the positive personality must make enemies. In compensation therefor, however, the friends he attracts are unusually staunch and true, and respect is almost universal. Bone had firm friends in all classes and walks of life; indeed, his avoidance of class distinctions amounted almost to genius. Amongst his opponents, scientific and otherwise, he paradoxically numbered many friends, and there were few who did not admire the courage of his convictions. Thus he took an active part in the local St. Albans politics against Sir Francis Freemantle. To an expression of regret at the death of one of his chief constituents and opponents, Sir Francis added that he had learnt greatly to respect Bone's criticism and views.

Bone was educated at Middlesbrough High School, then at the Quakers' School at Ackworth, where the headmaster, one Frederick Andrews, became, according to Bone himself, one of the abiding influences of his early school days. From Ackworth he went to Stockton High School, which was fortunate enough to possess as science master a man of outstanding personality, " a genius in his power of realistic description," to quote Bone's own words. To the inspiration of this teacher the pupil avowedly owed a deep debt of gratitude. It should be mentioned here that Bone had early decided upon a scientific career. This was in the maternal tradition, for his mother's brother, the late T. C. Hutchinson, was manager and part owner of the Skinningrove Iron Works, and amongst the blast furnaces young Bone was wont to spend most of his spare time. Leaving Stockton High School, he passed a year at the Leys School, Cambridge, proceeding as a student to Manchester University, where the two outstanding personal influences were Theodore Nield and H. B. Dixon.

During all these early years Bone had the inestimable advantage of a very happy home life and understanding parents for whom he entertained the greatest affection. He was healthy and robust and took an active part in school and college games and sports. In addition he was fond of music and joined in amateur operatics. He played both organ and piano and attended concerts in Manchester. He liked the theatre, debating societies, and politics, and was genuinely interested in religious questions. The family traits had appeared in full force. All the essentials were already there. Time, the power to recognize opportunity and the courage to seize it with both hands, were all that were needed to effect the expansion to a rare breadth and completeness of character and achievement

The thoughts and activities of a dominant personality are rarely incongruous. Bone's career as a scientist and citizen, therefore, pursues a direct logical course. In 1892, having won a scholarship, he left Manchester and studied for a year in Heidelberg; a fruitful interlude which gave him a command of German, whetted an inherent taste for travel, and broadened his scientific outlook. On his return, he became officially engaged to and later married Miss Kate Hind, the daughter of a prominent citizen, twice mayor of Stockton. This was another manifestation of his incontrovertible loyalty to his breed; he had known Kate Hind as a boy and had very early marked her down as his future wife. The two families shared very much the same outlook and had the same social background. It follows that Mrs. Bone was broad-minded and intelligent, musical and artistic, hospitable and domesticated. Though untrained, she was greatly interested in his scientific work and shared his love of entertaining his scientific friends and students. After the marriage Bone left Manchester to join the staff of the Battersea Polytechnic, but London did not agree with Mrs. Bone's health, and he himself hankered after broader spheres. 1898 saw him once more in Manchester in the laboratory of H. B. Dixon.

* Reprinted by permission from *Obituary Notices of the Royal Society of London*, No. 7, Vol. 2.

Followed several very busy years. The arrival of three children, first a daughter, then a son, and then another daughter, was a compelling incentive to extra endeavour in his work, for though his general tastes were simple, he regarded really adequate holidays as a necessity rather than an extravagance and considered them well worth the additional hours put into correcting examination papers. His clan complex appears to have been very definitely developed for, not content with having his own immediate family with him on the long annual summer vacation, he would take also his mother, his sisters-in-law, and his aunts. Later, his friends and acquaintances and students would share his time and hospitality at what was almost his second home. In the old manor farmhouse at Burnsall he would entertain his guests, introducing them to one of his dearest delights, the joy of long walks amid the beauties of his beloved Yorkshire dales.

In 1905 he was appointed first Livesey Professor at the University of Leeds. From this period date many of his most important researches, the fame of which took him to America on a highly successful lecture tour. In this connexion fate played him two of her contradictory tricks. Berths had been booked for him and a companion on the " Titanic." At the last moment the companion fell ill and the passages were cancelled. Bone used to tell of the complexity of his feelings when, over a cup of tea in a café in Leeds, he heard the newsboys cry out the news of the disaster to the ill-fated ship. Fate saved him from this catastrophe, however, almost to overwhelm him in another. The postponed lecture tour successfully accomplished, he was taken ill on the return voyage with ptomaine poisoning and all but died.

1912 saw his next and last move back to London. It was then that I first met him at an interview for the post of demonstrator. I was appointed and told to report for duty at 10 a.m. a month hence. I duly arrived, but knocked in vain at the door of Bone's room. I knew no one in the Imperial College, except a fellow student from Zürich and M. O. Forster. I called on them and returned at 11 a.m. Still no reply, so I set off to explore the Royal College of Science. Noon saw me once more approaching Bone's door which suddenly opened, disclosing the great man himself. Seeing me, he demanded, " And who may you be ? "—only his actual words were rather more forceful ! My explanation drew forth the angry challenge, " Didn't I tell you to be here at 10 o'clock ? " On my riposting that I had been there not only at 10 but also at 11, and now at 12 o'clock did not like the peculiar warmth of his welcome, he laughed in high good humour, led me into his room and soothed my rather ruffled feelings completely by saying " Thank heaven for somebody who will speak up for himself." All who knew Bone will recognize that this episode is completely in character. It began for me a lifelong friendship which not only stood the strain, but was indeed strengthened by many similar sword-crossings.

At the Imperial College, Bone had the most magnificent opportunity of his scientific career. To create something new is the born artist's real desire whether he be poet, painter, musician, or scientist, and into the creation of a new department of fuel technology at the Imperial College, South Kensington, Bone threw himself with whole-hearted vigour. Whither his urge for self-expression bore him the years have amply shown. Under his inspired leadership rose a research school of world-wide renown.

Meanwhile, the family decided to settle at St. Albans. His wife's health suffered in London, and the children's education had to be considered; in both these respects St. Albans filled the bill. Two short years afterwards, however, tragedy struck. While on holiday at Burnsall, his wife died after an operation. Broken down by his personal calamity, another calamity saved him. It was the summer of 1914. The declaration of the world war troubled him exceedingly for Bone was a pacifist. The ensuing mental conflict proved salutary, but even more so was his characteristic allegiance to the family. On the outbreak of war, his only brother chanced to be on a visit to Germany and was forthwith interned. Bone was left with the responsibility of looking after the prisoner's affairs and thus forced to occupy his mind with troubles other than his own. During 1914—18 he carried out various investigations and researches in chemical and fuel problems connected with the war, and also trained skilled chemists for munition factories and the like, but loyalty to his own ideals prevented him, it is said, from carrying out suggested investigations on the use of poison gases.

