HARVARD FOREST
BULLETIN No. 14
RICHARD T. FISHER, *Director*

A THERMOELECTRIC RADIOMETER FOR SILVICAL RESEARCH

With Preliminary Results on the Relation of Insolation to the Growth of White Pine

BY

P. R. GAST
HARVARD FOREST
AND
NORTHEASTERN FOREST EXPERIMENT STATION

HARVARD FOREST, PETERSHAM, MASS.
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FOREWORD

This study is a joint project of the Harvard Forest and the Northeastern Forest Experiment Station of the United States Forest Service. The writer wishes to express his appreciation of the generous aid, so freely given, which made this work possible. He is especially indebted to Professor R. T. Fisher, Director of the Harvard Forest, for guidance and criticism in the silvical aspects of the study, and for raising funds among anonymous donors previous to the availability of a grant from the Forest Production Research Fund to carry on this work; to Dr. W. T. Bovie, former Assistant Professor of Biophysics in Harvard University, for guidance and criticism of the biophysical philosophy and methods, for fertile suggestion, and for allowing full use of the ample facilities of the former Harvard University Biophysical Laboratory; to Mrs. Charlottänna Mikalson Gast for assistance in the construction of apparatus, manipulation and observation, and calculation of the results. Later work in the development of the thermopile has been possible through the courtesy of the Eppley Laboratory, Inc., who permitted the use of their precision radiometric equipment and built some of the thermopiles.

ABSTRACT

SILVICAL research on reproduction, growing space, and transformation of organic materials in the forest floor has been handicapped in the measurement of insolation values by the lack of a suitable radiometer.

Study of what is known of the relation of radiation to plant growth shows that the radiometer should be sensitive to all radiation from the short infra-red to the long ultra-violet, capable of integrating all sun and sky radiation at normal incidence, non-selective, very sensitive, calibrated in absolute power units, continuously and automatically recording and rugged.

The thermoelectric determination of the temperature difference between an exposed and a shielded body is considered to be the best means of measuring radiation. The construction of a series of models resulted in the production of a radiation "sensitive" which satisfies the requirements within practical limits. This radiometer may be described as a spherical hot-junction thermopile.

Observations with one of the evolutionary sensitives, the massive base thermopile, gave evidence of certain important relations between forest canopies and the amount of radiant energy penetration: (1) with greater intensities in the open a smaller percentage penetration results, (2) observation of percentage penetration on clear days only gives too low a value for the average percentage penetration, (3) the percentage penetration of the complete solar spectrum (λ 2.5 to 0.29 μ) is quite different from the percentage penetration by short wave lengths in the blue and ultra-violet, (4) a minimum of forty complete daily records of radiation, well scattered throughout the growing season is necessary for an adequate determination of the radiation environment under a forest canopy.

The radiation environment was measured for three groups of pines for which the annual leader increment was measured. This increment was found to be directly proportional to the cumulative radiation intensities of the three sites in which they were growing.

It is concluded that the radiation intensity is an important factor in forest growth and reproduction. But it is impossible on the basis of this study to ascribe the proportional effects due to direct influence on photosynthesis and indirect influence of increased nitrogen availability through accelerated decay of the organic material at the higher soil temperatures in the more exposed sites.

CONTENTS

LIST OF FIGURES

A THERMOELECTRIC RADIOMETER FOR SILVICAL RESEARCH

1. IMPORTANCE OF SOLAR RADIATION MEASUREMENTS TO SILVICULTURE

THE importance of solar radiation in the handling of forests has been recognized since almost the beginning of silviculture. While there was still little need for the art of silviculture, the start of the fundamental science is discernible in the discussion of the effect of climate on plants and the prescription for nursery and transplanting practices. In the "Res Agriculturae" of Pliny the Elder (about A.D. 77) the relation between temperature and aspect is discussed, the absence of vegetation under pine is noted, and the relative shade cast by pine, oak, sycamore, cypress, beech, elm, aspen, walnut, and apple compared.

One of the principal objectives of silviculture has been the replacement of mature forests by means of natural seeding. The methods of doing this have been largely based on the observation that the appearance of seedling growth is associated with the amount of radiation [1] which reaches the forest floor. For different species and under different conditions the practice has ranged from the removal of single trees in the stand (selection cutting) to the clear cutting of comparatively large areas (clear cutting by strips). But apparently equivalent amounts of radiation are not equally

[1] Radiation is used in place of "light" throughout this paper because the use of the term light should be confined to its legitimate association with the reaction of the human eye to visible radiant energy. The reactions of a plant to radiant energy are complicated and different from the reaction of the human eye. Loose thinking and faulty experimentation have resulted from the use of the term "light" in connection with plant studies because the fact that the reaction of the eye is a unique phenomenon is thus obscured and forgotten.

successful in initiating seedling reproduction, either of different tree species in the same site, or the same species in different sites. The amount of insolation which is necessary for successful reproduction has been a subject of controversy and of experiment.

In the three centuries from 1500 to 1800 the need of establishing forest lands as permanent sources of wood became apparent. By that time the increase in population with its consequent necessity for larger quantities of wood created a serious deficiency in supply. Regulations were established providing for the regeneration of the forest after cutting. Different cutting methods which attempted to insure reproduction were advised and subjected to practical test by hunting masters in charge of the forests. By the beginning of the nineteenth century these silvicultural practices were reduced to well-differentiated formal "systems." These systems were more or less rigid procedures defining the extent to which the forest canopy should be opened in order to obtain young growth of a particular species. In principle they were largely based on the observed effect of "light" on the growth and development of the young trees.

Gradually there developed an appreciation of the fact that the forest canopy must be opened up so as to provide the minimal amount of radiation necessary for growth; and further that the different species require different minimal amounts. By listing the different species in the order of their minimal requirements, so-called "scales of tolerance" have been developed.

It was discovered that the minimal requirement of a particular species in one environment is not the same as the minimal amount required in another location, but the relative importance of the various environmental factors has not been clearly defined. Fricke (1904), for example, placed emphasis on the importance of soil moisture. Other characteristics of the soil, such as texture, have been emphasized and attempts have been made to correlate these characteristics with the growth and development of the different tree species.

Another important objective in American silviculture is the regulation of composition. This is accomplished most easily by cutting back undesirable elements in the young stand, thus handicapping them in the competition for solar radiation and food supply. The radiation demands of the different species indicate the relative suppression which is necessary when the other factors are equal.

The production of desirable form and quality depends upon the allotment of growing space (Gevorkiantz and Hosley, 1929). By control of growing space during the development of the stand, maximum production is assured. Solar radiation use is an important consideration in determining the optimum growing space for different species and for different site conditions, especially in the handling of mixed stands.

The best treatment of the annual litter fall is an important problem. The manner of its decay is of great significance for the maintenance of growth and for the initiation of reproduction. The course of the rotting determines the rate of release and the availability of the nutrients locked up in the organic materials. The physical characteristics of the soil are also affected. A factor influencing the course of the decomposition of the litter in the forest floor is the temperature, which is dependent upon the insolation intensity.

For the study of these problems there has heretofore been no adequate radiometer available.

