WATER
IN THE
PHYSIOLOGY
OF
PLANTS

BY

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PREFACE

In writing a modern scientific monograph, the writers must choose between a detailed treatment of the literature and a brief exposition of the facts and principles of the subject. In this volume, we have attempted to cite most of the relevant literature; in Chapter 1, the broader reviews; within the subsequent chapters, the more specialized papers. From these, we have repeated the minimum of material essential to a connected discourse on the subject, feeling that interested students will refer back to the original papers for details.

Thus, whereas this is intended as a reference work, it is hoped that its reading will not be so tedious as to preclude its use in the classroom. If any part seems needlessly long, it is because we deem the material of particular concern to certain workers in the field, or because it pertains to our own research. For this, our only excuse is that one usually reports most accurately that subject in which he is personally interested.

One further choice that must be made in treating so broad a subject is that of vocabulary. One could use the loose and rather indefinite terminology of two or three decades ago; or he may employ the more accurate wording of the modern plant physiologist; or he might adopt the highly technical language of the physical chemist. Again we have compromised. This volume has been written for use by present day botanists and plant physiologists; hence, we have used their language. At the same time, we have cited several recent treatises that employ, almost entirely, the vocabulary of physical chemistry. We realize the need for more accuracy in the definition and use of technical terms; also the desirability of a universal language for all scientists. On the other hand, the writing of a monograph for a certain group in a language with which they are not familiar is futile.

If the language of physical chemistry is to be adopted by physiologists, and most modern students will agree that it should be, two changes must be made. First, physical chemistry must become a required course for all undergraduates in physiology, and its terminology should be introduced and used relatively early in their careers. Second, physical chemists must develop a deeper appreciation for certain fields of physiology which, up to the present, have been somewhat or even totally neglected. Although many of the living systems with which the physiologist deals may be so complex as to offer little hope for thermodynamical analysis by present methods, their tremendous importance with respect to the well being of man, both through his own physiology, as well as that of the plants and animals upon which he depends for food and clothing, demands constant and sympathetic study. And the exact vocabulary of physical chemistry must be adapted to these complex functions if it is to be of use in their study. Though the thermodynamicist may be content to treat only the initial and final states of a system, the physiologist is interested in every mechanical detail of its operation, and his studies must deal with the description as well as the mathematical aspects of its functioning. Ultimately, all these problems must submit to analysis in terms of the molecular mechanics of the systems involved.

With regard to the above problem, we hope that this volume will serve two purposes. For plant workers, we trust that it will develop an appreciation for the exact analytical methods of the physical sciences. Much of the progress in the field of water relations has resulted from use of such methods. For the physical chemist, on the other hand, we hope to have presented a challenge to broaden, if need be, his view of the physical universe to encompass those many living systems upon which his very existence depends. There should be some common ground where these two may meet to work out their common problems for the mutual benefit of all. And if such cooperation between fundamental and applied scientists will lead to a warmer feeling of appreciation by both for their common interests, much good will have been done. The field of plant water relations presents many problems upon which such cooperative effort may be profitably spent. We hope that our volume may present these problems in such a way that many workers will be stimulated in their study.

In conclusion, we would like to express our appreciation to our many friends who have contributed to the writing of this monograph. Through conferences, discussions, and, in some instances, almost daily contacts, they have helped clarify some of the intricate problems involved in plant water relations. For reading parts of the manuscript we are especially indebted to Dr. L. E. DAVIS; for use of manuscripts, which at the time of writing were not yet published, we thank Dr. B. S. MEYER and Mr. T. C. BROYER; for counsel and advice in the development of the concepts of osmosis and osmotic pressure we express our appreciation to Drs. N. E. EDLEFSEN, F. A. BROOKS, MAX KLEIBER, H. A. YOUNG, H. G. REIBER and R. B. DEAN. Translations of many foreign papers were kindly put at our disposal by Dr. F. J. VEIHMEYER and Mr. T. C. BROYER. For encouragement throughout the preparation of the manuscript and aid in its final organization we are grateful to Dr. W. W. ROBBINS.