In 1916, Bone married Miss Mabel Isobel Liddeard, a clever and charming woman who was of great assistance to him in his work. She died in 1922. This second blow to his family happiness threw him back even more closely upon his work which he proceeded to attack with redoubled vigour. His department grew rapidly and flourished and, on his retirement in 1936, he had the pride and satisfaction of knowing that he had in turn passed on to others a worthy heritage.

Such is the bare outline of Bone's life and career. Two characteristics stand out crystal clear—his vigour and breadth. His scientific work echoes these two traits. The field he ploughed and furrowed, sowed and reaped was unusually wide.

Much of what Boswell said of Johnson is peculiarly applicable to Bone : " Man is in general made up of contradictory qualities. . . . In proportion to the native vigour of the mind the contradictory qualities will be the more prominent. . . . At different times he seemed a different man in some respects ; not, however, in any great or essential article upon which he had fully employed his mind and settled principles of duty." The defects of Bone's qualities were often apparent and to lesser natures perhaps seemed to submerge them. He was self-willed and at times " irritable in his temper," but the Johnsonian parallel still holds good for " he was of a most humane and benevolent heart which showed itself not only in a most liberal charity but in a thousand instances of active benevolence." His religious outlook was modern. Brought up as a Wesleyan and coming early under Quaker influence, he retained an interest in both churches to the end. He professed no dogmatic or sectarian faith, however, but was satisfied to avow an undenominational and non-ecclesiastical

Christianity such as he believed to be expounded in the " Pilgrim's Progress "—a book on which he was an acknowledged authority and which he believed capable of a very liberal interpretation. His knowledge of the Bible astonished even those whose chief business is its study. He had a great respect for serious religious opinion of any creed, but could not and would not tolerate cant or hypocrisy or any form of religious persecution. His was the true religion of visiting the fatherless and the widow and had its expression in his many charitable works. He was an active member of the General Committee of the National Children's Homes and Orphanages and a generous donor to its funds. His sympathy for those in trouble inside and outside his own circle of relatives was practical, and he was always ready to obtain relief for scientific workers in distress. In dealing with such cases he took endless trouble to find help. Lonely people, especially old ladies and students from abroad who were friendless, won his ready sympathy and were warmly received into the family fold.

After the war, most of Bone's holidays were spent in travelling abroad or cruising. The homely enduring delights of Burnsall did not check the desire to see other places or blind him to the more flamboyant beauties of scenery on a grander scale. He holidayed in Canada and the West Indies, Palestine and the Mediterranean countries, Switzerland and Scandinavia, and went forth on all his journeyings mentally well prepared; for he was an inveterate reader and had " accumulated a vast and various collection of learning and knowledge which was so arranged in his mind as to be ever in readiness to be brought forth " and had a " certain continual power of seizing the useful substance of all that he knew and exhibiting it in a clear and forcible manner so that knowledge which we often see to be no better than lumber in men of dull understanding was, in him, true, evident and actual wisdom." His reading covered archaeology, geology, economics, history, and, strangely enough, he was an ardent student of military history. This predeliction, in complete contradiction with his views as a pacifist, was always a source of amusement to his children. He never missed a battleground in his travels with them, and one can see them listening, tongue in cheek, as their peace-loving father expounded with obvious glee and in great detail all the history of the campaign and the plan of battle. In retrospect, knowing how much he enjoyed a mental fight, the pacificism and not the military history seems the incongruity. He hated ecclesiastical show, pomp and ritual, but loved old churches and cathedrals and, like the ordinary sightseer, took them all in his stride. This was probably no real contradiction in tastes, but a staightforward inheritance from his maternal grandfather who was a great lover and collector of the old and beautiful, especially furniture, china and glass, all of which things are part of the treasure trove of historical and ancient churches.

One last link with Boswell who writes this of Johnson : " Though even awful of deportment, he possessed uncommon and peculiar powers of wit and humour." It is undeniable that Bone possessed the rare and godlike gift of inspiring " awe "—for Boswell uses the word in its true sense. It is also undeniable that Bone had a rare sense of humour. It illuminated the man, compensated for his sterner and less lovable qualities, and made of hours passed at his own fireside a vividly remembered joy. His fund of stories was inexhaustible, and he was a born narrator. In the North Country tradition, his stories were often told against himself. His native wit would out, even to his own disadvantage. On the occasion of being interviewed for a post, the interviewer was hostile, an attitude Bone was quick to sense. Questions became more and more personal until at last came, " What is your religion? " Swift and terse came the reply, " I'm damned if I know." The fact that this was probably true enhances rathers than detracts from the story, as the best humour always carries the sting of truth.

Something has been said in passing of his interest in politics. Another lasting interest should be mentioned. Bone was a keen cricketer. When he could no longer take part in the game himself, he was assiduous in his attendance at playing fields. During his last illness the Test Match was being fought. Only a few hours before he died, he was eagerly asking about individual players and how they stood in the game. He was very loyal to his interests and loves.

Looking back, perhaps the greatness of Bone's character was best shown by the way he faced his last eighteen months of illness. Whatever he felt inwardly, he never let any of his family see the slightest trace of fear or pessimism before each of his major operations. He always emphasized the most optimistic views of his medical advisers, although his critical mind would never have allowed him to do this with any other subject. It was a feat of mental control of which very few would be capable.

G. I. Finch.

Scientific Activities.

Bone's scientific work had a singleness of purpose which makes it easy to view it as a whole. From the moment when his training was such as to enable him to become an investigator, till the time of his death, the whole of his energy was applied to investigate fuels and their combustion. He intended to be a master of his subject and he became one. Reviewing the work as a whole, and realizing that it was no doubt technical applications which supplied the impetus to it from his earliest years, a remarkable feature is that these applications did not in any way warp the plan of his work which was purely scientific; the other marked feature throughout was its thoroughness. There was nothing slipshod; infinite pains were taken. Thus the work sometimes appears ponderous, but is always marked by something new and something interesting. The pains he took were well rewarded in discovery. Practically all Bone's work was carried out along with collaborators, and they no doubt experienced his exaction, but all would agree that the training which his horror of slipshod work and the singleness of his purpose provided, was an invaluable experience.