2. DESIRABLE CHARACTERISTICS OF A RADIOMETER

To determine the desirable characteristics of a radiometer the relations between radiation and forest physiology must be considered in some detail.

Knowledge of the radiation environment in which plants grow has been won at different times and by different methods. Various kinds of radiation have been thus distinguished as visible or "light," infra-red, Hertzian, ultra-violet, X-ray or γ, and cosmic. But the differences between them are qualitative and not fundamental.

About the nature of radiation it is at present profitless for the biologist to inquire with the hope of obtaining a philosophy from which he can deduce the quantitative effects of radiation on plant life. He may well learn from the physicists, who are becoming increasingly distrustful of deductive reasoning and are turning more and more toward a purely "operational" viewpoint (Bridgeman, 1927) and the experimental determination of the relation between cause and effect. The classical "horrible example" of failure to profit by experiment is pertinent here. There were still many inexplicable light phenomena when, aided by the experiments and the authority of Newton (about 1670–80), the corpuscular theory was established as the "true theory." Adherents to this theory discounted the theory that light was transmitted from the source in much the same manner as waves in water. And this was in spite of the experimental evidence, much of it taken from Newton's own writings, which was in support of the undulatory theory. The advance in the treatment of light phenomena was thus held back for more than a century. Recently, consideration of the processes whereby radiation is generated, and an explanation of the chemical and electrical results of the absorption of radiant energy required that it again be treated as discrete units of energy. But it is still impossible to explain many light effects by this newer — and older — theory, and so it is necessary to retain both concepts. To quote Sir William Bragg (1921): "For the present we have to work on both theories. On Mondays, Wednesdays, and Fridays we use the wave theory; on Tuesdays, Thursdays, and Saturdays we think in terms of flying energy quanta or corpuscles."

The two concepts have in common a view of radiant energy as a periodic phenomenon. A defining characteristic of a wave-like periodic phenomenon is the wave length, or its reciprocal, frequency. See appendix 1 for a discussion of wave length.

A logarithmic scale of wave lengths may be used to give a diagrammatic survey of the radiation groups which compose the great electromagnetic spectrum (Fig. 1). The visible portion is a narrow band from 0.4 μ to 0.8 μ in wave length. (For wave length the Greek letter lambda λ is the usual symbol.) The λ of the "short" infra-red is from 0.8 to 15 μ, of the "long," from 15 to 2000 μ (2 mm.). The λ of the "near" ultra-violet is from 0.4 μ to about 0.05 μ.

Solar radiation is limited by absorption in the atmosphere to visible radiation and a comparatively small part of the ultra-violet and infra-red on either side of it. This portion of the great spectrum (Fig. 2) is cut off at the short wave length end, λ 0.29 μ, by the absorption of shorter wave lengths in the ozone of the atmosphere; at the long wave length end waves longer than 2 μ to 5 μ are absorbed by water vapor. The length of the waves at the long end varies with the amount of water vapor in the atmosphere (see Fig. 2).

The first requirement of an insolation radiometer for silvical studies is, therefore, that it should be sensitive to radiation from λ 0.29 to 2.5 μ. Radiation outside this band, that is, radiation of wave lengths shorter than 0.29 μ and longer than 2.5 μ, may well be important to plant growth. But such radiation is derived from sources other than the sun. The cosmic radiation presumably comes from stars; X-ray emanations are naturally emitted by radioactive materials in the earth's crust, otherwise they as well as the shorter ultra-violet must be produced artificially; the longer infra-red is low-temperature radiation from the clouds and the earth; natural Hertzian radiation results from electrical processes in the earth's atmosphere. The effects of these bands of energy are secondary to those of insolation and must be measured by means other than those used for insolation intensities.