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This book has been produced during troubled times. Because publication has been delayed, many current papers are not cited in the text. Some of these we are reporting here in an effort to bring our Bibliography up-to-date.

Workers on the properties of liquids and solutions are in general agreement that the unusual behavior of water results from coordination of its molecules by hydrogen bonding. Assuming a bonding energy of 4.25 K cal. per mole, TAFT and SISLER (1947) calculate that, of the energy absorbed upon heating, 11 per cent is utilized in breaking bonds during melting of ice, 16 per cent is used raising the temperature from the melting to the boiling point, and 73 per cent goes in the vaporization process. WEISSLER (1949), using the velocity of sound at different temperatures to determine coordination, concludes that water undergoes a decrease in association of about 7.2 per cent between 0°C. and 100° C. Sound waves will detect molecular aggregates that are stable for 10^{-6} seconds. A previous value of 13.2 per cent was found using Raman spectrum analysis. The difference is due to the fact that the latter method detects aggregates that are stable for only 10^{-14} seconds.

In contrast to TAFT and SISLER, SEARCY (1949) calculates a value of 6.4 ± 0.5 K cal. for the H-bond energy in water. He concludes that repulsive as well as attractive forces contribute to the dipole energy.

Using a new formula to determine an index of association in liquids, PARSHAD (1947) has calculated values between 240 and 325 for a series of non-polar compounds;

values of 403 to 745 for some common associated organic liquids; and a value of 5010 for water. The theory that liquids contain points of abnormal coordination (holes) within their structure is receiving continued support and many calculations are being made on the activation energy required for movement of molecules from position to position (flow). Studying thermal conductivity of liquids, PALMER (1948) finds that in associated liquids H-bonds assist in the collisional transfer of heat. This is brought about by *(1)* causing orientation of the molecules in the direction of flow, and *(2)* assisting transfer by rupture of bonds at the high-temperature end and reforming them at the low-temperature end. If the entropy of vaporization can be considered a measure of H-bonding, then in water 80 per cent of heat transfer is by this mechanism.

As the picture of water structure becomes clearer, many of the anomalous properties of solutions are being elucidated. Swinging from early assumptions, based on studies of dilute solutions, that all solutions are perfect and that apparent deviations result from association or compound formation, physical chemists went to the other extreme and proposed that all solutes are completely ionized with abnormal behavior resulting from the interaction of force fields (DEBYE and HÜCKEL). Now a middle course wherein ionic and molecular interaction as well as chemical bonds are given due consideration seems best. With the introduction of spectrum analysis distinctions can be made and the type of bonding identified. Gradually the relations between the thermodynamic properties and the molecular structure of solutions are being studied, and concentrated as well as dilute solutions are being given consideration (REDLICH, 1949). The literature on the properties of solutions is too large to consider here and the reader is referred to the Journal of Chemical Physics, the Journal of Physical Chemistry and Chemical Reviews as fertile sources.

Coordination of water is reflected in the high internal pressure or cohesional force which this compound exhibits. TEMPERLEY (1947) has shown that liquid water can support tensions up to 60 atmospheres in glass tubes. Using air-free water in Berthelot tubes SCOTT *et al.* (1948) could develop a tension of only 32 atm. Though these values differ appreciably, the latter is sufficient to explain the flow of sap to the tops of the tallest trees. Hydration phenomena have also received attention. For example, SIMHA and ROWEN (1948) conclude that, in systems containing moist cellulose, silk, and wool, behavior at low moisture levels can be explained in terms of adsorption theory; at high moisture levels the systems can be analysed in terms of a theory of polymer-liquid mixtures; in between the two extremes a transition occurs.

