

# PRESIDENTIAL ADDRESS

## THE CAPTURE AND USE OF SUNLIGHT

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### Introduction

Without sunlight life on earth, at least as we know it, would cease to exist. In fact, life could not have originated in the absence of sunlight, or of some comparable form of energy. What then is the nature of sunlight, how does it originate, and how is it caught and used on earth? These and related questions are the subjects of this discussion.

Taking the term "sunlight" in its broadest sense we may include not only the visible solar radiations (390-760  $m\mu$ ) which are perceived by the eye but also those shorter ultraviolet radiations (300-390  $m\mu$ ) which penetrate our atmosphere, plus additional wave lengths longer than the visible radiation. These longer wave lengths represent the infrared or heat rays and, as received at the earth's surface from the sun, range from 760 to approximately 2600  $m\mu$ . The unit " $m\mu$ " (milli-micron) is equal to one thousandth of one millionth of a meter and is the diameter of the smallest colloidal particles.

In addition to the wave concept of sunlight, there is also the corpuscular concept which pictures discrete particles or "photons" of light, each photon containing one packet of energy, the "quantum." These quanta are of various sizes, those of the shorter wave lengths such as the blue, violet, and ultraviolet are considerably larger than the quanta of the longer wave lengths, particular the red and infrared (fig. 1).

The intensity of the radiant energy received from the sun, when expressed as amount received per unit area per unit time, is termed "irradiance" and may be measured in g.-cal. per  $cm.^2$  per min. (1). "Brightness" on the other hand refers to the strength of illumination as perceived by the human eye and is commonly expressed as foot-candles or as meter-candles. Maximum sunlight intensities at the earth's surface in midtemperate zones occur at midday in summer and are on the order of 1.2 to 1.5 g.-cal. per  $cm.^2$  per min.—this latter amount of energy falling on 1 sq. ft. of surface is sufficient to raise the temperature of one quart of water 2.5 Fahrenheit degrees in one minute. These maximum irradiance values correspond approximately to brightness values of 8,000 to 10,000 foot-candles (fig. 2) (2).

Another important feature of sunlight is that of "duration" or length of day. In the midtemperate zones, hours of sunshine per day may vary from 9 for December to 15 for June. Obviously much less seasonal variation is found as equatorial latitudes are approached where daylengths are maintained near 12 hours. On the other hand considerably more variation occurs at higher latitudes (fig. 3).

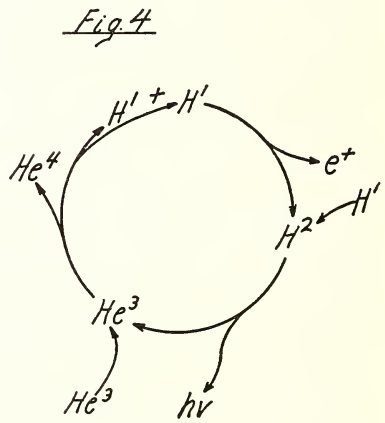
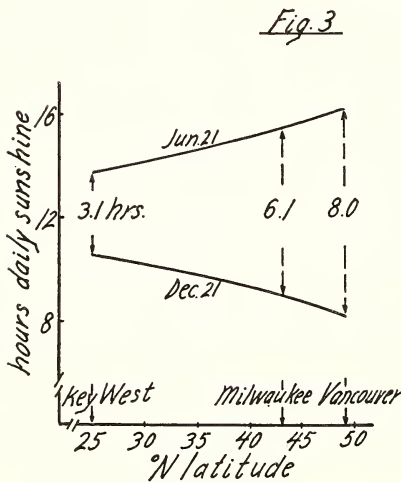
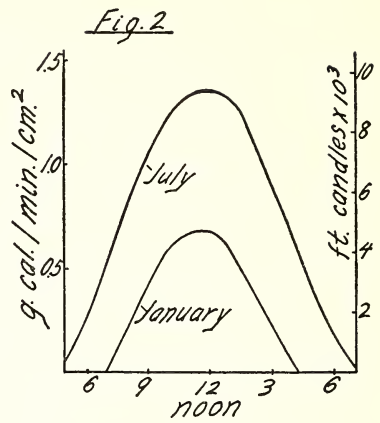
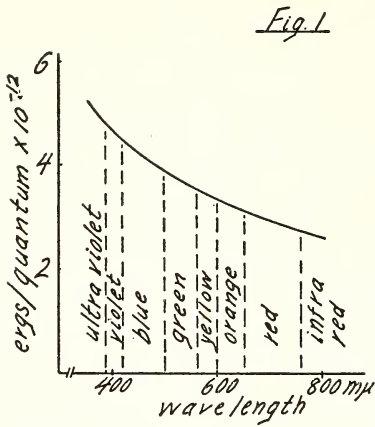