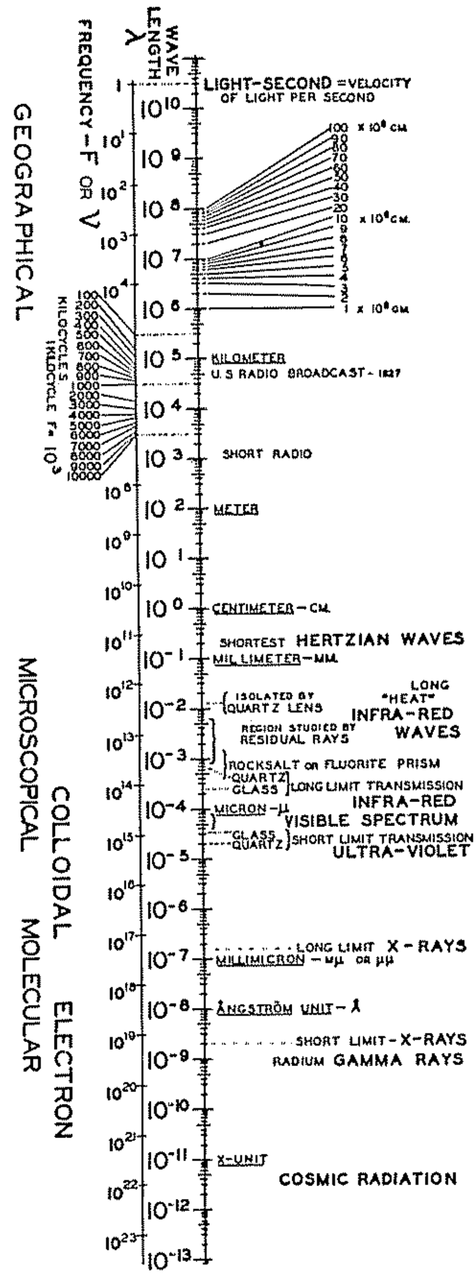


Fig. 1. THE GREAT ELECTROMAGNETIC SPECTRUM

For explanation see Appendix 2, p. 64

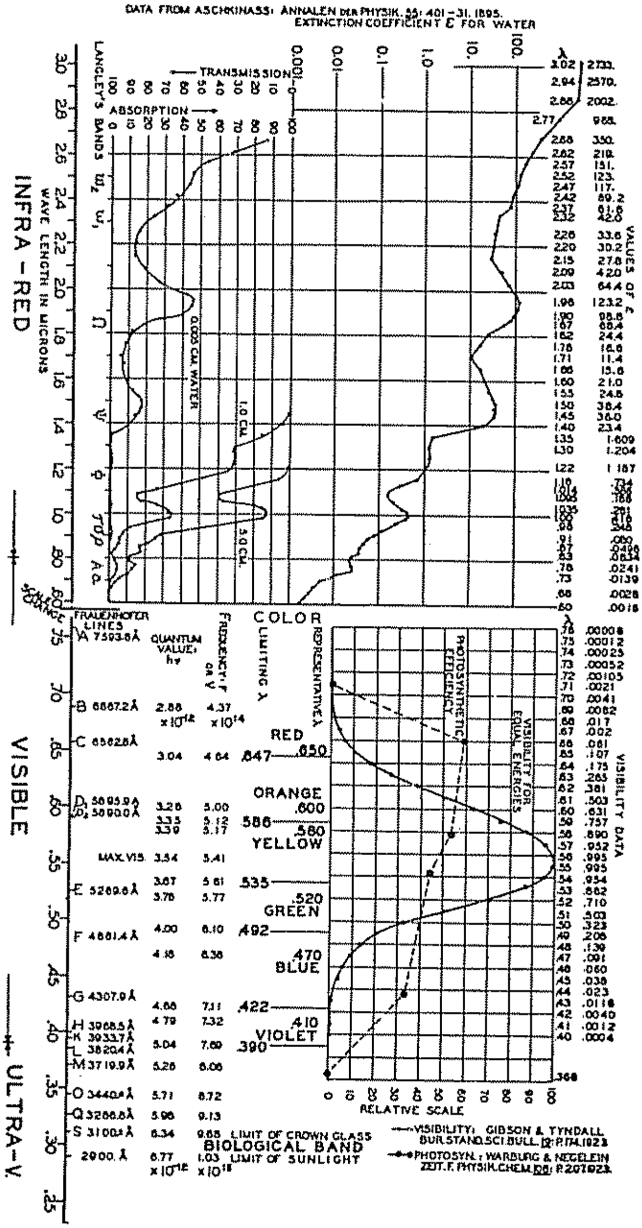


FIG. 2. THE SOLAR SPECTRUM
For explanation see Appendix 3, p. 65

Admittedly during a large part of the day a plant in the open receives an abundance of radiation so that carbohydrate formation proceeds at a rapid rate. It is quite as certain that the low radiation intensities found under a dense canopy are not sufficient to permit carbohydrate production at the maximum velocity. Radiation thus becomes the limiting factor.

One might suppose that there is some degree of opening up such a dense forest canopy as to assure that for any given species of plant the radiation intensity is no longer the limiting factor.

Secondly, then, the silvical radiometer should be capable of measuring radiation intensities over the wide range from the lowest intensities in the forest to full sunlight.

The attempt to measure solar radiation which has been diffused by clouds or a forest canopy raises another problem. A large part of radiation in the open is directed radiation and it would be possible, if necessary, by means of lenses or mirrors, to bring the rays to focus, so that a comparatively insensitive instrument could be used. But when one attempts to measure the radiation in the forest or on cloudy days in the open, the rays are indirect. The radiant energy does not come from a point source but from the whole sky. Lenses and mirrors cannot be used to focus the energy as an astronomer focuses the rays from a star into his light-sensitive instrument. The sensitivity must be inherent in the instrument, or it must be possible to amplify the registration.

Further, in order to give a time record it must integrate the rays coming from all directions at normal incidence.[1] If the radiation intercepted by a plane at normal incidence shows a given value in gram calories per sq. cm. per minute, it will be diminished by the cosine of the angle of incidence

[1] The rationale of a normal incidence radiometer is again discussed on p. 37. That such a radiometer is desirable for plant physiological research is the independent conclusion of Professor Sven Odén, whose studies on the influence of radiation on plant growth are shortly to be published as *Meddelande N:o 1 från Lantbruksakademiens i Stockholm Vetenskapsavdelning.*

if the plane intercepts the radiation at oblique incidence. See Appendix 4 for a discussion of the "cosine law."

The third requirement, therefore, is that the sensitivity be inherent in the instrument, which must be fully and equally sensitive to rays coming from all directions.

It is further required that radiation of all wave lengths from 0.29 μ to 2.5 μ, diffuse as well as direct, shall be integrated without any unequal weighting. The wave length composition of radiation in the open alters from minute to minute, with the variation in thickness and amount of gases and water in the air (Pulling, 1919). The green leaves of the forest canopy act as a selective radiation filter, and therefore the spectral energy distribution as well as the intensity of the radiation is altered. Since the various bands of radiation within the limits set, λ 0.29 μ to 2.5 μ, have different effects upon the plant, it is necessary to adjust the weighting (selectivity) or sensitivity curve of the radiometer for the phenomenon under investigation.

For the investigation of the influence of insolation upon plant growth, the ideal radiometer would integrate radiation in the same manner as the plant does in carbohydrate formation. But the construction of such an instrument will indeed be difficult.

Photosynthesis is highly selective in its use of radiation. It follows upon the irradiation of green leaves with energy of λ 0.7 μ to 0.4 μ inclusive. For the relative efficiency of the process there is but one set of satisfactory determinations at separate points of the spectrum. According to Warburg and Negelein (1923), the efficiency ranges from 59 per cent in the red to 33 per cent in the blue, with a value of 44 per cent in the yellow (Fig. 2).

But the photosynthetic efficiency curve is not satisfactory as a weighting curve. The absorption curve of the leaf must also be considered. Radiation which is reflected from the surface of the leaf or is transmitted through the leaf without absorption by the chlorophyll must be subtracted from the irradiation intensity of a given wave length. For computing the probable photosensitivity curve of carbohydrate formation it is necessary to obtain the product of absorption coefficient and photosynthetic efficiency for each band of wave lengths 0.01 μ wide.

If the relative absorption coefficients of a leaf of a species remained constant under all conditions, a radiometer with appropriate characteristics for that species could be constructed. Even this is apparently impossible. It has been shown that forest plants respond to change in color of the light in which they are growing. The leaves grown in the shade into which penetrates mostly diffuse sky light with a relatively high content in the blue compared with direct sunlight, show a higher efficiency in the blue than do specimens grown in the open. (Engelmann, 1884; Stahl, 1906; Harder, 1923). Some of this information is not as well substantiated as it might be because of the comparatively early date at which the work was done, but undoubtedly the absorption coefficients of sun and shade leaves are different. Obviously the radiometer must be modified according to the plant in which photosynthesis is to be studied.

Again, the problem of measuring the spectral energy distribution, like the problem of measuring total intensity, presents quite different aspects in the open from those presented in the shade of the forest. In the open where the radiation is directed, the spectropyrheliometer may be used, but the lenses of this instrument cannot focus the diffuse radiation of the forest. While it might be possible to construct an optical device which could be placed in front of the instrument and which could by suitable mechanical arrangements be moved so as to sweep a fair sample of the radiation into the slit of the instrument, the expense entailed is so great as to discourage any attempt to construct it. Moreover, the radiation conditions under the forest canopy are not uniform and it is highly desirable to use a comparatively inexpensive instrument so that scientific records may be obtained simultaneously from a number of environments.

With an instrument which is equally sensitive to all wave lengths, integrating all radiation at full power values, it may be possible to construct screens whose spectral transmission would approximate the spectral carbohydrate formation curve for the shade or sun leaf of a given species. The fourth requirement of a good radiometric device is that it be non-selective.

More should be obtained from competent radiation studies than relative data based on "percentages of insolation in the open." In temperate, moist latitudes the insolation in the open in the same spot is probably never identical in spectral energy distribution and intensity for any two seconds in a number of years. Assuredly it is no fixed and dependable value.

The fifth requirement is that readings of the instrument should be capable of being expressed precisely not merely on an arbitrary scale, true for itself, but in terms of the fundamental units of measure, such as the gram-calories received on a unit of area in a unit of time. The available energy can then be expressed as a percentage of the demands of the plant. The percentages found by all workers in the field and in the laboratory are then comparable.