Although osmotic pressure measurements continue to serve in the determination of the molecular weight of large molecules, little change has occurred in the theoretical aspects. BURSTRÖM (1948) has attempted an evaluation of the significance of turgor of the living cell. Departing from the classical definition "turgor is the pressure acting from inside the cell on the cell wall" (p. 58, last line), BURSTRÖM by devious analysis arrives at the expression $T = O - E$ where $T =$ turgor pressure; $O =$ osmotic value of the cell sap; and $E =$ osmotic value of the external medium. To us this T is simply a net or corrected osmotic pressure. It is shown as such in BURSTRÖM's Fig. 2 (page 61). It could equal our turgor pressure only when the cell is in equilibrium with the external solution of concentration E. As in several previous cases (CRAFTS, 1943), we feel that this redefinition of terms is not justified. It leads to such confused statements as—"T increases as the cell loses water—" (page 62, lines 1 and 2), "turgor—expresses a pressure realized in the cell—," "This deduction of turgor pressure—exactly shows the pressure actually exerted from within the cell on the cell wall" (p. 63), and "The turgor pressure must decrease when a cell absorbs water and the wall pressure increases" (p. 64).

This dilemma seems to arise from a failure to appreciate that (in our symbols) when $OP = DPD$, $T = 0$, when $OP = TP$, $DPD = 0$, and at all other states $OP = DPD + TP$. While these relations are most easily examined at equilibrium, a state of flux does not invalidate them. And the definitions which they imply are simple, clear, and in accord with classical considerations of osmotic pressure.

In the field of cell water relations a number of valuable contributions have appeared. In a general discussion of swelling and shrinking (Trans. Faraday Soc., 1946) water-holding forces in biological systems received critical consideration. The nature of vacuolation of protoplasm following certain types of swelling is made more clear by FAURÉ-FRÉMIET. SEIFRIZ presents convincing arguments for a distinction between osmotic pressure and imbibition, and discusses swelling and shrinking phenomena in the light of known protoplasmic structure.

In a subsequent general discussion on interaction of water and porous materials (Faraday Soc. Discussion, 1948), BENNET-CLARK restates his belief that water secretion from the cytoplasm into the vacuole of the plant cell actually occurs. In considering LEVITT's (1947) claim that secretion values reported are thermodynamically unsound, BENNET-CLARK casts doubt on the validity of the value used by LEVITT to represent water permeability in calculation of water velocity.

LUNDEGÅRDH further identifies an active water mechanism in roots with the absorption of salts from the culture medium. As in previous work, he assumes that "anion respiration" provides the energy.

Recent findings have added to our understanding of auxin-induced water uptake by cells. In an important paper LEVITT (1948) offers convincing evidence that auxin-enhanced water absorption by potato discs is not active water uptake, as suggested by several investigators, but rather a result of altered plasticity of the cell wall. The manner in which auxin may increase wall plasticity is not understood but KELLY (1947) has shown that it is an aerobic process in *Avena* coleoptile segments. AUDUS has critically reviewed the problem of cell elongation (Biol. Rev., 1949).

Studies on water secretion and transport by *Nitella* cells have been extended by OSTERHOUT (1949). That the pumping mechanism demonstrated in *Nitella* under somewhat arbitrary conditions could operate in certain kinds of cells seems validated by a theoretical consideration by FRANCK and MAYER (1947) of an osmotic diffusion pump.

The absorption of water by root systems is being given detailed consideration by KRAMER, whose book on the subject is in press. FREY-WYSSLING (1941) has demonstrated guttation under conditions of high water absorption and low transpiration in several woody species, and DANIEL (1949) observed xylem exudation from excised roots of several coniferous species. Studies on the effect of certain salts on increasing root pressure and tissue resistance to infiltration in sunflower, tomato, and dahlia were made by VOLK (1944).

HAGAN (1949), by measuring water intake by excised root systems of sunflowers growing in moisture-deficient soil, has verified the autonomic diurnal cycle of root activity studied by GROSSENBACHER (1938). The diurnal cycles continued for about 6 days but were terminated if the roots were aerated with N_2 or CO_2. Similar cycles observed in roots washed free of soil indicate that the activity is a function of the root and not of its environment. Such roots in water exuded water during the day and withdrew it during the night. HAGAN attributes this activity to changing hydration of the cytoplasm.

MITSCHERLICH (1947) has pointed out that water requirements of plants follow the law of plant growth. Water requirements are high for plants having short vegetative periods and they decrease with increasing nutrient supply. More specific data on the effects of potassium and calcium on the water relations of plants were given by WOESTMANN (1942). Potassium induced water storage, water uptake, and transpiration, probably through its effect of promoting hydration of the protoplasm. Calcium diminished protoplasmic hydration and consequently lowered protoplasmic permeability and hence water absorption. Water storage and transpiration were reduced. Plants deficient in nitrogen showed decreased transpiration, a failure of guard cells to function normally, and an increase in cold resistance and protoplasmic viscosity (GESSNER and SCHUMANN, 1948).