Fig. 1. Wave length and quantum size of visible light and adjoining regions.

Fig. 2. Diurnal sunlight curves for July and January at 40° N. latitude. After Meyer and Anderson (2).

Fig. 3. Effect of latitude upon maximum and minimum day lengths. Data from Meyer and Anderson (2).

Fig. 4. Radiant energy (hν) release through H<sup>2</sup>-He<sup>3</sup> pathway.

Modern theory (3) concerning the origin of sunlight pictures the sun as a huge mass of broken atoms, atomic nuclei, and electrons at temperatures ranging from 6,000° C at the surface to 26,000,000° C in the interior. At these inconceivably high temperatures reactions take place between various atomic nuclei which result in the release of tremendous quantities of energy. Thus, collisions of hydrogen and carbon

nuclei may lead to a cycle involving nuclei of  $N^{13}$ ,  $C^{13}$ ,  $N^{14}$ ,  $N^{15}$ ,  $C^{12}$ , and additional hydrogen nuclei to release electrically charged positrons, helium nuclei, and radiant energy. Or collisions of hydrogen nuclei may pass through a  $H^2$ - $He^3$  nuclear pathway to form the stable  $He^4$  nucleus, positrons, and again releasing radiant energy (fig. 4). It is this radiant energy which showers the earth with life-giving sunlight. Calculations indicate that such conversions of hydrogen to helium equivalent to one percent of the sun's mass are sufficient to supply one billion years of sunlight.

### Life's Coming Into Being

Perhaps two billion years ago, so we are told (4), no life existed on the earth. The atmosphere may have been more or less completely devoid of oxygen but rich in methane, carbon monoxide, ammonia, cyanogen, and water vapor, with probably some hydrogen in addition. The sea was, in the words of J. B. S. Haldane (5), "a hot dilute soup." The sun bathed the globe with energy-filled light. Somehow, from this brilliant sunlight and the ingredients of that "hot dilute soup" life was gradually to emerge.

Very early nineteenth-century chemistry categorized organic compounds as substances which could be synthesized only by living organisms. However, in 1828 the German chemist Wöhler (6) synthesized urea from potassium cyanate and ammonium sulfate thus disproving the concept that organic compounds can arise only within living matter. The laboratory synthesis of countless other organic compounds since this beginning made by Wöhler has proved conclusively that organic synthesis is not the exclusive property of living organisms. It thus appears reasonable that the synthesis of organic compounds could have, in some former geologic period, preceded the existence of living organisms.

The phenomenon of abiogenesis or spontaneous generation, that is the formation of living organisms from nonliving matter, has never been observed, however. In fact the great French biologist of the 19th century, Louis Pasteur, was able to show that such a process as fermentation takes place only in the presence of living microorganisms and that when all life was killed by heat no new organisms and no renewed fermentation arose as long as the fermentation medium was protected from contamination. Other early workers, Redi for example, disproved the then current belief that maggots arose spontaneously from meat by the simple expedient of protecting the meat from egg-laying flies. How then is it reasonable to consider that living matter could ever have arisen from nonliving material?

At least two suggestions have been given which have a bearing upon this question (7). The first suggestion is that the change from nonliving to living matter is at best a very slow process so that the limited observational times in controlled studies of possible abiogenesis are far too short to permit the development of recognizable living forms. Moreover, in today's natural environments the formation of even rudimentary microscopic living forms would not be expected to occur

because of the multitude of living organisms already present in the sea and elsewhere where life might originate. These organisms are continually searching for and taking in food, and would thus consume precursory substances from which living matter might be formed. In contrast, initial pre-biological abiogenesis could have continued uninterruptedly over long periods of time since at that time no life was present on the earth and therefore early precursory substances would not have been used up as a food.