Without a record of the fluctuations of radiation intensity in the open it is impossible to ascertain the effect of the canopy in altering the intensity or the wave length distribution of the radiation. If observations are to be of any significance they should be taken in the open and shade stations simultaneously. Devices which involve consecutive measurements, first in the open and then in the shade, are faulty because conditions are changing continually between readings. A recording apparatus makes it possible to accumulate records through a long period of time, and consequently under a variety of conditions. The average and not the exceptional condition is thus discovered, as is the case when clear, bright days only are used.

The sixth requirement is that it shall be possible to use with the radiometer a recorder of comparatively simple and rugged construction.

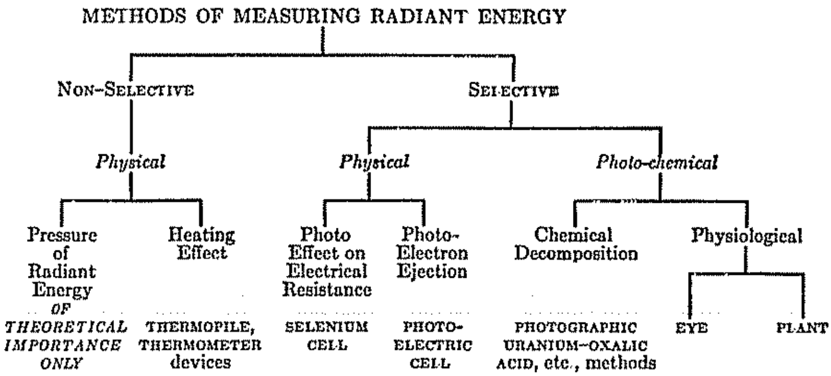
Another advantage of a recording device is that a cumulative record of the intensity in a given site, for a long period of time, can be obtained. The integration of intensity for a whole summer is physically impossible if the investigator must read a non-recording instrument.

A satisfactory ecological radiometer must therefore be

(1) sensitive to radiation from λ 0.29 μ to 2.5 μ,
(2) capable of measuring the lowest effective intensities,
(3) capable of integrating both diffuse and direct radiation at normal incidence,
(4) non-selective,
(5) standardizable in terms of power units per unit of area,
(6) capable of recording continuously and automatically,
(7) easily and safely transportable,
(8) capable of "carrying on" with a minimum of attention.

3. DISCUSSION OF RADIOMETRIC POSSIBILITIES

THE chemical and physical effects of radiant energy used in the radiometric devices provide the basis for their classification, according to the following scheme:



Of the possible methods the heating effect is the only one which is practicable and which satisfies the demand for non-selectivity.

Selective Methods

The selective methods have been used to advantage in physiological studies where the effective energy was mostly in the blue end of the spectrum. Thus the photochemical decomposition of oxalic acid in the presence of the uranium ion can be used to integrate ultra-violet radiation of λ 0.29 μ to 0.35 μ for the study of the biological effect of these rays (Anderson and Robinson, 1925). For the measurement of illumination a photoelectric cell can be modified so that it has the same sensitivity curve as the eye. But for the integration of radiant energy affecting photosynthesis, with a high sensitivity in red, the use of these selective methods leads to hazardous complications.

To illustrate: the eye is the ultimate photosensitive in photometric instruments such as the MacBeth Illuminometer. It has been used at government experiment stations and by others, although "the uselessness of photometric methods" and the possibilities of the thermopile were pointed out by Bates and Zon (1922).

It is indeed true that for photosynthesis to occur a leaf must be exposed to radiation which is also visible, λ 0.8 μ to 0.4 μ. But it is as certainly not true that radiation between λ 0.8 μ and λ 0.4 μ is wave length for wave length quantitatively equal in effect upon eye and plant. Yet the use of visual photometers has been justified on the ground of the fact, and the fallacy ignored.

A comparison of the photosynthetic efficiency and the visibility curves intimates that there is little relation between the integration of radiation by the eye and by photosynthesis. (Fig. 2.) The discrepancy is seen to increase upon consideration of the amounts of energy reflected from the leaf and transmitted through it without absorption.

Reflection from the surface of a green leaf is at its maximum at λ 0.54 μ to 0.56 μ in the very region, the yellow, where the eye is the most sensitive. The amount of reflection may range from 6 to 20 per cent (Shull, 1928), for diffuse radiation reflections averaging 25 per cent have been found (Coblentz, 1913, p. 308).

In a day when evolution is accepted as a commonplace it would seem that the use of the visual photometer should be excluded automatically. Adaptatively the eye of land animals was evolved to sense an environment of green. A non-luminous object is seen by energy reflected from it. Energy reflected is not absorbed, only absorbed energy can do work, and energy which cannot do work has no relation to the problem.

The same result is arrived at by another line of reasoning. Since the work of Willstätter and others (1911) it has been common knowledge that chlorophyll has but a small absorption in the yellow-green. And again, energy which is not absorbed can do no work, therefore yellow-green light has

