THE ROMANCE OF CARBON

BY

ARTHUR D. LITTLE

Arthur D. Little, Inc., Cambridge, Mass.

FROM THE SMITHSONIAN REPORT FOR 1926, PAGES 235–255

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As the chemist studies the material structure of the universe he finds it to be composed of about 90 substances of such persistent identity and character that he has come to regard them as elements. He has reason to believe that not more than 92 of these elementary substances exist and he suspects that these may, themselves, have been formed in the cosmic process by successive condensations of hydrogen and helium, the lightest and simplest of them all. He finds that the atoms of which these elements are composed are not the hard, round, indivisible little particles which he had long assumed them to be, but that they are instead complex systems of electrical charges, vibrant with intensest energy and relatively very far apart.

There is, therefore, for each of the elements an astronomy of its own, as awe inspiring in its order and minuteness and as far removed from the plane of our existence as that of the stars themselves. Each of the elements, also, has its own story of absorbing interest. There is helium, first discovered by the spectroscope in the atmosphere of the sun and now extracted from natural gas to carry airships above the clouds; radium, which in the beginning made its presence known by the image of a key upon a photographic plate and thereafter revolutionized our ideas of matter and supplied a new and powerful aid to therapy; gold, which since the dawn of history has furnished the motive for fierce endeavor, intrigue, exploration, crime, and wars. But these, and many others, are stories for another time. Our present theme is the romance of the element carbon, a fragment from a single chapter in the great romance of chemistry.

ATMOSPHERIC DUST

In considering carbon one is immediately struck by the protean aspects of its occurrences. To that ubiquitous individual, the man in the automobile, carbon presents itself as a nuisance in his engine

[1] Presented before the 71st meeting of the American Chemical Society, Tulsa, Okla., Apr. 5 to 9, 1926. Reprinted by permission from Industrial and Engineering Chemistry, vol. 18, No. 5, p. 444. May, 1926.

cylinders, while, because of carbon in his smoky exhaust, the motorist himself is often regarded as a nuisance by the pedestrian. The householder thinks of carbon in terms of coal and sees the wood in his fireplace transformed to charcoal. There was no romance in carbon to the London chimney sweep of a century ago, when little boys of five or six were sold for seven years for 30 shillings and forced up chimneys by their masters with slight regard for the danger of burning or suffocation. To these boys carbon became a personal matter, for many went unwashed for years. Even to-day the soot deposit over London amounts to 260 tons per square mile per year, and in many of our American cities the figure is undoubtedly as high. Three days after a recent storm the surface snow taken from an average square yard in front of our Cambridge laboratory yielded 2.85 grams of soot and cinder, the equivalent of 9¾ tons per square mile. In such amount and form carbon becomes a menace to health and property, a thing of loathing to a careful housewife, and a powerful incentive to the purchase of stock in laundry companies.

The burning of coal is a principal cause of atmospheric dust, and over a city like London or Paris the number of dust particles per cubic centimeter of air may exceed 100,000, while over the oceans the air may hold only a few hundred per cubic centimeter. But the dust is not without its compensations, for to it we must ascribe the blue of the sky, much of the glory of the sunset, and, in large measure, the gentle precipitation of rain.

CHARCOAL

It was probably in the form of charcoal that man first became acquainted with carbon as he stirred in his cave the dying embers of his wood fires. With the soot from burning fat he drew pictures on his cave walls of the animals he knew, and very fresh and vivid some of these pictures still remain. Such great masters as Dürer, Holbein, and Michelangelo have since enriched the world by famous charcoal drawings, and soot has served as a vehicle for the communication of thought in the exquisite calligraphy of China as it serves to-day in printer's ink. Manuscripts of Herculaneum written in carbonaceous ink appear unchanged after 1,800 years. Fortunately for our own standing with posterity, the fabric of our newspapers is far less durable than the ink it bears.

Before it was displaced by coal there was a very general use of charcoal as a cleanly domestic and industrial fuel, but its chief employment was in metallurgy and particularly in the smelting of iron. The reputation of charcoal iron still endures and is especially associated with that from Sweden. In England, timber for charcoal became scarce by the sixteenth century, and in 1740 coke, another form of carbon, was introduced and saved the declining iron industry. It is curious, however, to note how long it took to make the simple change. In 1619 Dudley, an English ironmaster, first substituted coal or coke, it is not certainly known which, for charcoal and continued his efforts through many vicissitudes for more than 40 years, only to end in commercial failure. Not until Abraham Darby, about 1730, renewed the attempt was success achieved and the modern iron industry initiated. Twenty-six years later Darby declared his furnace to be "at the top pinnacle of prosperity, making 22 tons [of iron] a week." Prosperity, like other things, is relative. The United States, in 1925, had an estimated production of over 50,000,000 tons of coke, most of which was consumed in smelting iron ore.

It was between two charcoal points that Sir Humphrey Davy, in 1821, first produced the electric arc, and carbon in denser form has since played a conspicuous and essential part in the development of the electrical industries. It still serves as the terminals in the arc lamp and, until displaced by the tungsten filament, was for many years the source of light in the incandescent lamp. Of it are composed the electrodes of batteries and of the great electric furnaces employed in the production of brass, aluminum, electric steel, and ferrous alloys. Grains of carbon form the variable resistance through which speech is transmitted in the telephone, and back of all the bewildering opulence of word and sound that comes to us by radio are similar grains of carbon in the microphone. In the photophone, which marvelously transmits speech along a beam of light, such refinement of delicacy was required in the contacts that they were made of carbonized dandelion down.