Bone gave a summary of his work in a lecture before the Society of Chemical Industry at the time of his reception of the Medal of that Society in 1933, and the following quotations show the influences which started him on his career :

" I have selected ' Forty Years of Combustion Research ' as my theme, because of all chemical subjects, not only does it lie nearest my heart, but it raises issues of profoundest general interest to philosophers and technologists alike."

" Born and bred as I was on Teeside, amid the roar and smoke of iron-smelting, steel-furnaces, rolling mills, engineering works, and shipyards, where thousands of tons of coal were daily swallowed up and the night sky reddened with the blaze thereof, from childhood upwards I have ever been a fire-worshipper, and the older I grow the more fervent do I become."

" When, 45 years ago, I entered Owens College, Manchester, for a training in chemistry and physics, with the intention of subsequently joining the then new enterprise of my uncle, the late T. C. Hutchinson, at the Skinningrove Ironworks, I came under the magnetic influence of the late Prof. H. B. Dixon, and was thereby soon diverted from my original path into that of scientific investigation, without, however, losing my industrial interests. Hence I have been enabled to envisage combustion from both points of view."

H. B. Dixon unfolded in his lectures at Owens College, Manchester, the state of combustion chemistry as it then stood. When Bone went there in October 1888 it fired, as he said, " my imagination and threw the prospect of iron and steel making quite out of my mind." After graduating three years later, together with his friend and fellow student, Bevan Lean, he begged to be enrolled as one of Dixon's research students, and his first paper was published in 1892 along with Lean, and was entitled : " The Behaviour of Ethylene on Explosion with less than its Volume of Oxygen." Dixon suggested the investigation. Dalton, Kerston and others had found that ethylene burnt with its own volume of oxygen only produced carbon monoxide and hydrogen. It had been thought that in the combustion of a hydrocarbon the hydrogen was burnt preferentially, but Dalton's much-neglected experiments were against such a view. Lean and Bone's work confirmed these older observations and they further found that when the amount of oxygen was reduced small quantities of methane and acetylene were also formed.

The following paragraph from the same lecture, read in the light of the whole of Bone's work, shows how much Dixon's teaching influenced him :

" It was a rigorous school of research to which we were admitted, and its discipline was such as only strong minds could stand. As I have already said elsewhere, Dixon's singularly clear and penetrative mind referred everything to the final test of a well-ordered experiment, critically carried out without hurry or bias, and with the results checked at every point. He impressed upon all the paramount importance of accuracy and truth, together with the highest standard of experimental work. His method was to advance an experimental proof step by step, by a process of exclusion, until it had been narrowed down to a single issue, which finally had to be tested in every way. We were taught also to criticise our results, to eschew all rash speculation, and to limit ourselves to such explanations as were proven or provable."

The following scheme, summarizing the subjects of Bone's researches and the dates of publication, provides a key to the development of his work :

	Period of publication.		
	Early.	Middle.	Late.
Organic chemistry	1893—1904	—	—
Union of carbon and hydrogen	1896—1901	1908—1910	—
Slow combustion of hydrocarbons	—	1902—1906	1932—1937
Thermal decomposition of hydrocarbons	—	1905—1914	—
Explosive combustion of hydrocarbons	1892—1897	1906	1934—1936
Flame propagation	1897	—	1927—1936
Combustion of carbon monoxide	—	—	1925—1930
Catalytic combustion	—	1906—1912	1925—1927
Combustion at high pressures	—	1906—1933	
Chemistry of coal	—	—	1919—1937
Blast furnace reactions	—	—	1926—1938

His work will reviewed in accordance with this scheme.

Bone left Manchester in 1896 for a while to study under Victor Meyer at Heidelberg. His natural abilities and excellent memory no doubt made the study of organic chemistry congenial to him and, in spite of Victor Meyer's interest in combustion, Bone worked on a problem of organic chemistry : " Indoxazen Derivatives." Returning to Owens College, Bone continued studies in organic chemistry and his next papers were published in the *Transactions of the Chemical Society*, along with W. H. Perkin, junr., who had recently been appointed to the Chair of Organic Chemistry. The investigations followed upon some work of Perkin's on the *cis*- and *trans*-tetramethylenedicarboxylic acids and dealt with the methods of preparation of ethyl butanetetracarboxylate which on hydrolysis leads to adipic acid. Trimethylsuccinic acids, the identification of which had been a subject of controversy, were characterised.

During the next ten years, Bone followed up the work in a characteristically exhaustive manner, publishing seven more papers in the *Transactions of the Chemical Society* along with his collaborators Sprankling and also

H. H. Henstock and J. J. Sudborough. The last of these papers appeared in the *Transactions of the Chemical Society* in 1904. These early escapades in organic chemistry no doubt provided him with experience which later he made use of in the study of the products of slow decomposition of hydrocarbons, and more particularly in the study of the constitution of coal.

Even during these researches in organic chemistry he was being drawn back towards his deeper interest, the chemistry of combustion. In 1894, and again in 1897, he is publishing with J. Cain and extending his first research to study the incomplete combustion of acetylene, mixtures of cyanogen and hydrogen and of pentane with oxygen. These investigations overthrew the dogma of the preferential burning of hydrogen in hydrocarbon flames. Considerable controversy, however, continued to rage round the question as to how hydrocarbons burnt, in which H. E. Armstrong took a prominent part. Bone, thinking that an explanation might be found in the formation of intermediate compounds, set out on a new line of inquiry into their slow combustion about which next to nothing was then known.

But about this time he was also taking up the cudgels to see whether hydrogen would combine with carbon directly at temperatures of over 1000° to give methane. Berthelot had obtained acetylene in the electric arc, but it was considered methane was decomposed at high temperatures into its elements. Bone's work which he was carrying out at this time with Jerdan suggested that a definite equilibrium existed between hydrogen, carbon, and methane at 1100° C. and that at the temperature of the arc, although acetylene was the main product, methane and some ethane were formed. The paper in the Chemical Society *Transactions* appeared in 1901 and was an extensive piece of experimental work involving the separation of methane and ethane by diffusion and well illustrates Bone's experimental ability. Later he resumed the attack on this problem partly to dispel criticism of the former work and partly to demolish what he rightly considered to be erroneous views about the production of acetylene such as those of Vivian Lewis. Eventually he and H. F. Coward showed that by passing hydrogen for a long period over 0·3 g. of pure carbon at 1100° C. it could be almost completely combined to form methane. He went to the trouble to get special lead-free Berlin procelain tubes, having found by analysis that those which purported to be lead-free contained traces of lead which were preventing the complete conversion of the carbon into methane.