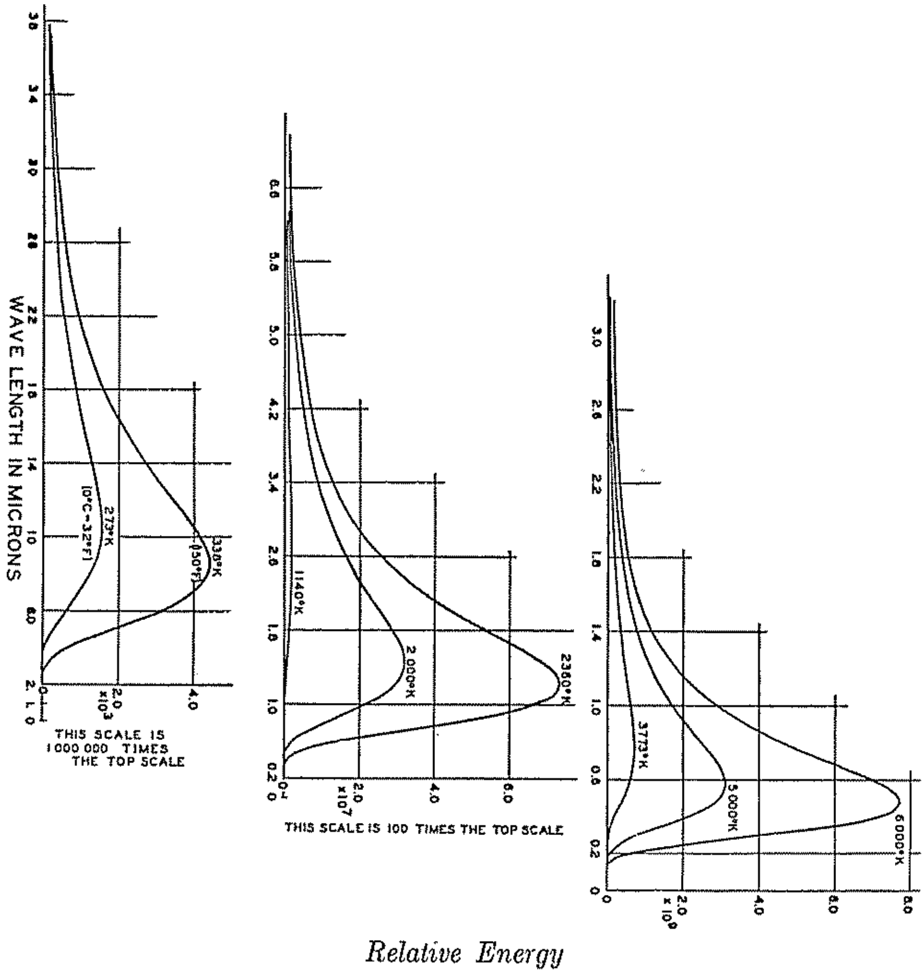
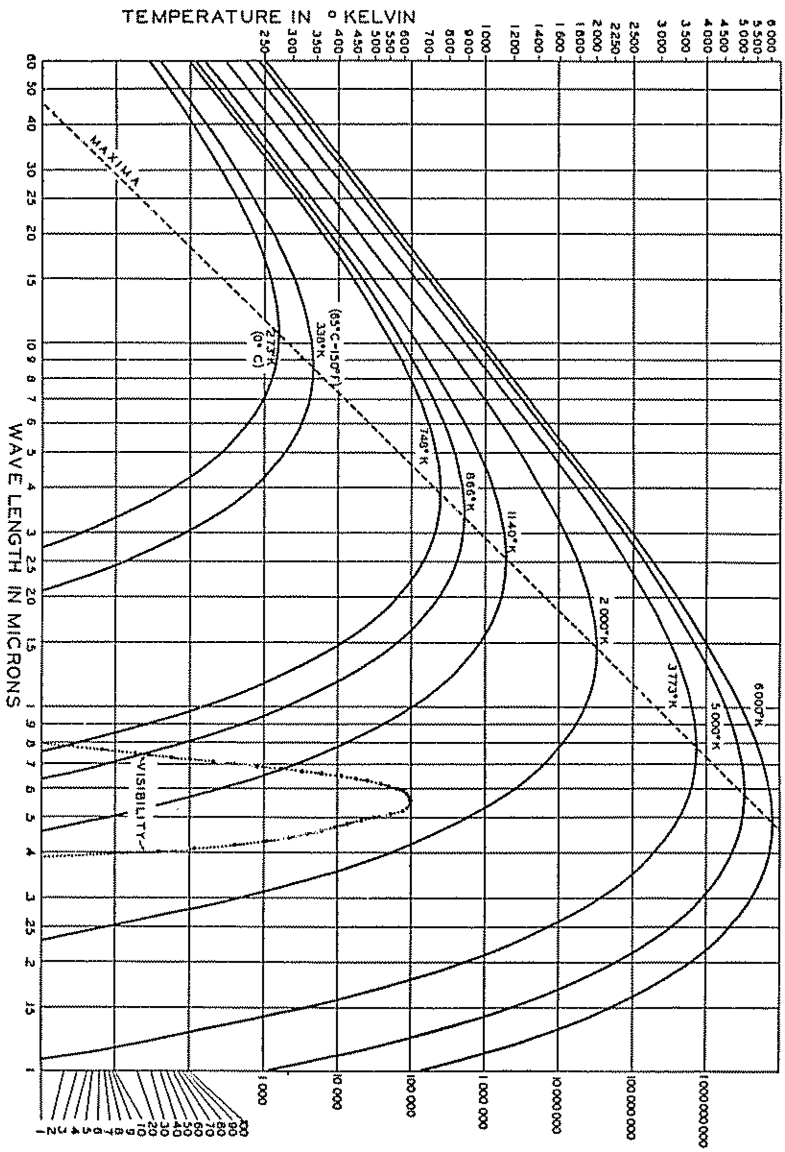


FIG. 3. "BLACK BODY" RADIATION CURVES COMPUTED FROM PLANCK'S FORMULA

For explanation see Appendix 5, p 68



Relative Energy

FIG. 4 "BLACK BODY" RADIATION CURVES PLOTTED ON LOGARITHMIC SCALES

For explanation see Appendix 5, p 68

no relation to the problem. It is certainly evident from these arguments that the energy integrated by the eye will have no relation to the energy integrated by the plant. This stricture on visual photometric methods applies also to any other selective method which is recommended because "its sensitivity curve approximates the sensitivity curve of the eye."

In the derivation of the quantitative values of the sensitivity curve of carbohydrate formation it may be convenient to use selective methods. If no attempt is made to integrate energy of widely varying wave lengths simultaneously in one apparatus, spectrophotometric devices in which a selective method is used are valuable, provided the accurate sensitivity curve of the selective method is known.

Neglect of any of the factors which enter into the calculation of the relative spectral sensitivity may, however, lead to incorrect results. Klugh (1925) deduced from a wedge spectrogram [1] that Ilford panchromatic plates are of equal intensity throughout the visible spectrum. He apparently assumed that the source was of equal intensity throughout the spectrum. This is not true. In obtaining a wedge spectrogram a tungsten filament lamp, a Nernst glower or an acetylene lamp is the source used, not sunlight. The relative energies in homologous parts of the spectra are quite different for the various sources (Figs. 3 and 4). The Nernst glower operates at approximately 2000° K, the acetylene flame at 2360° K, and sunlight has a spectral energy distribution appropriate to a body at 5000° K, to 6000° K. (See Kimball, 1926, Fig. 3.) The true values for the relative sensitivity are the product of the relative sensitivity for a given source and the reciprocal of the relative energy for the source at the wave lengths used. Thus, for the true sensitivity values at three wave lengths for Wratten Panchromatic plates, the following may be calculated.

[1] See Sheppard (1923) for a description of the wedge.

WAVE LENGTH λ in microns	RELATIVE ENERGY Nernst Glower at 2360° K	APPARENT RELATIVE SENSITIVITY Wedge Spectrogram and Nernst Glower	TRUE RELATIVE SENSITIVITY For unit energy	
			Spectrogram	Jones and Sandvik *
0.70	...	. .	...	1
0.68	280	7	1	
0.56	100	50	20	
0.55				9
0.50	. .			41
0.45	.	...	...	130
0.44	15.4	200	520	
0.35	.		.	410

* From data obtained with special sensitometer by Jones and Sandvik, 1926.

It is evident that the panchromatic plate does not avoid the difficulty common to all the selective instruments, namely, a much greater sensitivity in the blue than in the red. It cannot be used to integrate radiation affecting plant growth.

Non-Selective Methods

To pass to the non-selective methods: the non-selective heating-effect method depends upon the rise in temperature which follows the absorption of radiant energy. The rise in temperature of the receiver can be measured in many different ways. Mercury thermometers, metallic expansion thermometers, the change in volume of a gas under constant pressure, the vaporization of a liquid, the change in electrical resistance, or the thermoelectric effect may be used. A discussion of the thermoelectric effect is to be found in Appendix 6, p. 69.

The method is non-selective only in so far as the absorption is perfect for all wave lengths. Lampblack on the absorbing surface insures an absorption of from 97 per cent to 98 per cent of all radiation from λ 0.32μ to λ 7.0μ (Coblentz, 1913). Callendar (1911) devised a cup-like receiver in which multiple reflection of radiation from wall to wall insured complete absorption.