Charcoal, by reason of its porous structure, presents an enormous internal area, which may, in case of specially prepared or activated charcoal, be as great as 20,000 square yards, or about four acres, for a cubic inch of the material. As a result, it exhibits in very high degree the phenomena of surface attraction or adsorption, by which it is able to condense gases and vapors within its pores or to remove and hold coloring matters from liquids filtered through it. It has consequently long been employed as a decolorizing agent and in the form of bone black for refining sugar, while the more intimate knowledge of its properties forced upon us by the exigencies of the war has extended its use into far more important fields. The dire necessity of devising means for the protection of troops against attack by poison gas forced the chemists of the Allies to an intensive study of the factors conditioning the adsorptive power of charcoal for use in the canisters of gas masks. It was presently determined that dense materials like nut shells yielded a superior charcoal, and peach stones and coconut shells became overnight munitions of the first importance. The porosity and adsorptive power of charcoal from such sources was further greatly increased by secondary or so-called activating treatments, and charcoals were finally produced of such efficiency that very high vacua are obtainable by their use. They may condense within their pores several hundred times their own volume of ammonia and lesser, though still large, amounts of the poison gases used in warfare. A good activated charcoal will, for example, absorb three-quarters of its weight of chloropicrin and will, in less than 0.03 second, reduce a concentration of 7,000 parts per million to less than one-half part in a rapidly moving stream of air.

Such phenomena obviously mean that the adsorbed gases are held within the charcoal by the force of surface attraction under pressures equivalent to many tons per square inch and that they are in many cases condensed to liquid films.

At the close of the war these properties of activated charcoal were immediately utilized by Colonel Burrell and others in the now well-known charcoal process for the extraction of gasoline from natural gas at the casing head, by which many million cubic feet of gas are now stripped daily, the adsorbed gasoline being recovered by heating the charcoal.

GRAPHITE

Graphite, so familiar to us all in the business end of a lead pencil, is another form of carbon for which many uses have been found. It occurs in nature, the best coming from Ceylon, where it is found in large, lustrous flakes, and it is artificially produced in quantity by heating coke or anthracite coal to high temperature in the electric furnace. It is several times as dense as charcoal and is a good conductor of electricity. As it is infusible and very inert chemically it is largely used for crucibles, and as it is also very smooth and soft it is commonly employed in facing molds in foundries and as a lubricant for heavy machinery. It lends its luster to the kitchen stove.

DIAMONDS

In the form of soot, carbon is black, amorphous, and synonymous with dirt and grime; as coke and charcoal, it is dull, porous, and readily combustible; as graphite, it is dense, lustrous, and so soft that it leaves a mark on paper. It is opaque in all these forms. But carbon in society has quite a different aspect from carbon in its working clothes. There it is the diamond, transparent, sparkling, brilliant with flashing color, and so intensely hard as to be well named in Greek 'Αδάμας, the invincible. Confusion of this Greek name with the Latin *adamare*, to love, may account for the frequency with which diamonds are offered at the shrine of Venus. In Sanskrit the diamond is vajra, the thunderbolt, a designation not without appropriate significance, for diamonds of small size are often found in meteorites.

Whereas graphite is a good conductor, the diamond has about the same electrical resistance as glass. Its refractive index, upon which, with proper cutting, its brilliancy depends, is far higher than that of glass, and the diamond is transparent to X rays, whereas paste is opaque. Some diamonds, at least, are luminous in a dark room after exposure to sunlight, and Sir William Crookes has shown that the diamond may acquire and retain indefinitely the property of radioactivity. A diamond which he embedded for some months in radium bromide became olive green and so highly radioactive that it was luminous in the dark after nine years. The same distinguished chemist ascertained that after exposure in a vacuum tube to a high-tension electrical discharge diamonds phosphoresce in various colors. Most South African diamonds shine with bluish light, while those from other localities emit bright blue, apricot, red, orange, or yellowish green.

Owing to the anomalous fact that the boiling point of carbon at atmospheric pressure is below its melting point, carbon volatilizes at about 3,600° C. without melting. Sir William Crookes has, therefore, calculated that under a pressure of only 17 atmospheres carbon would liquefy at a temperature of 4,130° C. and on cooling crystallize out as diamond. The process is not patented and is commended to any who may be contemplating a diamond wedding.

Many curious associations and beliefs have grown up around the diamond. In the Middle Ages it was thought to afford protection from plague and pestilence; to warn its wearer of the presence of poison by turning dark; and by some subtle homeopathy to be an antidote for poisons, though in itself a deadly one. It insured victory to its possessor, banished ghosts and dispelled the devil; brought friends and riches, and deferred old age. Though diamonds are expensive, one seldom gets so much for his money, and, in view of these accruing benefits, it is difficult to understand why it is fashionable in Siam to wear your diamonds on Fridays only.

Diamonds occur in nature in the so-called "blue clay" of volcanic pipes and are believed to have been formed by the slow crystallization of carbon from iron or molten rock through the combined action of high temperature and great pressure. The theory finds support in the results obtained by Moissan, who produced diamonds, though very small ones, by raising molten iron to very high temperature in the electric furnace, introducing carbon within the molten mass, and flooding the furnace with water. The sudden external cooling of the metal subjected the interior to enormous pressure while it was still extremely hot. When the iron was finally dissolved by acid the diamonds were found. Some years later another Frenchman, Lemoine by name, turned Moissan's discoveries to more practical account in the perpetration of the famous diamond swindle, by means of which he mulcted Sir Julius Wernher of 1,671,000 francs. Sir Julius was, presumably, not seriously inconvenienced thereby, in view of his great holdings in the South African diamond mines, from which most diamonds are now derived. The initial discovery in these fields was made in 1867 by Dr. W. G. Atherstone, who identified as diamond a pebble obtained from a child on a farm on the banks of the Orange River.