In 1898 appears a note on gas analysis apparatus in the Chemical Society *Proceedings*. This was the forerunner of the well-known Bone and Wheeler apparatus and was a characteristic outcome of Bone's insistence on careful and accurate work. He was dissatisfied with existing methods and set himself to improve them on the lines of Frankland and MacLeod's methods. The design has been almost universally adopted, subsequent improvements having been incorporated.

It is interesting to note a short paper which Dixon published along with Bone on the analysis of natural gas at Heathfield, Sussex. Dixon did not bring Bone into his researches on detonation and this is the only paper that was published in their joint names. Bone, however, was destined later to greatly extend Dixon's work on detonation.

Bone's researches on the slow oxidation of hydrocarbons constitute his most significant early work : they mark the central feature of his life's work. The first paper of this series was published along with R. V. Wheeler in 1902 on the slow oxidation of methane. Methane and oxygen mixtures were heated in borosilicate glass bulbs for different lengths of time and the products were analysed. The products in turn were submitted to the same treatment and it was shown by a process of exclusion that the carbon oxides were derived from the oxidation of the methane and not by oxidation of the carbon monoxide or through the action of steam. This first paper contained no reference to the hydroxylation theory.

The second paper appearing in 1903 described a new method in which the gases were circulated round and round through a hot tube so that very much larger quantities of gas could be treated. This proved that the oxidation occurred *via* formaldehyde and left it a matter of conjecture whether a hydroxylated product, $CH_2(OH)_2$, was first formed, for no methyl alcohol had been found in the liquid products. On this occasion, Armstrong also published a paper setting forth his ideas about the oxidation of hydrocarbons and the importance of water acting as an electrolyte in the process. He revived the suggestions which he had made in 1874 that hydroxylation would occur step by step along with the formation of hydrogen peroxide. Shortly afterwards Bone and Stockings published the most exhaustive and characteristic of this whole series of papers. By the methods he had already employed for methane the products of the slow oxidation of ethane were studied. It was in this paper that he stated that " the combustion proceeds in several well-defined stages during which the oxygen enters into and is incorporated with the hydrocarbon molecule forming oxygenated intermediate products by successive stages of hydroxylation." They found no direct evidence of the production of ethyl alcohol (except when ozone was used) but showed that acetaldehyde and steam were the first products to be detected. They obtained hydrogen, methane and ethylene, but showed them to be secondary products arising from the acetaldehyde and formaldehyde produced. Investigations followed on the oxidation of ethylene and of acetylene to which the hydroxylation scheme was equally applicable. Although no vinyl alcohol was then isolated in the early stages of the ethylene oxidation, the isomer acetaldehyde was found to be formed. Strong evidence against some of Armstrong's views was adduced, particularly those relating to the intervention of water, which in a paper with G. Andrew was shown not to affect the oxidation of a hydrocarbon, although in agreement with H. B. Baker he found it to affect the combustion of hydrogen.

Bone's power as an investigator, his experimental ability, his literary talents, his thoroughness, his careful observation and attention to detail, and his use of the method of elimination of possibilities are strikingly shown in these series of papers. Much of his subsequent work was a development of these important investigations, and during the last ten years of his career he supervised much work designed to test and extend the views at which he had arrived.

The long paper which he published with J. Drugman in 1906 on the explosive combustion of hydrocarbons was also very important. In it he extended the view that the initial encounter of the hydrocarbon and oxygen results in the production of an oxygenated molecule in flame combustion just as it does in slow combustion, the same hypothetical hydroxylated substances being formed as transient molecules. He isolated aldehydes from the interconal gases of the flame. Thermal decomposition, he agreed, played a more prominent part in the flame, but still not a dominant part, the oxidation being a much more rapid process than any dissociation of the hydrocarbon. He allowed that his former work with Lean, and later with J. C. Cain, though it did disprove the theory of the preferential combustion of hydrogen, did not disprove the theory of the preferential combustion of carbon. But he argued that these later experiments on the different products obtained from mixtures of ethane, ethylene, and acetylene respectively with oxygen having the same C : H : O ratio, made such a theory quite untenable. He held the view that the oxygen was attached to the hydrocarbon molecule forming first a monohydroxylate; but in the detonation of ethylene mixtures he considered that a dihydroxy-product might be formed by single impact with an oxygen molecule. At this stage of his work he seems to have come to the conclusion that his and Armstrong's views were practically identical except for the intervention of water and the consequent production of hydrogen peroxide. Most of this work was carried out at Manchester, and Bone was elected Fellow of the Royal Society in 1905.

In 1906 Bone transferred to Leeds to organize a department of Fuel Technology at the University; the Gas Industry endowed the Livesey Chair and Bone became the first Professor of Coal Gas and Fuel Industries. While at Leeds Bone extended his work on the mechanism of the combustion of hydrocarbons by studying explosions at pressures up to fifty atmospheres. These investigations, carried out from 1906 to 1912, were published in the *Philosophical Transactions* in 1915, after he had moved to South Kensington. His collaborators in this work were H. Davies, H. H. Gray, H. H. Henstock, and J. B. Dawson. The high-pressure apparatus was designed with the help of Petavel, whose well-known manometer was utilized for recording the rate of rise of pressure. The maximum pressure measured in this work was about 400 atmospheres.

It was concluded that an equimolecular mixture of methane and oxygen reacted as a single transaction through to the dihydroxy-compound which then produced formaldehyde and water, the formaldehyde providing CO and H_2; only with mixtures with more methane than the mixture $3CH_4 + 2O_2$ was there any appearance of carbon separation. The effect of successive increase in the hydrogen–methane ratio on the oxygen distribution showed that methane was burnt in preference to the hydrogen, and carbon monoxide was found more effective than hydrogen " in pulling away oxygen from the predominating affinity of the hydrocarbons." Similar experiments were carried out on ethylene and on ethane, and all the results strongly supported the views which had been put forward in the earlier papers on the combustion of hydrocarbons through successive stages of hydroxylation. Under certain conditions carbon separated and steam was formed and this was explained by decompostion of the vinyl alcohol first formed prior to dihydroxylation. In the case of ethane it was found that (1) a flame of long duration increased the amount of carbon formed, (2) conditions leading to rapid cooling gave more aldehydes and steam, and (3) the high temperature of a detonating explosion gave opportunity for the carbon to be attacked by the steam formed. Although hydrogen appeared to show much less affinity for oxygen than methane, yet the liberation of energy, as shown by the rate of rise of pressure, was much greater for hydrogen.