WADLEIGH (1945) has made a new approach to the problem of plant-soil water relations. He devised a method for integrating the variables that account for the total soil-moisture stress against which the plant absorbs water. When leaf elongation of cotton plants was expressed empirically as a second degree function of soil-moisture stress, values close to 15 atmospheres for the stress inhibiting leaf growth were calculated (WADLEIGH and GAUCH, 1948). Additional data indicating that under good conditions of soil aeration and fertility the rate of vegetative growth increases with increasing soil moisture within the range from near the permanent wilting percentage to near soil saturation have been presented by HAYNES (1948). He concludes that corn plants subjected to daily periods of temporary wilting produce small vegetative growth when under humid conditions. On the other hand, WILSON (1948*b*) has shown that tomato stem tips can maintain their highly hydrated state at the expense of older mature tissues. Thus they can increase steadily in length throughout the day and night even when the plant as a whole passes through a diurnal cycle with the water balance on the negative side during the day.

MORTON and WATSON (1948) conclude that the rate of leaf production by apical meristem is unaffected by water supply. The number and size of cells per leaf increased with increasing water supply. Net assimilation was greatly reduced by water deficit.

Reviewing plant-water relations, Tageeva (1946) found that wheat plants have reduced water content as they mature; upper leaves dehydrate more than lower ones. Nevertheless, the upper leaves have a greater rate of photosynthesis than lower ones. Low water supply results in an increase in soluble carbohydrates leading to decrease in photosynthesis. Eaton and Ergle (1948) find that in certain plants such as cotton, water deficit may depress carbohydrate utilization to a greater extent than it does photosynthesis leading to an increased sugar content.

In the discussion mentioned above (Faraday Soc. Discussion, 1948) papers by van den Honert, Lewis, Fogg, and Crafts deal with water and food movement in plants and the relations of leaf cell walls and leaf surfaces. Van den Honert, considering the role of living root cells, xylem conductors, living leaf cells and the "gaseous part" (intercellular spaces, stomata, and air layer around the leaf) concludes that the greatest resistance to water movement is the "gaseous part." He agrees with Gradmann's (1928) views that this phase may exert limiting influence on water transport.

Lewis presents further data on the hydrophobic nature of the outer walls of leaf mesophyll, while Fogg pictures the effects of varying water conditions of underlying tissues on the nature of the leaf surface.

Crafts, in an analysis of the physical nature of sieve-tube protoplasm, and sieve tube walls, concludes that the mature, functioning sieve tube is a highly specialized structure. The optical nature of the walls and their high water content suggest that they have a loose open structure. The degradation of the sieve-tube cytoplasm attending maturation of these elements results in a loss of their semipermeability. It is concluded that this also denotes an open mesh structure. It is suggested that the open structure of sieve-tube walls and cytoplasm constitute specialization favoring a mass flow of the assimilate stream. Went and Hull (1949) present evidence for a temperature coefficient of less than 1 for both rate and intensity of sugar transport in the tomato plant.

The perplexing problem of stomatal behavior was reviewed critically by Wilson (1948*a*). Theories proposing that stomatal action can be accounted for by changes in permeability, changes in enzyme activity, or variation in colloidal hydration were not considered adequate as an explanation for the observed effects of light, temperature, and humidity on stomatal aperture.