The diamond has played its part in history, and seldom creditably. You will recall at once the complicated affair of the diamond necklace, in which, shortly before the French Revolution, Marie Antoinette, Cardinal Rohan, Cagliostro, and many lesser personages were involved. Great names are associated with all the largest stones. The famous Sancy diamond of 53 carats passed successively through the hands of Charles the Bold, de Saucy, Queen Elizabeth, Henrietta Maria, Cardinal Mazurin, Louis XIV, only to be stolen during the French Revolution. It was later owned by a king of Spain, Prince Demidoff of Russia, and an Indian prince.

The Orloff diamond, which weighed 194 carats, was stolen by a French sailor from the eye of an idol in a Brahman temple. From him it was again stolen by a ship's captain, who murdered him. It was at last bought by Prince Orloff for £90,000 and by him presented to Catherine the Great of Russia.

The sale of the Victoria diamond to the Nizam of Hyderabad for £400,000 is an impressive instance of form value. The diamond weighed 180 carats, or 576 grains, or one-tenth of a troy pound. The sales price of this particular piece of carbon was therefore at the rate of £4,000,000 sterling, or $20,000,000 per pound troy.

The Premier mine in the Transvaal has yielded much the largest diamond ever found, a gigantic stone weighing 3,025 carats. It was known as the Cullinan diamond and was bought by the Transvaal Government for presentation to King Edward. Even that was eclipsed by the diamond throne which Buddhists believe to have stood near the Tree of Knowledge, beneath which Buddha received his revelation. The throne was 100 feet in circumference and made of a single diamond. Unfortunately, it seems to have been lost.

But the diamond condescends to lend itself to the humbler purposes of mankind. The impure crystals and fragments known as bort and the inferior carbonado, or black diamond, are used to point the diamond rock drills so essential to the progress of great engineering works. Thus, without carbon so employed, the route to San Francisco might still be around the Horn.

COMBUSTION AND OXIDES OF CARBON

The making of fire was perhaps the greatest achievement of the human race, and, though there has been no posthumous award of medals to Prometheus, the phenomena of combustion include some of the most fundamental chemical changes with which we are acquainted. All of the ordinary forms of combustion, upon which we depend for light and heat, involve the burning of carbon or of compounds of carbon and hydrogen. Even the diamond may be burned in oxygen, and the product of its combustion is carbon dioxide, differing in no respect from the CO_2 produced when charcoal is burned in air. When hydrocarbons burn the ultimate products of combustion are carbon dioxide and water.

During all the long centuries which preceded the Welsbach mantle and the tungsten filament practically all artificial light was derived from incandescent carbon. It glowed in the firelight within the caves which sheltered the Neanderthal man and later in the smoky flare of pine-knot torches, rude oil lamps, and rushlights. In the flickering flames of many candles it lent brilliance to the courtly fêtes of Versailles, and the Argand burner, the gas flame, and the carbon filament have brought light into our own homes. There is an almost unthinkable complexity to flame within which molecular systems are disrupted as their vibrating atoms rush, with the discharge of ions and electrons, to form new systems while radiating energy as heat and light. Since light has always been regarded as the symbol of joy and life-giving power, it is not surprising that fire was sacred and adorable in primitive religions. The Parsees adore fire as the visible expression of Ahura-Mazda. The Brahmans worship it as that "which knowest all things." In the Jewish Holy of Holies was a "cloud of light" symbolical of the presence of Yahweh. Jewish synagogues have their eternal lamps as the Greeks and Romans had their perpetual and sacred fires. In Christianity fire and light have always been conceived as symbols of the divine nature and presence. Human history and literature teem with their romantic associations. What pictures are called to mind by the mere mention of vestal fires in the temples, of watch fires on the hill, of camp fires in the forest or in the field with troops. The driftwood fire depicts the wreck of stranded ships that missed the gleam of the beacon which brought others safely to port. Candles and altar fires, the pillar of smoke, and the burning bush have their deep religious significance.

The extinction of lights marks the end of the ceremony of excommunication, while the symbol of reconciliation is the handing to the

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penitent of a lighted candle. Both life and love are symbolized as flame, and the fire on the hearth and the light in the window are synonymous with home.

There is thus little cause to wonder that centuries ago the fire worshippers from India and elsewhere in the East journeyed to Baku and there built temples where hydrocarbon gases issued from the ground. The ruins of the temples in which their priests tended the eternal flames exist to our own times.

When air is passed upward through a deep bed of incandescent coke as in the manufacture of producer gas, or when an automobile is running on too rich a mixture, or otherwise when the supply of air is insufficient for complete combustion, carbon monoxide is formed. It is utilized in metallurgy as a reducing or smelting agent of the utmost value and constitutes a large proportion of the important fuel, water gas, made by blowing steam through red-hot coke. Like carbon dioxide, the product of the complete combustion of carbon, it is a colorless and odorless gas, but, unlike the dioxide, it is intensely poisonous. It combines with the hemoglobin of the blood, thereby checking the absorption of oxygen in the lungs, and death is due to asphyxia from want of oxygen. The affinity of hemoglobin for carbon monoxide is three hundred times that which it has for oxygen, and one volume of the monoxide in eight hundred of air is fatal in 30 minutes. Much higher concentrations may be more quickly reached when an automobile engine is running in a closed garage.

Carbon dioxide, the gas once brilliant in the sparkle of champagne and now more dully effervescent in vanilla sodas, plays a part of extraordinary interest and importance in the economy of nature. It is poured into the atmosphere in vast quantities from volcanoes and in great amounts from burning coal and forest fires. It is also formed by oxidation of organic matter in the soil, and according to Geoffrey Martin, one acre of good garden land in summer evolves more than 6 tons of carbon dioxide. As Faraday first showed, the gas is readily reduced by cold and pressure to the liquid form, and by rapid evaporation of the liquid it may be converted into a snowlike solid, the " dry ice " now sometimes displayed in restaurateurs' windows beside a discouraged thermometer. It is produced industrially, for liquefaction and distribution, from flue gases; by the burning of limestone, and as a by-product of alcoholic fermentations.