These interesting high-pressure studies were resumed when Bone was established in the new laboratory at South Kensington; and the results were published in a series of fifteen papers from 1921 to 1933. The first of these was on explosions in hydrogen–air and carbon monoxide–air mixtures. The papers had been written and a few final checks were being made, when an accident in the laboratory led to the death of A. W. Haward who was assisting Bone in this work. Although deeply affected by this untoward disaster, it was characteristic of Bone's courage to realize that what his collaborator would have most desired would be the uninterrupted prosecution of the work, and he set himself to carry on these high-pressure investigations with all the more pertinacity. He eventually succeeded in measuring explosion pressures of over 7000 atmospheres. It is only necessary to refer to Bone, Newitt, and Townend's book on " Gaseous Combustion at High Pressures " to realize how meticulously careful Bone was in all such high-pressure work and rules had to be implicitly obeyed.

Bone and Haward's investigations of the combustion of hydrogen–air and carbon monoxide–air mixtures showed that the rate of rise of pressure was much more rapid for hydrogen than for carbon monoxide. Not only the time to maximum pressure was delayed in the case of the latter, but also the rate of pressure fall after maximum pressure was diminished. Even 1 per cent. of hydrogen, however, in the carbon monoxide–air mixture counteracted these effects. Bone considered that hydrogen was burnt as a termolecular process, $2H_2 + O_2 \longrightarrow 2H_2O$, but that carbon monoxide combines with oxygen atoms : when hydrogen is present, the burning of the carbon monoxide is assisted by the reaction $CO + H_2O = CO_2 + H_2$. The anomalies connected with the combustion of carbon monoxide, thus found, led him to a very exhaustive attack on the effect of pressure on its combustion.

The rest of the high-pressure work was carried out along with his assistants, D. M. Newitt and D. T. A. Townend. A remarkable effect of nitrogen on the combustion of carbon monoxide was found. Taking mixtures of carbon monoxide with mO_2 and nH_2 where $m + n = 4$, it was found that nitrogen greatly increased the time to maximum pressure, lowered the maximum pressure, and retarded the rate of cooling. The results previously found with carbon monoxide–air mixtures were thus accounted for by this specific effect of nitrogen, which was not shown by argon, or by excess of carbon monoxide, and was prevented by a small quantity of hydrogen. It was supposed that the nitrogen absorbed vibrational energy by resonance from the carbon monoxide and that the energy was only slowly given out in the cooling period. It was found that although nitrogen oxides were produced in much greater profusion in carbon monoxide explosions than in hydrogen explosions, these resulted as a secondary effect, and did not account for the delaying action of the nitrogen. The nitrogen was first activated in some way by the carbon monoxide, and then part of the activated gas was oxidised to nitric oxide. The effect was only noticeable at pressures higher than 10 atmospheres' initial pressure.

Observations were then extended to higher initial pressures (175 atms.) in order to study the effect of dissociation, which could be suppressed by excess of carbon monoxide. Results in carbon monoxide–oxygen mixtures with an excess of 4 mols. of CO were compared with mixtures with an excess of 4 mols. of oxygen, and it was concluded that neither dissociation nor nitric oxide formation accounted for the effect of nitrogen, which appeared to depend on the absorption of radiation. Further experiments with helium confirmed the observations with argon and provided experimental data for the determination by D. M. Newitt of the volumetric heats of CO_2 and steam. Using a bomb one metre long, with quartz windows, it was shown that emission in the ultra-violet was less when excess nitrogen displaced excess oxygen and that the nitrogen peroxide absorption bands were only visible in the products after the gases had cooled down; the formation of the nitric oxide was not found to occur till after all the radiation in the flame which affected the spectrum plate had been emitted. These results appeared to confirm the previous conclusions.

Partly in order further to investigate the effect of pressure on the delaying action of nitrogen and partly to determine the effect of pressure on the production of nitrogen oxides, experiments were carried out at still higher pressures. With the financial assistance of Imperial Chemical Industries and the advice of Sir George Hadcock, F.R.S., a bomb capable of withstanding 10,000 atmospheres was constructed. Explosions were carried out at maximum initial pressures up to 750 atmospheres in the case of hydrogen–air and 1000 atmospheres in the case of carbon monoxide–air, reaching maximum pressures as high as 7000 atmospheres. The delaying effect of nitrogen was a maximum at 150 atmospheres initial pressure, and did not increase above this pressure.

With the rapid cooling on expansion of the explosion products obtained by the aid of bursting disks, it was found that as much as 5·4 per cent. of nitric oxide could be obtained 0·06 second after the pressure maximum with mixtures containing $3O_2 + 2N_2$ at 70 atmospheres' initial pressure. This was more than twice that obtainable in the products without the use of the bursting disk. Experiments were also made by continuously burning carbon monoxide and 50 per cent. O_2/N_2 in a pressure vessel at 100 atmospheres, but under these conditions not more than 2 per cent. of nitric oxide was obtained in the exist gas. Other experiments in the high-pressure vessels were made on the behaviour of hydrogen and steam in suppressing the effect of nitrogen. Measurements had not been made during Haward's work with less than 1 per cent. of hydrogen; it was found, however, that the effect of hydrogen only commenced at 0·65 per cent.; quantities greater than this appeared to alter the character of the explosion and cause a kind of "knock." Hydrogen appeared to be more effective than steam.

The main impression made in reading the account of these researches is the thoroughness with which these difficult and elaborate experiments were carried out. They reflect Bone's tenacity of purpose; no difficulty was too great that it could not be surmounted and work was carried to the limit of the possibilities of the experimental methods he had chosen. They reflect, too, his ability in choosing assistants capable of carrying out his programme.

These high-pressure investigations led on to his work on the combustion of carbon monoxide. He was determined to discover whether it could be burnt without the intervention of steam. Dixon in 1880 had found that careful drying of carbon monoxide–oxygen mixtures prevented combustion. Armstrong had persisted that water, an "electrolyte," was necessary. Bone gives a full account of the history of the problem in his paper with F. R. Weston (*Proc. Roy. Soc.*, 1926, **110**, 615).

Bone first set himself to settle whether water is necessary for the combustion of carbon monoxide at ordinary pressure and then to find out the effect of increasing the pressure. The results were that after drying carbon monoxide–oxygen mixtures with the utmost "Bakerian" precautions and leaving them to dry over pure P_2O_5 for six months or even longer the mixture would ignite and propagate flame, provided the energy of the igniting spark was sufficient. The bulbs were fired, photographed and the combustion witnessed by H. E. Armstrong, A. Smithells, Sir R. Robertson, and H. B. Baker.