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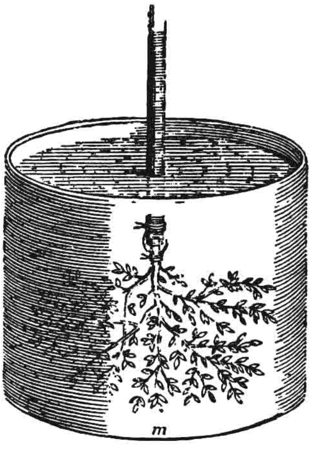

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Chapter I

INTRODUCTION

The relation of water to plant cells is at the same time one of the oldest and one of the most modern of physiological problems. MALPIGHI, HALES, KNIGHT, and a host of early plant scientists recognized this important field of study. Survey of modern literature proves that water relations still claim the attention of leading plant physiologists. Viewpoints change; methods improve; still the underlying principles of water absorption and utilization challenge the researcher. Almost all plant functions involve water relations in some form or other; provision of adequate water for maximum growth of plants is the basis of successful agriculture in many parts of the world.

Writing a concise monograph on water relations is a difficult task for it involves selecting from an immense literature material relevant to modern concepts and problems. To be of value, furthermore, such a monograph should contain original work by the authors or it should involve synthesis of new concepts from previous publications. Availability of modern abstracting and reviewing agencies renders almost useless a mere compilation or uncritical review of published articles.

This volume aims to attain both of the above objectives; it also attempts to aid students in becoming familiar with contemporary literature in the field. A balanced treatment of the subject involves a description of the structure of water and aqueous solutions, a review of the concepts of the mechanism of osmosis, consideration of the water relations of individual cells, and finally, analysis of the functions of absorption, movement, retention, and loss of water by organized plants. It is obvious that space cannot be devoted to a detailed historical review. Mainly as an aid to students, the following introduction to source materials is included.

Works of MALPIGHI (1675), HALES (1738), and KNIGHT (1801) are of historical interest only. Ideas in their time were confused by failure to clearly distinguish between the water relations of plants and animals.

Discovery of the microscope stimulated interest in plant structure. The earlier works on conducting systems are thoroughly covered by STRASBURGER (1891) and HABERLANDT (1914). Meanwhile DUTROCHET (1827), PFEFFER (1877), VAN'T HOFF (1887 and 1888), and DE VRIES (1918) laid the foundations for a physical analysis of cell water relations through their studies on osmosis and osmotic pressure. Work by BERKELEY and HARTLEY (1906), MORSE (1914), FRAZER and MYRICK (1916), and BERKELEY, HARTLEY, and BURTON (1919) provides a quantitative basis for such analysis.

Theoretical treatment of osmotic systems by LEWIS (1908), HALDANE (1918), BANCROFT and DAVIS (1928), and others has materially broadened our concepts while reviews by FINDLAY (1919), MEYER (1938), and URSPRUNG (1938) have marked progress in this field. Of treatments in physico-chemical texts, those of WASHBURN (1921), LEWIS and RANDALL (1923), GLASSTONE (1940), and GETMAN and DANIELS (1943) are noteworthy.

Application of physical principles to the problems of water conduction in trees led to the cohesion theories of DIXON (1914) and RENNER (1915). Measurements by MACDOUGAL (1926) have largely substantiated the theoretical considerations involved as have biophysical studies by BODE (1923).

The general field of plant water relations has been covered by the works of LIVINGSTON (1903), MAXIMOV (1929*a*), and WALTER (1931*b*). URSPRUNG (1938) has presented a detailed review of most of the early work including his own and that of his collaborators. Ecological aspects of water relations are stressed by MAXIMOV (1929*a*), WALTER (1931*b*), and MONTEMARTINI (1943). Applications of the principles of soil physics and plant physiology to problems of water utilization by plants have been made by BRIGGS and SHANTZ (1912) and MAXIMOV (1929*a*) ; and more recently by VEIHMEYER and HENDRICKSON and their associates (see papers from 1927 to 1946). The relations of soil salinity to plant growth have been investigated at the U.S.D.A. Salinity Laboratory. This and other works on soil salinity have been reviewed by MAGISTAD (1945).

Thermodynamic treatments of plant and soil water relations are given by EDLEFSEN and ANDERSON (1943) and BROYER (1946), and also by STERN (1933).

Specialized aspects of water relations involve the binding of water by cellular constituents including cellulose, proteins, and the living protoplasm. Hydration of cellulose is treated by STAMM (1936), HEUSER (1944), and WISE (1944). Protein hydration is discussed by GORTNER (1938), SCHMIDT (1938), and SPONSLER, BATH, and ELLIS (1940). SPONSLER (1940) and FREY-WYSSLING (1938) have studied hydration phenomena of the living protoplasm.