Animals exhale carbon dioxide as the result of the oxidation in the lungs of organic wastes in the blood stream. It is normally present to the extent of about 4.5 per cent in human breath, and in a long life a man may exhale more than 20 tons of the gas. For the conduct of the processes which result in its production nature provides the average man with a lung area of about 100 square yards, or enough for a tennis court. The accumulation of carbon dioxide in the blood provides the normal stimulus to respiration.

Pure air contains about 0.03 per cent of carbon dioxide. In crowded halls the proportion may rise to 0.5 per cent. Since under ordinary atmospheric conditions the gas dissolves in water about volume for volume, it is constantly being washed down and slowly attacks the silicated rocks with formation of calcium and magnesium carbonates, by which soft waters are rendered hard and much trouble is caused by boiler scale. Ultimately such waters find their way to the sea, where marine animals, the chambered nautilus, the coral polyp, the oyster, the humble clam, and, most important of all, the minute foraminifera fix the calcium carbonate in their shells. If you rub down to a thin paste with water a piece of chalk you will find upon microscopical examination that it is composed almost entirely of the tiny shells of foraminifera. Such are the chalk beds of England, which, often more than 1,000 feet in thickness, extend across the island for 280 miles and at the coast line rise in those white cliffs to which England owes her name of Albion. But the chalk bed stretches far beyond the coast of England, over much of France, through Denmark and Central Europe, south to Africa, and even into Central Asia. Chalk and limestone are carbon compounds, and the overwhelming evidence is that, wherever found, they are the product of aquatic life in regions once submerged.

CARBONATES

The Latin word for a coin was *nummus*, and, for a reason which will presently appear, it gives its name to the nummulitic limestones, which extend over vast areas of North America and, in a band often 1,800 miles in breadth and of enormous thickness, from the Atlantic shores of Europe and Africa through western Asia to northern India and China. Of it the pyramids were builded, and from a knoll-like outcropping was fashioned that other memorial of antiquity, the Great Sphinx, before which even the centuries seem to pause.

This variety of limestone has been formed by the slow accretion in marine deposits of innumerable billions of the shells of foraminifera of the genus *Nummulites*, which is characterized by shells of extraordinary complexity of structure and a disk or coinlike form.

But limestone has been formed by other agencies, and its formation is still proceeding on a grand scale through the activities of the coral polyp in many of the warmer waters of the globe. Two and a half million square miles of ocean bottom are covered by coral mud and sands. The gigantic structures of the coral islands and the barrier reefs, of which one extends for 1,000 miles along the Australian coast, are the work of tiny bits of animated jelly, which abstract carbonate of lime from the sea water and so deposit it that it reproduces their own radiated structure. All the structural works of man fade into nothingness when compared with the results of the life activities of the minute foraminifera and the coral polyp. Höyborn calculates that the limestones and dolomites contain twenty-five thousand times the amount of carbon dioxide now present in the air. And chalk is still forming over 50,000,000 miles of ocean bottom.

In its metamorphosed form of marble, limestone exhibits the widest possible range of texture, color, and degree of purity. In it the greatest sculptors have found a medium for their best expression, and of it were built the exquisite lacelike fabric of the Taj Mahal and the structures which were the glory of Greece and Rome. The pearl, which in all ages has been associated with beauty and with riches, is in reality no more than a brilliant sarcophagus of carbonate of lime formed around an intruding parasite by the pearl oyster. There are, nevertheless, as Browning says:

> "Two points in the adventure of the diver—
> One, when a beggar he prepares to plunge;
> One, when a prince he rises with his pearl."

Like all carbonates, the pearl dissolves in weak acids with evolution of carbon dioxide. When, therefore, Cleopatra dissolved the pearl in vinegar she prepared the most expensive carbonated drink that history records.

CLIMATIC INFLUENCE OF CARBON DIOXIDE

Despite the minute proportion of carbon dioxide in the atmosphere its climatic influence is of extraordinary importance. The blanket which keeps the earth warm is composed wholly of carbon dioxide and water vapor, which absorb the heat that would otherwise be radiated from the earth. According to Arrhenius the removal of all carbon dioxide from the atmosphere would cause the temperature of the earth's surface to drop 37° F. The quantity of water vapor would, therefore, so diminish as to cause an almost equal drop, and the whole earth would be bound in Arctic ice. Thus an increased and uncompensated fixation of carbon dioxide by the rocks would bring on a new glacial period, whereas a slight augmentation of its proportion in the atmosphere would restore the tropical climate and the exuberant vegetation of the Carboniferous Age. Fortunately, there is now maintained a delicate balance in the carbon cycle in nature. The ocean is estimated to contain forty times as much carbon dioxide as the atmosphere, and, as equilibrium is disturbed by the fixation of carbon dioxide by the rocks and plants, a compensating portion of the ocean reserve passes into the air.

PLACE IN ORGANIC CHEMISTRY

Carbon is the central element of the organic kingdom. It is closely related to life and to energy. Most of the energy for the world's work in machine or animal or man is derived from the oxidation of carbon. Plants absorb carbon dioxide from the air to an estimated yearly amount of 13,000,000,000 tons and, under the stimulus of sunlight, fix the carbon in their structure in such compounds as cellulose, starch, and sugar. All vegetable and indirectly all animal life owes its existence, therefore, to the sun's rays acting upon the carbon dioxide in the atmosphere. The initial step in this fixation of carbon is probably the transformation of carbon dioxide to formaldehyde through reaction with oxygen and hydrogen, the elements of water. As the result of this reaction plants exhale oxygen, whereas animals in a reverse process, as we have seen, exhale carbon dioxide. Bailey has recently synthesized glucose by subjecting formaldehyde to the light of a mercury arc lamp.