Still not satisfied, Bone then made further tests. He was determined to remove all suspicion that there might be any water present in the gas mixture or in the electrodes at the time of firing. They were rigidly dried to a limit, employing an "elaborate ritual"; this time the drying period was 1000 days. The bulbs were fired in the presence of H. B. Dixon and W. E. Garner.

The second part of the work related to pressure experiments. The apparatus was dried by heating and circulating nitrogen for periods of weeks, and the gases were dried for periods of a year. It was found that with the relatively weak energy of the spark employed, ignition did not occur below 2 atmospheres, that at 2·75 to 5 atmospheres it took place with difficulty, but that at 10 atmospheres ignition occurred every time.

Spectroscopic observations carried out by his assistants Newitt and Weston showed that the steam lines, which were prominent in the indirect combustion of carbon monoxide in the presence of water or hydrogen, were replaced by the continuous and banded spectra characteristic of the direct combustion when the mixtures were dried. As the pressure increased the latter spectrum predominated even when hydrogen was present. The emission range in the ultra-violet was reduced when nitrogen was present at high pressures. In 1934 further spectroscopic observations were published. Carbon monoxide was burnt in oxygen in a special bomb, provided with windows, up to pressures of 100 atmospheres, and it was found that the steam lines were suppressed at pressures higher than 30 atmospheres.

By this very elaborate and characteristically pertinacious piece of experimental work, Bone established that carbon monoxide can burn without the intervention of steam, and that as the pressure is increased above 10 atmospheres the direct method is favoured. A man of less energy and obstinate power of will might have drawn such conclusions from a few special experiments, but there would have still been doubts; Bone determined to remove all doubt, however much trouble it entailed.

Bone commenced researches in 1903 on the catalytic combustion of hydrogen and carbon monoxide along with R. V. Wheeler, G. W. Andrew, and H. Hartley at temperatures well below their ignition temperatures. Employing a variety of typical surfaces, he and his associates were led to conclude (i) that the power of accelerating gaseous combustion was possessed in varying degrees by surfaces, basic, acidic and metallic; (ii) that the accelerated surface combustion was dependent on a prior occlusion of the combustible gas and probably also of oxygen; (iii) that the rate of the absorption determines the rate of the reaction and therefore the latter is dependent on the pressure of the combustible gas. Bone disagreed with Bodenstein's conclusion that with platinum oxygen absorption alone determined the rate of the reaction, for he found that prior treatment with the combustible gas greatly accelerated the rate of combustion at the surface. He also showed that his results were inconsistent with the alternate reduction and oxidation hypothesis. By this work, Bone claimed to have anticipated in a general way the views of Langmuir that such catalytic reactions are preceded by activated adsorption at the surface of the catalyst, and in his lecture given before the Society of Chemical Industry he quotes the following sentence from a private communication from Langmuir, "the general view point which you had in 1906 was much ahead of others of that time, and is in many ways closely related to that which I have developed independently from a rather different experimental basis."

Bone published a further series of papers on catalytic combustion (1925—27) in the *Proceedings*, more particularly relating to the catalysis of carbon monoxide–oxygen mixtures in contact with gold, with nickel and copper and their oxides, and with a fireclay surface. He pointed out that "the dominant factors in one set of circumstances may be demonstrably different from those prevailing in another," and his experiments led him to somewhat different conclusions from those come to by Langmuir and others who worked at much lower pressures and higher temperatures. He concluded that the activated adsorption was not confined to the surface layers, and that both the carbon monoxide and the oxygen had to be adsorbed for the reaction $2CO + O_2 \longrightarrow 2CO_2$ to occur at these lower temperatures. In the case of the oxide surfaces no reduction of oxide to metal occurred but merely the formation of oxygen–metal–CO complexes on the surface. The action at the fireclay surface depended on the pressure of the complete combustion mixture ($2CO + O_2$) and on the carbon monoxide pressure for other mixtures.

In some very careful work on the effect of moisture on the catalytic activity of such surfaces, it was found that drying caused a temporary increase in activity by removal of the film of water which "lags" the surface. Prolonged drying, however, ultimately altogether stopped the catalysis at the silver and gold surfaces whose activity could be re-established on introducing moisture; in the case of fireclay the loss of activity could not be so restored.

This summarises in a few words the main results of Bone's extensive work on catalytic combustion. It has been carried on and extended in other directions by G. I. Finch, F.R.S. Bone was impatient of half-developed theories. In that same lecture he remarked "while much remains to be done in the way of classifying the subject of catalytic combustion by further experiments, let us beware of the creeping in of mystical notions that will blur and distort our vision. For when one hears not only of supposed 'deactivation' on the hot walls of containing vessels, but also of 'reaction-chains' executing Brownian movements thereon, one wonders whether, were Vernon Harcourt to come to life again, he would not be incited into breaking heads against laboratory walls." Bone looked at things in a large macroscopic way; he took a dislike to the microscopic behaviour of things.

In conjunction with C. D. McCourt, Bone developed (1908—12) the "incandescent" surface combustion process whereby an explosive mixture of gas and air in proper proportion for combustion, or with slight excess of oxygen, was caused to burn without flame in contact with a granular incandescent solid. The process was adapted to crucible and muffle furnaces, to steam raising in multitubular boilers and to "radiophragm" heating for cooking and other purposes. For six years two large gas-fired surface combustion boilers were run on coke oven gas at Skinningrove Iron Works with a thermal efficiency of 92·7 per cent. of the net calorific value of the gas. In this connexion he was asked to lecture in other lands. Quoting from the lecture already referred to, he best tells his own story :

"I received in August 1911 a cabled invitation to expound and demonstrate the process experimentally at the Annual Congress of the American Gas Institute at St. Louis on October 19th of that year, all expenses of myself and two assistants to be paid by our hosts. Accordingly, we took out nearly a ton of apparatus, and duly lectured and demonstrated to an enthusiastic audience for upward of three hours on the afternoon in question, the longest infliction I have ever perpetrated. Immediately afterwards we were banqueted for some hours with topical musical and pictorial interludes in real Western style; and, on my rising to respond to the toast of my health, the band struck up ' The Man that Broke the Bank at Monte Carlo.' On my inquiring what it meant, it was explained that the expenses of our show had literally cleaned out the American Gas Institute, who had perforce to send the hat round their industry to meet them, and that it was a tribute to a professorial Bone that had skinned them so easily.