In tracing the changes in design of successive radiometers one notes an increasing tendency to use the thermoelectric effect. The chief contributors to the advance of these designs have been Coblentz (1908, et seq.), Moll (1921, see also Gorczynski, 1924), and Kimball and Hobbs (1923). A discussion of the advantages of the various methods of measuring the temperature change is contained in Ferree and Rand (1917).

Eleven devices using different types of receivers and methods of measuring temperature were designed, constructed, and tested by the writer during 1922–1925. The characteristics which have been advanced as necessary for the ideal silvical radiometer were the result of the study of the field and laboratory performance of these different designs.

The first decision was that non-selective heating effect methods offered the only possible method of advance, the second, that the thermoelectric effect was the easiest way to register the temperature change.

One type of thermopile built in 1922 had two parallel oblong receivers of mica. Otherwise it resembled the plane thermoelectric recording pyrheliometer of the Weather Bureau. (Kimball and Hobbs, 1923.) A summer's study in the field showed that the biological radiometer should integrate radiation as of normal incidence.

An instrument designed to be independent of the cosine law attempted to follow the construction of the Moll thermopile (Moll, 1921; Gorczynski, 1924). This did not attempt to make the mass of the hot and the cold junctions equal as advised by Coblentz. On the contrary, it attempted to maintain the temperature of the cold junctions at a constant level by increasing the size of the body to which the cold junctions are attached and which determines their temperature.

4. THE MASSIVE BASE RADIOMETER

The massive base radiometer, now interesting only as an evolutionary model, but by which the 1925 data were obtained, carried the massive cold junction principle of Moll to an extreme. A nickel plated brass base (Figs. 5 and 6) conserves the temperature of the cold junctions which are held by silver plates against the truncated horizontal prism at the top. They are electrically insulated from both the base and the plates by a layer of Bakelite varnish on the surfaces with which they are in contact. The hot junctions of the pile are on the top of a thin hemi-cylindrical aluminum plate.

The pile is formed by arc-welding iron and constantan wires 0.003 of an inch in diameter after the method of Kimball and Hobbs (1923). The wires are twisted together and pinched in tweezers which are connected with one lead of a 110 volt A.C. current with a series resistance so that the current passed is about 1 ampere. The other end of the circuit is connected to a sharpened carbon. When the twisted wires are brought up to the carbon an arc is formed which burns back the wires as far as the tweezers, forming a small bead. The junction thus formed is tested for strength by applying an appropriate amount of strain, learned by experience.

The plate to which the hot junctions are attached by Bakelite varnish mixed with lamp-black is supported by the wires of the pile. The whole is covered by a glass dome attached to the base by de Khotinsky cement.

In setting up the thermopile the long axis of the receiver was placed north and south (the sealing-off spot on upper right of dome to the north). It was anticipated that in the east and west traverse of the sun the light would always be at normal incidence to the surface of the receiver. Investigation showed that this was not altogether true. The angle of incidence or "polarization effect" caused the record to be

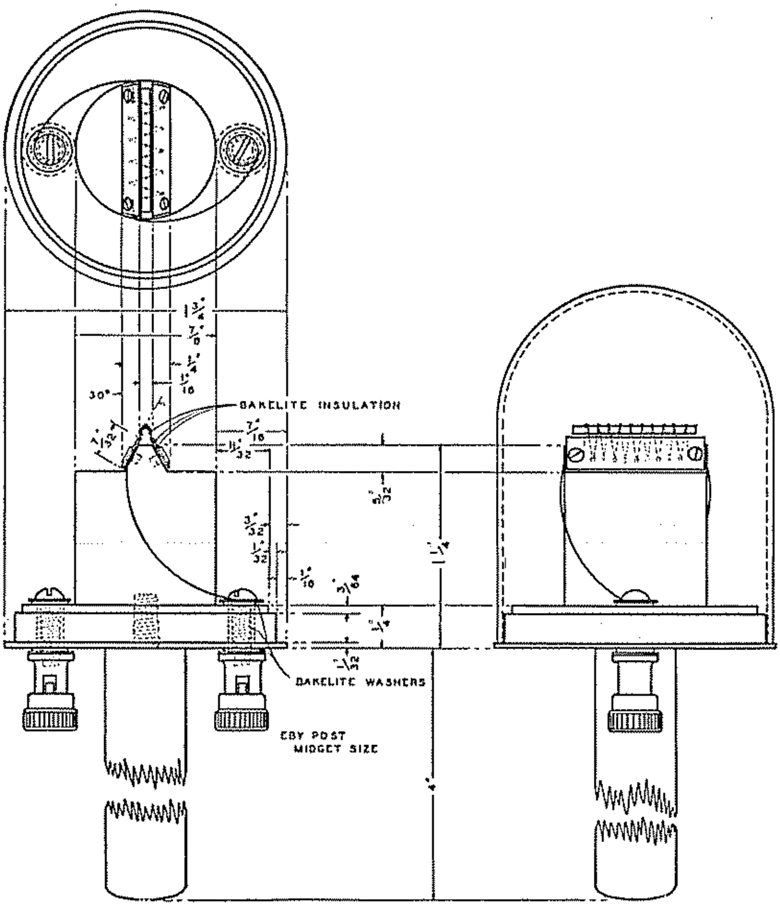


Fig 5. DETAIL DRAWING OF THE MASSIVE BASE THERMOPILE

too small by approximately 15 per cent when the sun was at an angular distance of approximately two hours (30°) from the zenith (see Fig. 9). This was a serious fault.

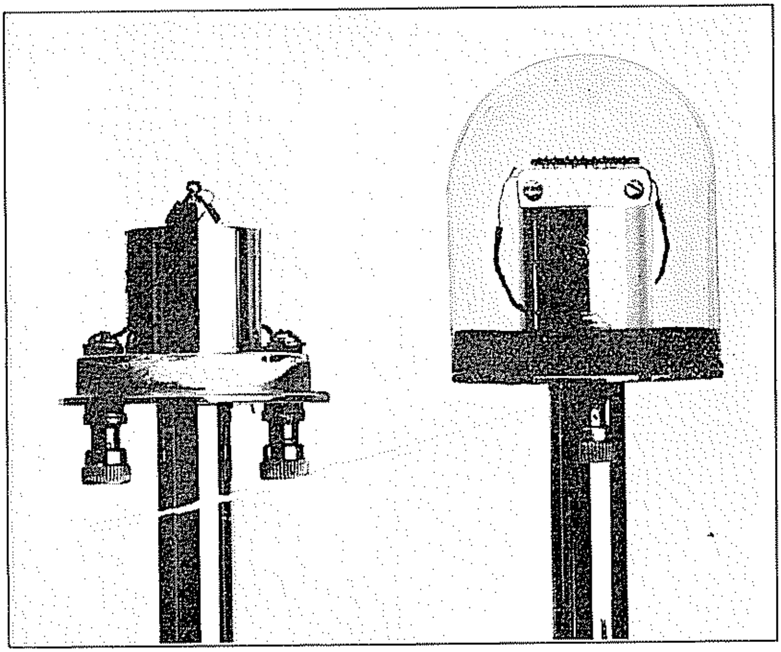


FIG. 6. THE MASSIVE BASE THERMOPILE

Of greater importance even than the "polarization effect" as a reason for discarding this type was the massive base. This, by storing heat, caused a lag in the rate of change of temperature of the cold junction as compared with the hot. Though a bright nickel surface does not come to a radiation balance with its environment as quickly as a blackened one, it was believed that the effects of the lag in the heating and the cooling of the cold junction were equal and averaged out in the course of the day's record. But since it is necessary that the radiometer be also capable of recording precisely the minute to minute variations, it was not satisfactory. It is to be anticipated that the use of the Moll thermopile as a pyrheliometer would show the same defect but to a smaller degree.