In comparison with all the other elements carbon is strikingly notable for the enormous number of its compounds. The known compounds of all the elements other than carbon are only about 25,000, whereas the compounds of carbon reach the astonishing total of 200,000. This is due in large measure to the peculiar fact that the atoms of carbon exercise a powerful attraction for each other, by reason of which carbon compounds are built up which may contain many carbon atoms linked together in straight or branched chains, or in one or several rings, or in more complex configurations which include both chains and rings of carbon atoms in association with those of other elements. Hydrogen is thus associated in the great majority of carbon compounds, which very often also contain oxygen.

The amazing complexity of structure that carbon compounds may attain is indicated by the fact that compounds are known which have more than 200 carbon atoms in a single molecule, beside which a diagram of the solar system appears too simple to talk about.

Organic chemistry, which is the chemistry of the compounds of carbon, is further complicated by the fact that many carbon compounds contain the same elements in the same proportions, but differ from one another in their properties. Thus 86 compounds of the formula $C_{10}H_{12}O_3$ are known, and Cayley has calculated that 802 of the formula $C_{13}H_{28}$ are possible. Obviously, then, the properties of carbon compounds must depend not only upon the kind and numbers of atoms composing them, but also upon the manner of arrangement of these atoms within the structure of the molecule. Long-continued intensive study of the reactions of carbon compounds has enabled chemists to determine the structural arrangement of a large proportion of them and even, in very many cases, to build up or synthesize the compounds themselves from simpler substances or even from their elements. Among such notable triumphs are the synthesis of the vegetable coloring matters, indigo and alizarin; the long list of coal-tar compounds, including hundreds of brilliant dyes and many powerful drugs; high explosives; and the remarkable product known as bakelite.

Fortunately for the student, organic chemistry is characterized by the frequency with which the carbon compounds occur in series of closely related members and in groups or families exhibiting marked resemblances in structure and more or less alike in properties. Among such series, for example, are the paraffin and olefin hydrocarbons, and among such groups we find the cyclic hydrocarbons as benzene; the alcohols, ethers, and acids; the carbohydrates, like starch, cellulose, and the sugars; and so on. The student is assisted also by the frequency with which groups of carbon and associated atoms enter into combination as entities, called radicals, and so become familiar to him as structural units. Those who insist upon a speaking acquaintance with each of the carbon compounds are referred to the 4,700 pages of Richter's Lexicon, the Who's Who of carbon chemistry.

Some faint conception of the industrial importance of the carbon compounds may be gained by casual reference to a few of the industries that are directly based upon them. They will be found to comprehend the major portion of the invested capital, the annual turnover, and the workers of the nation. First of all is agriculture with its ramifications into prepared foods, canning, and packing. Closely related thereto are lumbering, naval stores, paper and textiles, and the special industries based on individual agricultural products as rubber and sugar. Of lesser importance, though only by comparison, are explosives, celluloid, artificial silk, solvents, dyes, and the thousands of other synthetic products of the laboratory. Of supreme significance are, of course, the fuels, coal and coke, natural and artificial gas, and finally, petroleum, which not only provides light and heat and flexible power, but supplies the lubricants without which the wheels of industry could not turn. Upon the reducing power of carbon fuels are based the steel and other metallurgical industries, and without the energy of their combustion we should have no steam-power plants, locomotives, motor cars, or ocean liners. Even the internal-combustion engines of the ox team and the jinrikisha would be stalled.

SOURCE OF ENERGY

The economic position of a nation is determined in large measure by the supplies of energy available to its people, and their social progress is similarly conditioned by the extent to which the price of energy permits its broad and general utilization and so increases manifold the effectiveness of the human factor in production. Cheap energy, efficiently used, is the formula for high wages and low prices.

Most of the energy upon which civilization depends to-day is derived from carbon and the compounds of carbon and hydrogen. In use, their potential energy is always first transformed into heat energy. The burning of 12 grams of carbon to carbon dioxide liberates 97,000 calories, and the combustion of 4 grams of hydrogen sets free 136,600. Since coal consists essentially of carbon with variable amounts of volatile hydrocarbons, while petroleum is a complex mixture of hydrocarbons, our reserves of coal and oil constitute vast reservoirs of potential energy. One pound of coal burned delivers heat sufficient to raise the temperature of 7 tons of water 1° F., an amount of energy that would lift a ton more than 1,500 feet. The same amount of petroleum burned would develop nearly 30 per cent more heat. Cheap coal and abundant petroleum must, therefore, be counted among the greatest material assets of a nation, and the United States has been bounteously supplied with both. It contains about 50 per cent of the world's reserves of coal, and despite the long drain upon our petroleum resources, we are still supplying 70 per cent of the world's production.

COAL

All the vast quantity of coal contained in the world and the still more vast amount of lignite originally came from carbon dioxide once present in the atmosphere. Long years ago, under the influence of sunlight, the plants constituting the rank and exuberant vegetation of the Carboniferous Period withdrew carbon dioxide from the air and built the carbon into their structure just as plants everywhere are doing to-day. A spruce tree weighing 1,000 pounds when dry has derived less than 3 pounds of mineral matter from the soil, but it contains more than 500 pounds of carbon combined with oxygen and hydrogen, the elements of water. In the warmth and humidity of the Coal Period, when the proportion of carbon dioxide in the atmosphere was perhaps greater than at present, trees unlike living conifers, but more resembling the ginkgo, grew luxuriantly with great ferns, giant club mosses, and gigantic horsetails. Ferns with fronds 10 to 20 feet long so deluged their surroundings with their spores that some coals seem to be almost wholly made of the spore cases. More than 2,500 species of fossil plants have left their record in the coal measures for us to read to-day. As these plants crowded each other in the swamps and died, fermentation and decomposition set in with gradual elimination of much of their substance as marsh gas and carbon dioxide, but with the proportion of carbon in the residue constantly rising. As the land sank or rivers rose, clays and sand were deposited upon this residue, which gradually was compacted into coal. It is thus possible to trace a perfect gradation from wood or peat, through brown coal and lignite to bituminous coal, and finally to anthracite and graphite.