A second suggestion in favor of pre-biological abiogenesis lies in the probable different composition of the earth's atmosphere during early times (8). Evidence, including reduction-oxidation potential studies, points to a lack of oxygen in the earth's atmosphere at the time life originated. This would mean a corresponding absence of the ozone screen now normal to the atmosphere, a screen which is instrumental in absorbing much of the sun's ultraviolet radiation. Thus a more effective form of radiation would have reached the earth's surface—a radiation having photons with larger quanta and with wave lengths more actively absorbed by chemical reactants in preliving systems.

A contemporary view of the initiation of life on this earth, therefore, is one which envisages photochemical reactions which utilized energy from the then ultraviolet-rich sunlight, together with appropriate catalytic systems. The well known role of the adenosine phosphates in storing, transforming and mobilizing energy in the metabolism of living organisms is suggestive of the probable great importance of phosphorous in energy transfers also in preliving systems. If life originated in an oxygen-impooverished environment, as is conjectured, less highly oxidized forms than the phosphates—such as the phosphites and hypophosphites—would have had the advantage of greater solubilities and greater reduction—oxidation potentials, both of which would act to increase the effectiveness of phosphorous in energy transfer systems. According to Gulick, suggested beginnings of organic synthesis in an atmosphere containing methane, ammonia, carbon monoxide, hydrogen, and water vapor, and promoted by photochemical energy include the formation of carbon-carbon bondings in compounds such as ethane ( $\text{H}_3\text{C}-\text{CH}_3$ ),

ethylene ( $\text{H}_2\text{C}=\text{CH}_2$ ), and acetylene ( $\text{HC}\equiv\text{CH}$ ). Hydrocarbon- and ammonia-addition products then could form amines, such as ethylene

amine ( $\text{CH}_2=\text{CH} + \text{NH}_3 \rightarrow \text{CH}_2=\text{CH}-\text{NH}_2$ ). Other suggested reactions include the formation of cyanamide from carbon monoxide and ammonia

( $\text{CO} + 2\text{NH}_3 \rightarrow \text{NH}_2\text{C}\equiv\text{N} + \text{H}_2 \rightarrow \text{H}_2\text{NC}\equiv\text{N} + \text{H}_2\text{O} + \text{H}_2$ ). Additional cyanamide

syntheses of nitrogenous compounds involve the reaction of cyanamide with ammonium phosphite to form guanidine phosphite which in turn can go to phosphoguanidine, a high-energy phosphocompound. Further syntheses are thought to have led to the formation of complex macromolecules of proteins containing nucleic acid. Such proteins as found in viruses and genes have the property of growth and self-duplication. At some such stage rudimentary living organisms may have originated.

### The Use of Sunlight by Green Plants

The green plant is nature's number one converter of the energy of sunlight into stored and useful forms. Photosynthesis on earth is accredited (9) with using approximately 400 billion tons of CO<sub>2</sub> annually in the production of 300— billion tons of photosynthate. Contrast these figures with the huge steel industry which on a world basis produces annually some 100 million tons of steel. Photosynthesis is thus some 3,000 times greater in magnitude than is the production of steel. It is of interest to note that most of the global photosynthesis is believed to occur in the oceans, perhaps nine-tenths of the total as compared with one-tenth on land. This is explained on the basis of three-fourths of the surface of the earth being composed of water to one-fourth of land, and also by higher photosynthetic rates per unit surface area of ocean as compared with land. How this can be true is explained by the considerable depth (100 meters) in which the phytoplankton (free floating plant life) exists. This fact permits extensive photosynthetic activity by these numerous but minute plants. The occurrence of phytoplankton is not limited to salt water but exists in fresh water as well. Here, also photosynthesis with its attendant capture of light energy is active. It has been estimated (10) that in a typical lake—Lake Mendota in Wisconsin, for example—the annual yield of photosynthate by the phytoplankton is well over a ton per acre.