A further difficulty with this type was caused by the differences in expansion of the metal base and glass dome with temperature, which eventually broke the de Khotinsky seal. With volume changes in the temperature of the gas under the dome during the day, there was a tendency for moisture to accumulate inside the dome, which ultimately ruined the thermopile by rusting out the iron wires.

Because of these defects the massive base type was abandoned and a new type of thermoelectric radiometer was devised.

5. SPHERICAL HOT-JUNCTION THERMOPILE

This type embodied three improvements over its predecessor, the massive base thermopile. The first was the use of individual spheres for each of the hot-junctions. The second was the use of approximately equal masses for hot-junctions and cold-junctions; and the third was the enclosure of the whole in a tipless electric light bulb. The details of the construction of this improved type can be seen in the figures 7 and 8.

The construction of this type was made possible through the development of an apparatus for "spot welding," since soldering, the only other available method, was not satisfactory.

"Spot welding" depends upon the temperature rise due to the resistance at the point of contact of the pieces to be welded. None of the existing apparatus was able to make the welds required, partly because they were too crude and clumsy, but also because welding cannot be done in the air because of oxidation. A more convenient apparatus was constructed [1] which made it possible to weld in an atmosphere of hydrogen. Thereby oxidation was prevented; indeed, if the metals were covered by an oxidized layer the hydrogen at the high temperature reduced the metals, giving a perfect weld without an oxide interface. This was accomplished by building the spot welder with a glass dome to be placed over the parts to be welded. A slow constant stream of hydrogen which was passed into this dome from the top forced out the air.

In the spherical hot-junction thermopile the spherical hot-junctions (Fig. 7), five in number, are nickel silver beads

[1] The successful development of the apparatus is partly due to the mechanical ingenuity and construction ability of Mr. Gaddas, formerly of the Harvard Biophysical Laboratory. The writer takes this opportunity to express his indebtedness to Mr. Gaddas, not only for aid in this instance but also in others too numerous to mention.

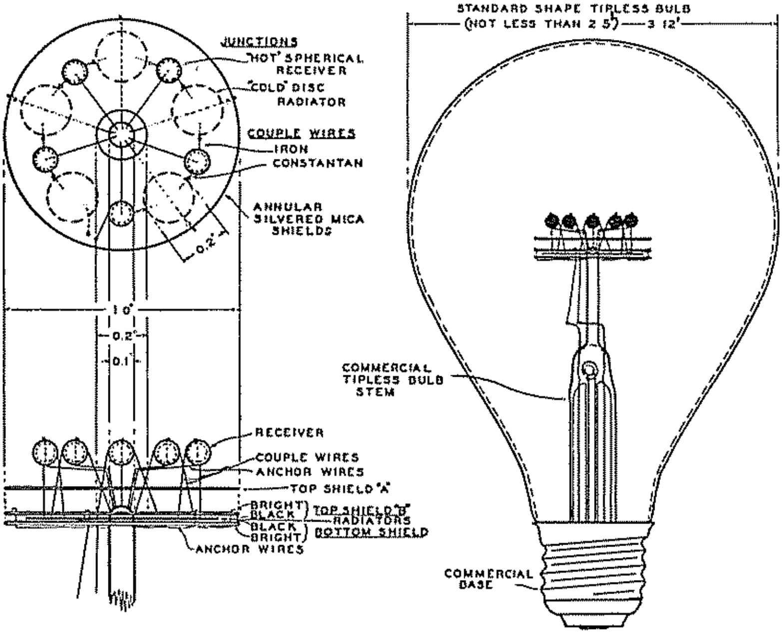
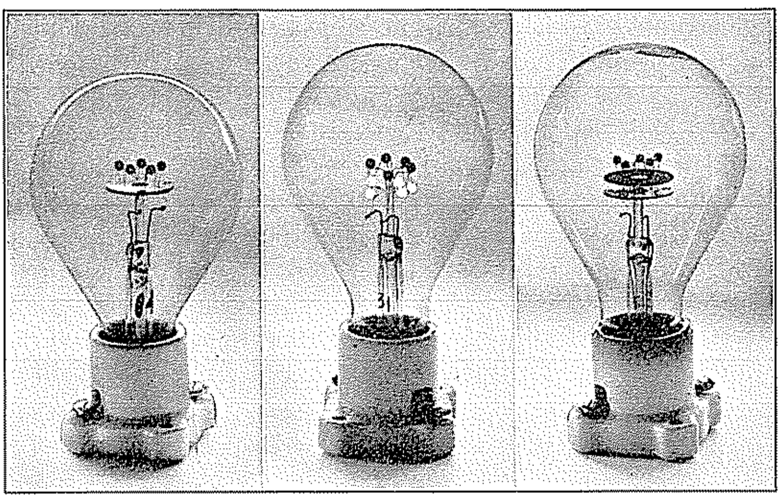


FIG. 7. DETAIL DRAWING OF THE SPHERICAL HOT-JUNCTION THERMOPILE



(Type A) (Type B) (Type C)

FIG. 8. THREE TYPES OF SPHERICAL HOT-JUNCTION THERMOPILES

0.1 inch (2.5 mm.) in diameter to which the constantan and iron wires 0.003 inch (0.09 mm.) in diameter are "spot welded." The cold junctions are discs of pure nickel 0.2 inch in diameter and 0.02 inch thick (5 × 0.5 mm.). To these the thermocouple wires are also spot welded. The cold junctions are shielded by the silvered annular shield of mica which also serves to keep the thermocouple wires separated. The "anchor wires" of the electric-light bulb stem support the spherical hot-junctions and the annular ring. After the hot-junction spheres are mounted on the lamp stem and welded, they are coated with lamp-black mixed with a minimum of insulating varnish. The whole is then baked in an electric oven in which the temperature is gradually raised to 170° C in seven hours. The stems are then sealed into bulbs, evacuated, the evacuation tip sealed off, mounted and baked on the threaded brass base, and the leads soldered to the contacts of the base. Incidentally, it may be remarked that glass blowers found it impossible to seal the stem and the tipless bulb together without several unusual tools; it is much easier to use a machine.

The use of the exhausted electric light bulb prevents leaks, as glass seals are used throughout. This type is therefore free from the difficulties of rusting out of the iron wires and from condensation on the interior of the glass bulb. There is also another advantage in the use of a perfect seal for this apparatus such as we have not had previously in any pyrheliometer. If a thermopile is enclosed in a partial vacuum it possesses a greater zero stability and the sensitivity is increased (Coblentz, 1921). In this type of thermopile the sensitivity is approximately doubled.