As the result of successive depressions and uplifts of the land, the strata in every coal field are repeated many times. There may be as many as 100 coal seams, varying in thickness from a fraction of an inch to 40 feet or more, and separated by much thicker strata of limestone, iron ore, sandstone, and shale. In Nova Scotia the rock system comprising the coal measures is 13,000 feet in thickness, and in Pennsylvania and West Virginia it is 4,000 feet or more.

In the intervals between coal strikes we mine in this country about 600,000,000 tons of coal a year, a quantity which Charles P. Steinmetz calculated was sufficient, if used as a building material, to construct a wall, like the Chinese wall, entirely around the United States, while with the chemical energy contained in the next year's coal we could lift this whole stupendous structure into space to a height of 200 miles. There are so many other uses for coal, however, that neither operation seems worth while at present prices.

The production and distribution of coal in the United States is a business of such vast proportions and complexity that the mere maintenance of human relations within the industry involves problems so acute and difficult as to lead to frequently recurring crises, like the recent anthracite strike, in which, for 165 days, the miners received no wages, while the operators incurred enormous losses and the public got along as best it could. The basic difficulty in the whole coal situation is perhaps the fact that the mine capacity of the country is 40 per cent greater than the demand. With the many mines and far too many miners it is difficult to insure prosperity and employment to all.

The problems of the coal consumer are of corresponding magnitude, although perhaps less acute. His initial problem is to secure an adequate and regular supply of fuel at the lowest reasonable price, and his secondary concern is to utilize that fuel to the best advantage. Under present conditions the first is largely beyond his control, while as regards the second he commonly fails from lack of knowledge or from willful disregard of the requirements of good practice. The proportion of carbon dioxide in the flue gases of a boiler plant is a good index of its efficiency of operation. It varies from 5 per cent in small inefficient plants to 15 per cent or more in large plants operated at high efficiency. Under such conditions there is a saving of 60 per cent in the fuel cost of heat energy in the large plant. This and similar considerations constitute the argument for superpower systems.

In its consideration of the fuel problem the general public is chiefly influenced by two factors—the cost of fuel and the smoke nuisance. The exasperations due to both are doubtless familiar to all. Within a few weeks anthracite, in small lots, has sold in New York for as much as $48 a ton, while for years many of our cities have been immersed in a Stygian atmosphere, depressing as viewed, unhealthful when breathed, and defiling to all with which it comes in contact. In Pittsburgh the soot deposit per square mile varies, according to the Mellon Institute, from 600 to 2,000 tons per year. One jumps to the conclusion that this is wholly due to outpourings from industrial plants, but in Chicago it was found that 57 per cent of the nuisance was caused by domestic fires and the furnaces in apartment houses.

There have been many proposals for the relief of these deplorable conditions, and those that are of promise involve the initial processing of coal with the recovery of by-products and delivery to the consumer of a smokeless fuel, which may be coke or gas or an artificial anthracite. The whole fuel situation is, in fact, in a state of flux, and revolutionary developments are impending. Nowhere is this trend more evident than in the gas industry.

GAS

Gas has been well described as cleanly, smokeless, sootless, dustless, ashless, instantaneous, flexible, controllable. It is in all these respects an ideal fuel as millions of householders and thousands of industrialists in the districts fortunate in the possession of natural gas well know. Gas as fuel possesses form value—the ability to serve—in very high degree. It is, therefore, not surprising that its development has been consistent and progressive since William Murdock first lighted his Redruth home by gas in 1779. The first gas company in the United States was organized in 1816 to light the streets of Baltimore, but within the last five years the use of gas in Baltimore has been greater than in the preceding century. In the country as a whole the production of manufactured gas has doubled within the last ten years, and to-day the invested capital in the gas industry approximates $4,000,000,000 and its annual production exceeds 400,000,000,000 cubic feet. Imposing as these figures are, the industrial use of gas has just begun, and the inevitable house heating by gas has hardly started. Having learned to cook by gas, we shall presently extend its use to the gas-fired refrigerator.

Some 4,400 American cities and towns are now served by gas, but many others are still without it. They will before long be served by supergas plants designed for long-distance transmission. Already manufactured gas is being delivered 60 miles from its point of production. We have heard much of superpower plants at the coal mines, but their sponsors commonly ignore the fact that the enormous quantities of condenser water required for such plants are very rarely available at any mine. Supergas plants, on the contrary, require very little water, but may, nevertheless, distribute potential heat energy over wide areas.

As long ago as 1881 Sir William Siemens said:

> I am bold enough to go so for as to say that raw coal should not be used as fuel for any purpose whatsoever and that the first step toward the judicious and economic production of heat is the gas retort or the gas producer in which coal is converted either entirely into gas or into gas and coke.

Very recently, as the result of much research in France and Germany, an entirely new field has been opened to the gas companies through the production, from water gas, of methyl alcohol and gasoline. It has been a serious and not wholly undeserved blow to the distillers of wood in this country, who have not yet learned that the price of progress is research. It promises, none the less, ultimately to afford the gas companies a means of equalizing the present spread between their summer and winter load and the broader gap confronting them as their activities are extended to include house heating.

PETROLEUM PRODUCTS

While the origin of the coals and lignites must be regarded as established beyond question, there is another series of carbon products secondary only to them in importance, the beginnings of which are still the subject of some controversy. Concerning this series Le Conte says:

> Collected in fissures beneath the earth, or issuing from its surface, we find a series of products, some solid like asphalt, some tarry as bitumen, some liquid as pretroleum, some volatile as rock naphtha, and some gaseous. There is little doubt that all are of organic origin.