" I repeated the lecture twice in New York and also at the Franklin Institute in Philadelphia, and was overwhelmed with the generous hospitality which Americans always extend to their guests; unfortunately, I also contracted severe ptomaine poisoning, and returned home a physical wreck. A year later I had the honour of lecturing on the subject before the Deutsche Chemische Gesellschaft in Berlin and the pleasure of meeting F. Haber, Jacobsen, Otto Witt, Will, and other distinguished chemists, whose appreciative kindness remained a pleasant memory during the dark days of the Great War which broke out so soon afterwards."

From 1930 to 1937 Bone published a further series of six papers along with various collaborators on the slow combustion of hydrocarbons (methane, ethane, ethylene and acetylene). The method employed in most of this new work was to heat the gaseous mixture in a silica bulb, measuring the length of the induction period and rate of reaction by the pressure change. The final products, gaseous and liquid, were analysed, deriving therefrom an accurate measure of the distribution of carbon amongst the products to balance with the carbon in the hydrocarbon, or by cooling the reaction vessels down rapidly a precise knowledge of the main products formed at various stages of the reaction could also be obtained. The most reactive mixtures were found to be those which would give rise directly to alcohols; the induction periods and reaction times were shortened by aldehydes and by alcohols. Peroxides were not found except in those stages of reaction in which most aldehyde is obtained. Large amounts of alcohols were found by Newitt and Bloch to be formed in the pressure oxidation of methane and ethane.

In 1927, as a result of investigation of the phenomenon of " knock " in internal combustion engines, views had been expressed that the combustion of hydrocarbons was autocatalytic (Egerton and Gates) and that peroxides were first formed (Callendar and Mardles). There followed much other work, for instance, the combustion of ethylene (Hinshelwood and Thompson), the combustion of butane, etc. (Pease), all of which indicated that the hydroxylation theory was an incomplete explanation of the process of combustion of a hydrocarbon, and that it was necessary to introduce the chain reaction mechanism first applied to the combustion of phosphorus by Semenov. Bone fought for the sufficiency of the hydroxylation theory and defended it not only on the grounds that the opponents had not provided definite positive evidence of the formation of peroxides, but also he supported it by a wealth of careful experiment.

Suffice it to write here that Bone was retentive of the ideas he had already formulated and was slow to modify them because he rightly refused to put forward any modification until he was convinced of the basis of the new facts or had satisfied himself by experiment that such was necessary. His last paper on " The slow combustion of methane, methyl alcohol, formaldehyde and formic acid," although it repeats that the hydroxylation theory " rests securely on a firm basis of unimpeachable analytical facts," concedes that " the slow oxidation is autocatalytic " and that the aldehydes formed are peroxidised to some extent. A considerable amount of misunderstanding arose owing to the hypotheses being applied to different classes of hydrocarbons. Bone did not examine the behaviour of higher hydrocarbons, and what may be true for methane is not necessarily so for butane.

The experiments carried out in these latter years are undoubtedly the most careful and complete experimental study which has yet been made on the slow combustion of the simpler hydrocarbons, and show that the hydroxylation scheme specifies the main products, though it does not formulate precisely how they are formed, in fact does not tell the whole story. Bone gave a summary of his views and the evidence on which they were based in the Bakerian Lecture (1932), and a year later in a lecture to the Chemical Society. These papers show the power Bone possessed of marshalling a bold array of experimental evidence.

Perhaps the most striking section of Bone's later work was that which he carried out on Flame Propagation with the help of R. P. Fraser. Bone soon recognised and in every way encouraged the development of Fraser's special talents for photography. While in the course of studying detonation in gaseous mixtures, W. Payman and R. V. Wheeler published a generalisation about flame speeds in different blends of limit mixtures which Bone considered was untenable, and he set out to demolish it with characteristic thoroughness. In the course of this work many anomalies were discovered, such as propagation of flame at different speeds in the same mixture. Some beautiful photographs were obtained of methane–oxygen mixtures burning in closed and open tubes showing the streamers of burning particles from the spark and the burst of luminosity as compression waves pass back and forth through the burnt products. Amongst other matters studied were the effect of ethylene on the combustion of electrolytic gas first noted by Sir Humphrey Davy, similar effects of acetylene, the influence of electrical and magnetic fields on the propagation of flame, the determination of the conditions for maximum speed of a flame in carbon monoxide–oxygen mixtures and the effect of moisture thereon. These flame investigations culminated in three papers in the *Philosophical Transactions* (1929, 1931, and 1936) in which are collected the most beautiful examples of flame photography which have been achieved.

The progressive drying of a carbon monoxide–oxygen mixture was found to greatly lower the flame velocity, but this hindering effect could be overcome by imposing a strong electric field on the medium. It was shown that under the influence of successive superimposed shock waves, the speed at which flame starts may be raised in successive abrupt stages each one giving rise to a new uniform flame speed, until the speed nearly approaches that of the shock wave itself. If the region in front of an advancing flame is under the influence of shock waves detonation might be set up ahead of the advancing flame, and in confirmation of the observations of C. Campbell and D. W. Woodhead the detonation flame photograph may possess a banded appearance, due to the head of detonation travelling in a helical path through the tube. This latter phenomenon was studied in great detail by means of a camera for very high-speed flame photography consisting of a stainless steel mirror rotating in a vacuum up to speeds of 30,000 r.p.m. As Bone remarks in a Royal Institution Lecture (1933) : " It is indeed a wonderful instrument and our only regret is that Dixon did not live to see it." Bone and Fraser examined the effect of electric fields on detonation flames, which were found to reduce the speed or even to cause detonation to cease when orientated so as to draw out electrons from the flame front.

They sum up their conclusions as follows :

" A new view of the detonation-wave in gaseous explosions is advanced. For it can no longer be regarded as simply a homogeneous ' shock wave,' in which an abrupt change in pressure in the vicinity of the wave-front is maintained by the adiabatic combustion of the explosive medium through which it is propagated; but it must now be viewed as a more or less stable association, or coalescence, of two separate and separable components, namely of an intensively radiating flame-front with an invisible shock wave immediately ahead of it; and whether persistent ' spin ' is developed or not depends upon the stability or otherwise of their association.