Let us now consider briefly how green plants are believed to use the energy of sunlight. Some of the quanta of the visible light which strikes the green cell are absorbed by the chlorophylls of the cell. Additional light quanta are absorbed by the yellow carotenoid pigments and may, particularly in algal cells, be transferred to chlorophyll. The absorbed energy is then utilized as photochemical energy in the promotion of reactions which result in the splitting of the photosynthetic raw material, water, with the release of gaseous oxygen. The hydrogen from the water is not released as a gas but reacts indirectly with the other photosynthetic raw material, carbon dioxide, to form simple carbohydrate compounds. High energy phosphate compounds are believed to be formed and to function in energy transfer in the complex process of photosynthesis (11). Needless to say, a great many individual steps are involved in the overall photosynthetic process. These include, basically, the steps of the light phase in which the initial absorption and transfer of light energy occurs. Following this is the so-called dark phase (the "Blackman reaction") which also consists of numerous steps—chemical reactions—which gradually advance the initial carbon compounds to carbohydrates and/or other photosynthetic products (fig. 5).

The efficiency of photosynthesis in the capture of light energy can be expressed in terms of quanta, or in terms of percent. Theoretically, three or four quanta of (red) light are required for each molecule of carbon dioxide reduced (12). This would represent 100% efficiency within the photosynthetic system. Actually, eight, nine, ten, or even more quanta of light are required for continued photosynthesis in carefully controlled experiments with actively photosynthesizing algae or

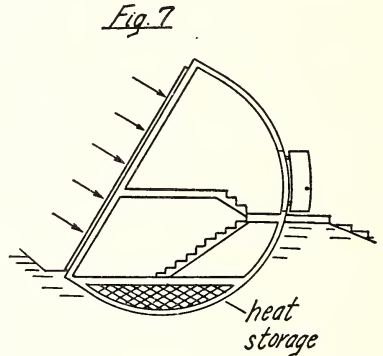
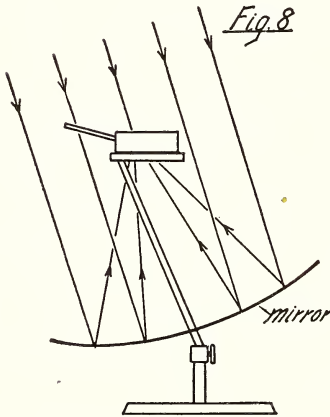
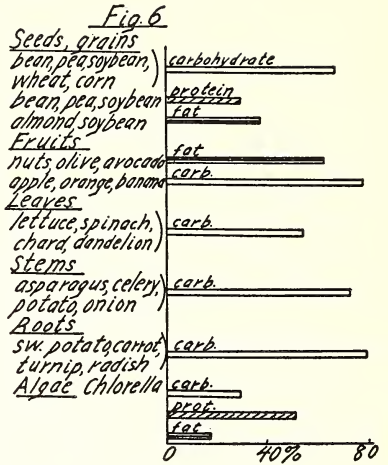
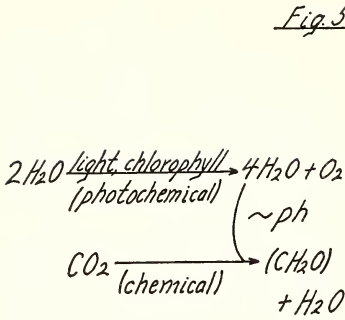


Fig. 5. Simplified schema of photosynthesis ~ph represents high-energy phosphate; (CH<sub>2</sub>O) represents carbohydrate.

Fig. 6. Food contents of some plant parts. Data from Albritton (13).

Fig. 7. Solar heated "house of tomorrow." After Anderson, Hottel, and Austin—in Daniels' and Duffie's "Solar Energy Research" (16).

Fig. 8. Paraboloid mirror solar cooker. After Ghai (16).

green leaves. Ten quanta would therefore represent an efficiency of 30 percent in the use of light energy under the most favorable conditions. For land plants growing in the field, much light energy is lost by reflection from leaf surfaces, transmission through leaves, or absorption by non green leaf and cell structures. As the result, the overall photosynthetic efficiency is reduced to values on the order of 1 to 2 percent.