The genesis of the petroleum series is, nevertheless, still attributed by some to the formation and reactions of carbides within the earth's crust, but the weight of evidence certainly favors the assumption that the hydrocarbons of the petroleum series are the product of the decomposition of plant or animal remains and most probably the latter.

Bitumen, asphalt, and jet were undoubtedly the members of the petroleum series first recognized and used by man. Jet beads are found among the deposits in the paleolithic caves of Belgium and Switzerland. The Greeks prized jet as an amulet protecting its wearer against the perils of the sea, and in the eighteenth century Whitby jet, found in the neighborhood of Whitby Abbey, in England, was a fashionable, though somber ornament.

ASPHALT

Asphalt and bitumen are complex mixtures of compounds of carbon and hydrogen, in which the carbon content commonly ranges from 85 to 95 per cent. They occur in so-called lakes, deposits, and fissures in many parts of the world. One of the largest of these asphalt lakes is found in the island of Trinidad, and one of the most interesting is located in Los Angeles County, Calif. The Trinidad lake has an area of 115 acres and is 135 feet deep at the center. It has been the source of much of the asphalt used in road making, roofing, sheathing paper, and asphalt shingles. The California lake has been a pitfall and a sepulcher for thousands of prehistoric animals and a mine of richest treasures for the geologist. Here mammoths were entangled like flies on sticky paper, and the saber-toothed tiger, seeking water in the pools of its treacherous, dust-covered surface, or springing upon his ensnared prey was himself enmeshed to leave his bones commingled with those of myriads of other victims.

In Utah there is a notable deposit of high-grade asphalt known commercially as Gilsonite. It occurs in veins often as much as 18 feet in width, extending, in some cases, for 8 miles, and the deposit is estimated to contain more than 30,000,000 tons of the material.

In Egypt, at one time, the terms for "asphalt" and "mummy" were synonymous owing to the practice of the Egyptians of preserving the bodies of the dead by wrapping them in asphalt-coated cloths. Thousands of years ago the Persians carved vases and animals in asphalt and set the eyes in statues with it. There was, near Babylon, a great asphalt lake, and the bricks of the walls and palaces raised by Semiramis and the kings of Babylon were bonded with asphalt cement. An inscription of about 600 B. C. records that Nabopolassar, the father of Nebuchadnezzar, "made a road glistening with asphalt and burnt brick," which we may assume to be the earliest asphalted block pavement.

NATURAL GAS

At the other extreme of the petroleum series and commonly associated with petroleum, we find natural gas which has been termed "nature's bonus to America"—a bonus so generous that our 1924 production amounted to 1,142,000,000,000 cubic feet, or 2.7 times the output of manufactured gas in 1925.

The intrinsic value of natural gas as an asset to the Nation, its unique form value as a fuel in steel works and other great industrial plants, its cheapness and convenience as a source of light and heat in more than 2,000,000 American homes, and finally its remarkable potentialities as a raw material for synthetic products would have led a more provident and perhaps deserving people than ourselves to organize its development upon a basis both careful and farsighted. Instead, its exploitation has been characterized by a reckless and appalling waste at the wells, in transit, and in use. Even the leakage after the meter has averaged 19,000 cubic feet per year, per house. Much of this waste may be attributed to lack of coordination between the gas and petroleum industries and much more to the economic and legal structure, which permits the first driller of a well to appropriate the gas belonging to his neighbors unless they themselves immediately sink wells.

The gas is held, under pressures which may exceed 1,000 pounds to the square inch, in the porous rock strata underlying the field. It varies widely in composition in different localities, but that from a given field is usually quite constant in character. Though it may contain the lighter members of the paraffin series in very different proportions, it usually consists chiefly of methane and carries about 75 per cent of carbon, or 37.5 pounds per 1,000 cubic feet. Much carbon black for printer's ink and other purposes is made from natural gas by methods of incomplete combustion which yield only about 1.3 pounds of black per 1,000 cubic feet burned. The fuel value of the gas is usually somewhat over 1,000 B. t. u. per cubic foot, so that 15 cubic feet carry the heat equivalent of a pound of good coal.

From the low-pressure gas associated with petroleum it is possible to recover, by compression or absorption in oil or charcoal, varying amounts of a light gasoline of especial value for blending purposes. The yields in some cases may be as high as 5 gallons per 1,000 cubic feet of gas, but are commonly much lower. The total amount so produced in 1925 is estimated to be about 30,000,000 barrels, or about 11.5 per cent of our consumption. Of all the States, Oklahoma has contributed much the largest proportion of this natural gasoline.

Of even greater interest for the future are the possibilities of producing from natural gas by synthetic methods alcohols, esters, glycols, and other organic compounds in great variety, as well as motor fuels of new types.

DEVELOPMENT OF PETROLEUM INDUSTRY

There are still many stately homes in New Bedford and other New England towns to bear witness to the prosperity which the whaling industry once enjoyed. The perils which attended the long voyages of its hardy crews and sturdy ships were incurred in a search for carbon compounds for lighting and lubrication. The romance of its adventures as recorded in "Moby Dick" and the "Cruise of the Cachalot" has since, however, been far exceeded by the greater romance of petroleum. Where a kill of the whaler might yield 80 barrels of oil, the wildcatter now brings in a discovery gusher producing thousands of barrels a day, and the world rushes in to share his fortune.

Petroleum has been known from the earliest times and was, to some slight extent, used even by the ancients. Baku, famous in antiquity for its sacred fires, is now more famous for its forests of derricks pumping oil. Here was struck the Droojba fountain, from which 2,000,000 gallons of oil a day spouted in a stem, 18 inches in diameter, to a height of 300 feet, with a roar which was heard for miles. Can any other industry offer such a spectacle or one presenting such potentialities of sudden wealth?