Problems of permeability are reviewed periodically in the Annual Review of Physiology. In 1945 this topic was covered by S. C. BROOKS. Work on the uptake and exchange of solutes is described by HOAGLAND (1944) and KROGH (1946). Theories of membrane permeability are extensively treated in the works of BROOKS and BROOKS (1941), DAVSON and DANIELLI (1943), and HÖBER (1945).

Osmotic quantities of cells and their interrelations have received detailed attention by THODAY (1918), HÖFLER (1920), BECK (1928), and MEYER (1938, 1945). Cryoscopic determination of osmotic pressure values has been stressed by WALTER (1931*a*) and his associates. URSPRUNG (1938) has compiled much of the work on the plasmolytic method. HARRIS (1934) has accumulated an abundance of data on freezing point lowering of plant saps, particularly as related to distribution of the plants.

BENNET-CLARK, GREENWOOD, and BARKER (1936) have renewed the interest in active cell water relations. Papers by BENNET-CLARK and BEXON (1940, 1943, 1946), MASON and PHILLIS (1939), VAN OVERBEEK (1942, 1944), and LYON (1942) treat various aspects of the same subject.

Water relations are intimately involved in frost and drought resistance. Reviews by LEVITT (1941) and SCARTH (1944) report work on frost resistance. MAXIMOV (1929*a*, 1929*b*, 1941), TUMANOV (1929), VASSILIEV and VASSILIEV (1936), MARTIN (1930), and AAMODT and JOHNSTON (1936) have covered drought resistance.

The role of water in the physiology of plant cells has been studied in detail in recent years. KÜSTER (1935), URSPRUNG (1938), and GUILLIERMOND (1941) have provided monographs covering this subject, while BRAUNER (1932) and STRUGGER (1935) describe methods for studying the physiology of cells. The AAAS' monograph "The Cell and Protoplasm" (1940) covers many aspects of cell physiology as does also the monograph of the American Society of Plant Physiologists, "The Structure of Protoplasm" edited by SEIFRIZ (1942).

Finally, REED (1942) gives a historical view of plant water relations with additional reference material; two recent books covering the field of physical biochemistry by BULL (1943) and HÖBER (1945) provide a wealth of information for the student of cell physiology.

Chapter II

STRUCTURE OF WATER

Introduction:— Most cells originate in a highly aqueous medium; they use water in growth and other vital processes; in most instances, they consist largely of water throughout their life span. Logically there should be an intimate relation between the functions of cells and the properties of water and dilute aqueous solutions. A study of plant water relations impresses one that this is true.

Water enters into the composition of carbohydrates, proteins, and other compounds making up the walls and protoplasts of plant cells; it is combined with various colloidal constituents of cells as water of hydration; it is involved in many metabolic processes in the plant; and it exists as a liquid in the solutions occupying the vacuoles of living cells and the lumina of conducting elements. Due to the many forces tending to reduce the activity of water molecules, it may be difficult to distinguish between the various states in which water exists within the plant.

Combining the elements hydrogen and oxygen, water in its simplest form corresponds to the formula H_2O. Many more complicated forms have been proposed to explain its various properties. Most of these involve association or polymerization.

Water boils at 100° C. and freezes at 0° C. when under one atmosphere pressure; it is liquid throughout the temperature range at which plants thrive. Many plants can survive freezing temperatures; certain spores can stand boiling; photosynthesis and transpiration may take place through a range from near freezing to the thermal death temperature around 40° to 50° C. Many plant functions, however, find their optimum within the range from approximately 20° to 30° C. The occurrence over a large portion of the earth's surface of temperatures within these narrow limits depends, among other things, upon the large latent heats of vaporization and freezing of water, and upon its heat capacity and conductivity. HENDERSON (1924), discussing the fitness of the environment, points out the many unusual properties of water, most of which apparently contribute in some way to the well-being of plants. It is interesting to note the exceedingly narrow range of temperature and moisture within which our important economic plants thrive, and to point out the role played by water in maintaining these conditions.