### Man's Use of the Products of Photosynthesis

Man uses the products of photosynthesis for sources of energy as stored in food and fuel, and for protection against discomfort and disease. Foods derived directly or indirectly from photosynthesis consist chiefly of the familiar carbohydrates, proteins, and fats. Varying with the species, one or more of these foods are stored in most parts of higher plants (13). Abundant storage of foods occurs in seeds and grains such as those of beans, peas, soybeans, almonds, wheat, and corn. All of these contain a good deal of carbohydrate (fig. 6), some (beans, peas, soybeans) are rich in protein, and still others rich in fats (soybeans, almonds). Fruits also have served man as important sources of food compounds. Nuts, avocados, and olives are especially rich in fats; apples, oranges, and bananas in carbohydrates to name a few. Leaves, stems, and roots are more apt to be sources of carbohydrates rather than of fats and proteins. Edible leaves include those of lettuce, spinach, and chard; not forgetting dandelions! Edible stems are represented by asparagus, celery, potato tubers, onion bulbs, and bamboo stems—the latter edible only when very young! Edible garden roots are commonly those of sweet potato, carrot, turnip, and radish.

To these well known food sources should be added the algae. *Chlorella*, for example, has been found to possess a protein content of 50 per cent of its dry weight as compared to 44 per cent for soybean meal, and 12 per cent for wheat grains!

In foods, both energy and tissue-building substances are desirable. With fuels, however, stored energy which can be converted readily into heat and power is of utmost importance. The recently photosynthetically stored energy of sunlight is released as useful heat in the burning of wood in grates and stoves. In the burning of coal, oil, and gas for heat and power, man releases the energy of sunlight captured and stored millions of years ago. Under the then existing conditions of the mild temperatures, moist climate, strong sunlight, and abundant CO<sub>2</sub> supply prevalent in the carboniferous era, vegetation including giant tree ferns flourished, particularly in swampy places. Death of such plants was followed by preservation in the acid swamp waters. Thus layers of plant remains were deposited, preserved, and later covered by sediments. As a result of this deposition, pressure, and warmth, cellulose and lignified cell-wall materials slowly lost their hydrogen and oxygen to become coal, rich in carbon and energy. It has been calculated (14) that one pound of coal contains sufficient energy when harnessed in a modern engine to accomplish as much work as a laborer can do by hand in an entire day. Undoubtedly similar statements could be made for the closely related transformed products, oil and natural gas.

Products of photosynthesis have long been employed by man for his protection. Clothing to protect man's body from the elements has been fashioned from the fibers of plants (cotton, linen) or from the hair of plant-eating animals (wool), or from the hides of plant-eating-animals-eating-animals (leopard skins). Even many of our vaunted

modern synthetic fibers go back in their origin via the carboniferous-petroleum route to photosynthesizing plants.

Now that we have man fed, heated, and clothed by products arising out of photosynthesis and solar energy, what about shelter—in other words, housing? When man came out of the caves, or down from the trees, he needed some form of shelter of his own devising. What would be more natural, depending upon the materials at hand, than the construction of grass huts, palm or straw-thatched houses, and finally wooden houses? All of these and more, including tents, are products of photosynthesis made possible by the capture of sunlight. And when we come to live in plastic houses (there are even now plastic greenhouses) we shall still be beholden to sunlight and photosynthesis via the petroleum route.

Finally, sunlight functions as an aid to health and the pursuit of happiness. In addition to the direct effect of sunlight on vitamin D, sunburn, and the cut of bathing suits, the indirect effect on health through herbal medicines has long been exploited. Aside from the various concoctions, mostly of questionable value associated with witches, herb doctors, and tribal medicine men, we still have and use such green-plant drugs as digitalis from the fox glove, quinine from cinchona bark, opium and morphine from the poppy, and atrophine from the nightshade to name but a few.

### Man's Machines for Capturing Solar Energy

The problem of capturing solar energy for space heating, cookery, solar furnaces, engines, electric power, etc., is one of collecting and concentrating the diffuse energy of sunlight. Much less energy concentration is required, obviously, for the heating of houses than for the operation of a solar furnace. Both have been effectively accomplished.