The great Roman architect, Vitruvius, writing in the time of Augustus, says:

> (Some waters) flow through such greasy veins of soil that they are overspread with oil when they burst out as springs: For example, at Soli, a town in Cilicia, the river named Liparis, in which swimmers or bathers get anointed merely by the water. Likewise there is a lake in Ethiopia which anoints people who swim in it, and one in India which emits a great quantity of oil when the sky is clear. At Carthage is a spring that has oil swimming on its surface and smelling like sawdust from citrus wood, with which oil sheep are anointed.

The real romance of petroleum began, however, in America on August 28, 1859, when the Drake well came into production near Titusville, Pa. It was further stimulated by the classic report of Prof. B. Silliman on the economic value of rock oil, in which, with marvelous prescience, he forecast most of the industrial applications of petroleum.

The Drake well went down only 69 feet and yielded less than 30 barrels a day. It led, however, to such feverish exploitation of the Oil Creek district that before 1863 the number of wells exceeded 350. Some of these had records, for a time at least, of 1,000 to 3,000 barrels daily, and the market was so flooded with oil that 10,000,000 gallons are estimated to have run to waste in the absence of purchasers. To-day we are producing more than 700,000,000 barrels from about 300,000 wells, the deepest of which is down more than 7,500 feet.

In the porous strata of the oil sands, and beneath a protective cap of impervious rock, the oil and gas accumulate under pressure from the water below and move upward to the highest point which the conformation of the cap permits. The well penetrates this cap and brings in the initial gusher. The burden of the industry is, nevertheless, carried by the modest, dependable 25 or 50 barrel well, which stays on the job all the time.

The compelling demands of our complex civilization have led the oil industry to assume economic obligations so tremendous as scarcely to permit of their appraisal. Its lubricants have become a vital necessity wherever a wheel is turned. Billions of gallons of its kerosene bring light to isolated homes and are now beginning to drive tractors on the farm. Even the empty Standard Oil tins serve many score of useful purposes in the domestic economy of China and throughout the East. The tank wagon distributing fuel oil has become, in many American cities, more familiar than the coal cart, and we cook our food with water gas enriched with oil gas.

In the Diesel engine the heavier petroleum products develop power of extraordinary cheapness, which is widely utilized in industry. Diesel engines now drive submarines and freighters, and the Diesel locomotive is demonstrating its economy on branch railroad lines.

It is indeed in its relation to transportation that the dependence of modern civilization upon petroleum is most strikingly apparent. Oil has replaced coal in the latest ocean liners and generally throughout the navies of the world, while gasoline supplies the energy for a circumfluent system of transportation which clogs our city streets and crowds our highways. It has even enabled transportation to assume a three-dimensional phase, which has carried man into the air and endowed him with vast new potentialities for good and evil.

In 1898 there were only four automobiles in the country, and one of these was in a circus. Another was used for exhibition purposes, and the two remaining were objects of curious interest as mechanical freaks. To-day there are 20,000,000 automotive vehicles on our roads. Taking cars and trucks together, they are estimated to consume an average of 10 barrels each of gasoline a year.

Our fathers might well have asked, "By what conceivable industrial and financial structures can such vast responsibilities be met?" That they are met in a truly remarkable way is due to the fact that the petroleum industry has boldly directed its own course in production, transportation, and distribution, undeterred by precedent or established usages. It is, throughout, and most distinctively, an American industry which has developed its own methods; its particular and often vivid types, as the wildcatter and the driller; its own forceful and creative personalities.

The United States petroleum industry has produced more than 8,500,000,000 barrels of oil. It is still contributing 70 per cent of the world's production, and there remain an estimated 9,000,000,000 barrels in reserve. The price of its raw material is subject to such range and violence of fluctuation as would put most manufacturers out of business, but the tank wagon is always on the route. Behind it is the second largest American industry and an investment of more than $9,000,000,000.

No mere figures can, however, convey an adequate impression of the vast extent and permeating ramifications of the petroleum industry. One must picture, if he can, the wildcatter with the spirit and optimistic courage of the pioneer; the driller, doggedly persistent and with a presidential economy of speech; the wild excitement of a discovery gusher; vast storage basins, which may hold 3,000,000 barrels in a single concrete reservoir; tank farms, like strangely ordered villages; pipe lines of a length far exceeding that of all the railways in any country in the world except our own; tankers on every sea; the endless procession of tank cars to and from more than 500 refineries, some of which are cities in themselves; thousands of cracking units and gasoline-recovery plants; the tank wagons on every road and innumerable filling stations. Yet the refineries often receive no more per pound for gasoline than one pays for cordwood in Boston and little more than Bostonians pay for anthracite.

An ample oil supply assures such benefits to industry and is so vitally essential in time of war that a somewhat menacing economic nationalism is developing around petroleum. We can, therefore, continue only at our peril the uncoordinated wastefulness which has always characterized our own production. As many have pointed out, this is chiefly due to the defective legal structure under which all owners in a field are now forced by the first driller to raise their oil or lose it to him. The remedy may well be in a Federal law compelling the development of the field as a unit, as Henry L. Doherty has recently urged before the Federal Oil Conservation Board.

There are still amazing opportunities for economies in oil refining, as by the general introduction of modern fractionating equipment and the improved processing of lubricating oils. Moreover a new phase, of great significance, now confronts the industry, for petroleum is about to take its place as a raw material of the first importance in the synthesis of organic chemical compounds. It is to-day the source of numerous alcohols and their derivatives and may soon provide the cheapest base for the synthesis of rubber.

Research has nowhere been more prolific in results of benefit to industry and to mankind than when applied to the chemistry of the compounds of carbon, and much of this fundamental research has been conducted by American chemists.

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