" According to the new view, detonation in an explosive gaseous medium is the propagation through it, as a wave, of a condition of intensive combustion, initiated and maintained in a shock wave by radiation from an associated flame-front; and that ' spin ' ensues whenever the conditions are such that the radiation from an attenuated flame-front causes a localised intensive excitation of molecules in the ' shock wave ' just ahead of it. The resulting ' head ' of detonation, in which an intensive combustion is thus localised, then begins to rotate in the medium, eventually pursuing a spiral track along the tube quite close to its walls. There is, however, no rotation of the medium as a whole, but only of such a ' head,' or perhaps ' heads,' of detonation."

These final investigations on the detonation flame are a fitting conclusion to the work on combustion of one who described himself as " ever a fire worshipper."

Bone and Townend were the authors of a very welcome book on " Flame and Combustion," published in 1927.

Bone's influence on the study of coal and fuel economy in general has been widespread. His book, " Coal and its Scientific Uses," published in 1918, drew attention to the importance of studying coal as a chemical substance. This book was followed in 1936 by a more comprehensive treatise : " Coal, Its Constitution and Uses," written in collaboration with G. W. Himus.

Bone often pointed out that the subject of a chemical survey of our British coal seams originated with the British Association Fuel Economy Committee, of which he was Chairman (1915—22), and that the Fuel Research Board itself was an outcome of that Committee's successful pioneering work; other influences no doubt shared in the birth both of the Board and of the Survey for which it is responsible. He was a consultant to the Board from its inception in 1917 to 1930.

In 1919 Bone started his researches on the constitution of coal. In common with many other workers, he selected pyridine for his first experiments on the extraction of the constituents, but abandoned its use at an early stage, largely owing to its toxicity. The bulk of his work on extraction was carried out with benzene under pressure, although his experiments with other solvents showed that resins could be isolated from coal in a pure state. A method for Soxhlet extraction of coals with benzene under pressure was evolved and applied to a large variety of coals. The extracted material (up to 15 per cent. of the coal substance) was resolved into four fractions: I, soluble in light petroleum; II, insoluble in light petroleum; III, soluble in ethyl alcohol; and IV, insoluble in ethyl alcohol. Fractions I and II were soluble and fractions III and IV insoluble in a mixture of light petroleum and benzene. It was found that the coking propensities of the coal were dependent on the contents of fractions III and IV, which fractions were replaced by phenolic bodies in brown coals and lignites. The residue after extraction of a coking coal was found to be completely non-caking on carbonisation, except when mixed with fractions III and IV obtained from a coking coal.

Bone also devised the standard " Bone and Silver " method for the determination of the total volatile matter in coal. He carried out experiments on the carbonisation of brown coals and lignites at temperatures below 800° C. as a possible method of enhancing their fuel values. He suggested that these coals could be considerably " up-graded " by suitable heat treatment, as a result of which the Bone–Wood fuel improver was devised. In 1926 Bone began work on the oxidation of coal and the residues from benzene-pressure extraction, by means of boiling alkaline permanganate. A method was standardised and applied to a large selection of coals representative of many geological and geographical formations. From the products of oxidation all the benzenecarboxylic acids, with the exception of benzoic acid, were isolated. Quantitative oxidations demonstrated the essential benzenoid structure of the main coal substance, with progressive development of the benzenoid character as maturity of the coal increased. The essential chemical identity between " dull " and " bright " coals was also shown.

In order to obtain more precise knowledge of the mechanism of alkaline permanganate oxidation under these standardised conditions, an extensive investigation was undertaken of the behaviour of a number of organic substances of known constitution when subjected to treatment identical with that which had been previously applied to coals. It was found, *inter alia*, that this method of attack was purely degradative and that no product of oxidation was more complex than the starting material. This communication to the *Proceedings of the Royal Society* early in 1938 was Bone's last published work.

Bone had maintained, from his earliest days, a very close connexion with the Iron and Steel Industry, so it is fitting to conclude the account of his scientific activities by reference to his work for that industry which he was still busily engaged upon up to the time of his death. While at Leeds he made a valuable study of the gas producer and of the reactions going on in the fuel bed and their variation with depth, and later at the Imperial College he commenced an exhaustive laboratory study of the reactions in the Blast Furnace which is still being prosecuted by his collaborator, Dr. H. L. Saunders. The fundamental information so obtained is of great use to the Industry.

The equilibrium in the system—oxides of iron, oxides of carbon—between 380° and 1200° C., was studied and this led to the investigation of the catalytic decomposition of carbon monoxide at 450° C. and the influence of the carbon so produced on the reduction of the ore. This carbon formation, so long as it is confined to the surface of the ore, has a disintegrating action upon the ore and hastens reduction, but accumulation of the carbon is detrimental. The reduction at 750° by the carbon impregnating the ore was found to be more rapid than the direct reduction by the blast furnace gas. Measurements of rate of reduction of oxides of iron by blast furnace gas and the effect of small additions of steam and hydrogen thereon were made over a temperature range 450—1000° C. when the variables were (1) the CO_2 content in the reacting gases, (2) the time of contact between the gases and the ore, and (3) the velocity of the gas at the ore surface. Hydrogen was found to be more effective in reduction than the equivalent carbon monoxide at high temperature, and it also accelerated the carbon deposition reaction.

These laboratory investigations have been supplemented by a study of the composition of the gases and state of the reduction of the ore in the interior of a blast furnace in actual operation, showing the great importance of the proper distribution of the burden.

Bone held very decided views on economic matters; his free trade convictions were brought to bear on the problems of the British Iron and Steel Industry, and in a paper published in *Chemistry and Industry* in 1932, in the middle of the slump, he boldly advocated " the erection of three or four large modern plants with coke ovens, blast furnaces, steel works and rolling mills co-ordinated so as to ensure the greatest fuel economy and placed under scientific management " and suggests that this step would be a more effective help than any " tariff protection," because " the production of the iron and steel to meet the world's demands is fast becoming an international question of the first magnitude in which all the chief producing countries are equally concerned."

In 1931 Bone received the Melchett Medal of the Institute of Fuel and delivered the Melchett Lecture with the title " A Century of Fuel Economy." He unfolded in a masterly manner the progress of fuel economy in the manufacture of iron and steel, in the manufacture of coke and gas, and in power production through the century : " It began and ended," he said, " amid the depression and dislocation of the aftermath of a great war; but in science was the key of Promise which unlocked the gates of Doubting Castle and delivered its prisoners from Giant Despair and it will do so again for us."

Bone was honoured by the award of the Davy Medal of the Royal Society in 1936.

Taking Bone's scientific activities as a whole, in accordance with the true spirit of experimental investigation, by new discovery he left more to explain than he explained.

A. C. EGERTON.