Let us consider first of all domestic solar heating of water and of houses. The operation of solar water heaters through the absorption of heat by blackened coils of water pipe has been in use in California and elsewhere for many years. More recently insulated storage tanks have been included to insure hot water on occasional cloudy days as well as on sunny ones.

Space heating in homes by sunlight makes use of various light-capturing and storage devices. Direct illumination through large "picture windows" is one method. Excessive summer heating through southern exposure windows can be avoided by the use of overhanging eaves. On the other hand, windows tilted from the vertical may be used to capture winter sunlight more effectively (fig. 7).

Less direct solar heating has been effected by means of the circulation of air through chambers which are sun heated. Here it may be possible to store solar heat for limited periods by the use of heat-retentive substances such as gravel, water, or solutions present in the system. One unique example (15) is the use of sodium-sulfate solution in tanks in the walls of a house built in New England by a woman architect. At temperatures above 91° F,  $\text{Na}_2\text{SO}_4$  in solution loses its



water of crystallization with the absorption of heat. At temperatures below 91° F water of crystallization is added and heat is evolved. Thus the solar energy absorbed during sunny days is stored and released during cool nights and cloudy periods. It is reported that this system has been effective in keeping both the house and owner warm and comfortable over a period of several years without benefit of coal, oil, or gas for space heating.

In certain areas of the world where sunlight is abundant, but wood, coal, oil and/or other fuels are not, solar cookery may prove to be a boon to man. This condition exists in India and the Indian National Institute of Physics has developed a solar cooker (fig. 8) with a heat equivalent of 350 watts (16). In such cookers solar radiation is focussed on the cooking vessel by means of a 3-foot paraboloid mirror, or by many flat mirrors arranged in a paraboloid pattern. Such cookers are effective but their cost (\$15) is prohibitive for the class of people likely to use them. Mirrorized plastics are visualized as a means of cutting the cost of these cookers.

House cooling and refrigeration for the home and industry powered by solar engines have been developed. It is reported that Russia has developed such an installation capable of producing 250 kilograms (550 lbs.) of ice per day (17).

In contrast to solar refrigeration but similar to solar cookery, is the solar production of high temperatures. Furnaces operated by sunlight have been constructed which, as the result of great concentration of solar energy, produce very high temperatures—up to 3500° C. This temperature is higher than the melting point of tungsten.

Solar engines have been constructed as solar-energized steam engines. By means of large parabolic mirrors focussed on water boilers, steam has been generated at pressures up to 7 atmospheres (100 lbs. per square inch) and produced at rates of 100 lbs. per hour. Other engines use flat mirrors and steam, and still others are driven by expanding and contracting gases resulting from intermittent exposure to sunlight.

Solar water pumps and solar water distillation apparatus have been built to meet man's need for fresh water. An Italian pump has been constructed in which sulfur dioxide is vaporized by a "flat-plate" collector and the vapor used to operate a one-cylinder engine. Cooling is effected by the pumped water. Operative solar stills have been built for the purpose of converting brackish water or sea water to fresh water. Present developments suggest the feasibility of such stills to produce drinking water for man and his livestock. The large-scale production by solar distillation of the quantities of fresh water required for irrigation does not yet appear feasible.

Still other methods and systems for capturing the energy of sunlight have been studied. These include photoelectric cells and thermocouples for the generation of electricity, and photochemical methods for the decomposition of water to release energy-rich hydrogen gas. Thus far, these latter methods appear to be still in the theoretical and/or early experimental stages.

### Conclusion

In the foregoing discussion we have surveyed some of the interesting features involved in the capture and utilization of the energy of sunlight. Emphasis has been placed upon the nature and source of sunlight and its probable importance as an energy source in the synthesis of the earliest organic compounds and the origin of the simplest forms of life. Photosynthesis in green plants is a process of stupendous magnitude and of great antiquity. By it sunlight is trapped and transformed into the energy of foods and fuels. Modern man is now attempting to supplement the energy of former photosynthetic activity stored in fuels by direct capture and transfer of the sun's energy by the use of ingenious machines. Considerable promise is indicated in this direction but we are probably still a long way from solar-machine manufactured high-energy foods.

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