Structure:— Water has long been recognized as a compound of unusual character. TABLES 1 and 2 list some of the physical properties of common elements and liquids. Water stands out, having a very high heat of vaporization and a fairly high heat of fusion. (For further data of this type, *see* BERNAL and FOWLER, 1933, Table III). Of the compounds listed, water has the greatest surface tension, internal pressure, and dielectric constant. These latter properties indicate the interatomic forces present in the molecule.

Formed from hydrogen which boils at —253° C. under atmospheric pressure, and oxygen which boils at —180° C., water boils at 100° C. If normal in its properties water should boil at a very low temperature variously estimated at from —65° C. to —100° C. Its freezing point should

TABLE 1.—*Some thermal properties of water and several elements and compounds:*—

SUBSTANCES	HEAT CAPACITY PER GRAM FORMULA WEIGHT		HEAT OF FUSION CALORIES PER GRAM		HEAT OF VAPORIZATION CALORIES PER GRAM	
	Calories	Temp. ° C.	Calories	Temp. ° C.	Calories	Temp. ° C.
Hydrogen	3.4	0	15.0	....	108.0	—252.8
Oxygen	3.5	0	3.3	—219.0	50.9	—182.9
Nitrogen	3.5	0	6.1	—210.0	47.6	—195.5
Sulfur	5.3	0	10.4	119.0	66.3	444.6
Water, liquid	18.1	0	....	....	539.0	100.0
Water, solid	9.1	0	80.0	0	....	....
Carbon dioxide	8.7	0	45.4	— 56.2	87.0	— 60.0
Ammonia	8.8	0	108.0	— 75.0	327.0	— 33.4
Hydrogen sulfide	4.6	10	....	....	132.0	— 61.4
Sulfur dioxide	15.4	10	....	....	95.0	— 10.0

TABLE 2.—*Physical properties of water and some other common liquids:*—

SUBSTANCES	SURFACE TENSION		INTERNAL PRESSURE	DIELECTRIC CONSTANT	
	Dynes/cm.	Temp.	Atmospheres	E	Temp. ° C.
Water	75.6	0	16,400	81.000	17
Mercury	47.6	20	13,050	....	....
Carbon disulfide	35.3	0	5,400	2.600	0
Benzene	31.6	0	4,050	1.002	100
Carbon tetrachloride	29.0	0	3,640	1.003	110
Hexane	20.5	0	2,020	1.874	20
Ethyl alcohol	24.0	0	7,200	1.006	100

be around —100° C. to —150° C. In comparison H_2S, containing sulfur that boils at 444° C., is a gas boiling around —61° C.

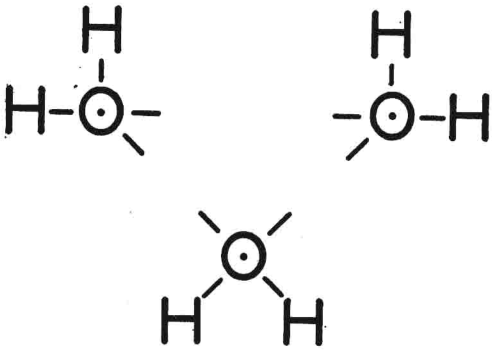

FIG. 1.—Trihydrol molecule as pictured by SUTHERLAND (1900).

Other anomalous properties of water include its minimum specific heat at 37.5° C., its maximum density at 4.0° C., and its great expansion upon solidification. This latter property has played an important part in all attempted explanations of the structure of water.

Early Theories:— The earliest concepts of the liquid structure of water pictured it as composed of spheroid molecules, heterogeneously arranged, and having the unordered motion of a very dense gas. As early as 1884, however, WHITING visualized liquid water as a solution of ice particles and RAOULT (1885) pictured association of water molecules into groups of four. VERNON (1891) explained the maximum density of water by association of the molecules from $(H_2O)_2$ above 4° C. to $(H_2O)_4$ below that temperature. In 1892 RÖNTGEN independently proposed that liquid water is made up of a saturated solution of ice in some other form of water. He pictured ice molecules as complex, but less dense than water; when ice melts the volume is decreased.