The glass enclosed radiometers are durable. The glass bulb can stand as much abuse as electric lamps endure without breakage, which is often a great deal. The wires of the thermopile are very much stronger than lamp filaments, and the assembly is not easily jarred from position. Dust can not enter to dull the receiving surfaces and any accumulation of dirt on the bulb can be removed by washing. Some of the bulbs have now been in use in the open on the Harvard Forest and in Boston for nearly four years and show no sign of deterioration.

6. CHARACTERISTICS OF THE SPHERICAL HOT-JUNCTION THERMOPILE

In practice three of these radiometers made as described above are mounted in series giving a total resistance of about eight ohms. Approximately 8.0 millivolts per gram calorie per square centimeter per minute (0.12 gr. cal. per millivolt) are developed by a series of three radiometers. This is more than adequate to run a recording microammeter of seventy ohms internal resistance, with a full scale deflection of 30 microamperes. From 160 to 220 ohms series resistance must be inserted to keep the readings on the scale.

Tests have been made for the relation between the electrical power generated by the thermopile and the radiation intensity. With a point source and the radiometer in fixed positions in relation to one another the deviation of a series of readings is within ± 2 per cent of the average for intensities from zero up to the intensity of full sunlight.

Polarization tests have shown that the ideal radiometer has not been realized. The radiometers do not have an equal sensitivity at all angles of incidence from 0° to 85° — because of interference of the balls it is not to be expected that at 86° to 90° the full sensitivity could be obtained.

A number of different types were built in the attempt to determine the factors entering into the unequal sensitivity.

In type A (Fig. 8) the top shield A (Fig. 7) is omitted and the bright specular mirror of the shield B is presented to the spheres. An uneven polarization curve with a maximum at about 45° is obtained (Fig. 9). This is the result of the reflection of radiation from the specular surface onto the sphere. As the relative position of the pentagon of spheres and the source is varied we may get two extreme forms of sensitivity curves between 0° and 30°, namely, curves A(1) and A(2).

For a radiometer composed entirely of spheres for both the hot and cold junctions (Type B, Fig. 8) a polarization curve is obtained which shows that the spheres do not conduct the heat so that the entire shell maintains an average temperature under all conditions of exposure. This point is discussed in more detail in Appendix 6.

The examination of the polarization curve of Type C seems to indicate that it is the summation of the Type B curve and the cosine curve. Type C (Fig. 8) has all three shields, the top surface of shield A is blackened. It is apparent that the radiation heats the shield A in the same manner as it does any plane receiver. The temperature varies with the angle of incidence according to the cosine curve. The spheres follow the curve of Type B, and are also heated by radiation from the shield A. The resultant curve is thus the summation of the two.

The best curve is obtained for Type D. This radiometer is the same in design as Type A, but in addition the top of shield B is smoked with burning magnesium. The diffuse

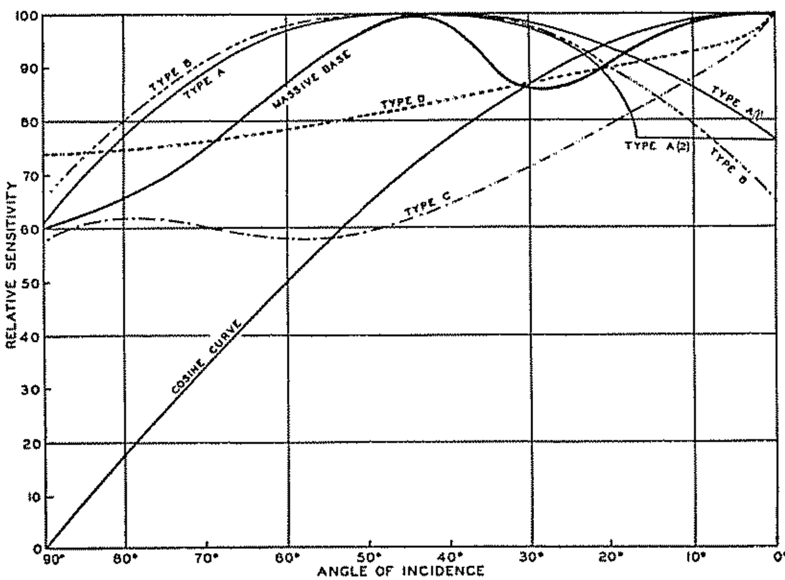


FIG. 9 POLARIZATION CURVES: RELATIVE SENSITIVITY OF DIFFERENT TYPES OF THERMOPILES WITH CHANGING ANGLE OF INCIDENCE

The cosine curve shows the variation in the "vertical component of sun and sky radiation" on a plane horizontal pyrheliometer with constant irradiation white surface prevents specular reflection. If the small peak from 0° to 5° is neglected the variation in relative sensitivity from 8° to 80° of angle of incidence is ± 9 per cent of the average.

That the type of polarization sensitivity represented by the cosine curve is unsatisfactory for silvical and ecological measurements can, it is thought, be taken as axiomatic. The foliage of most plants, taken en masse, represents some solid figure such as a cylinder, cone, or hemisphere. This is especially true of trees. Furthermore, these figures, considered as energy absorbing receivers, are not surfaces but shells; they have thickness, depth. Therefore the polarization curve of a plane thermopile mounted horizontally can bear no relation to the integration of radiation by the leaf surface of a tree. For the first approximation the ideal polarization sensitivity was considered to be an equal sensitivity for all angles of incidence. Perhaps some modification of this concept is desirable; broadleaf crowns differ from needle crowns in both shape and thickness. Exactly what shape of polarization curve best approximates that of the plant is yet to be determined.

The radiometer is non-selective. Due to the absorption in the thin soda-lime bulb the radiation integrated is limited to the region from λ 2.5 μ to about 0.32 μ. The transmission of this glass is about 82 per cent at λ 0.335 μ, 50 per cent at 0.31 μ, and 10 per cent at 0.29 μ (Stockbarger and others, 1928). Thinner bulbs are now available for use in the thermopile but the transmission data on them are as yet undetermined. For delimiting the radiant energy to small bands within this region, as λ 0.7 μ to 0.4 μ or smaller, light screens of colored inorganic solutions may be used. (Uhler and Wood, 1907; H. C. Jones, 1915; L. A. Jones, 1928.)

The first objective of this study has been reached. The spherical hot-junction thermopile with the matte-surfaced shield satisfied within practical limits all the requirements which are set up as essential in a silvical radiometer.

7. RECORDS FOR 1925

In 1925 the massive base radiometers were used to measure the radiation intensity factor associated with the growth of natural white pine (Pinus strobus L.) reproduction. These radiometers were faulty, as has been described above. But the checks with the later improved type of spherical hot-junction thermopile gave assurance that the facts discovered in the 1925 study are sound. This series of measurements is described here because they are the only full summer's data for a single group of sites which have yet been obtained. Subsequent records have been made on different material and for short periods only. It is planned to repeat more experiments of this type when it will be possible to obtain synchronous data on nitrogen and moisture supplies in addition to the radiation data.

The radiometers were used for observation at each of three locations, where there were already abundant white pine seedlings on the ground. The seedlings originated after the seed year of 1914 over the whole area which had been thinned in 1911–12. Areas *A*, *B* and *C* were clear cut at the same time in 1917, but are now to be distinguished on the basis of composition. *A* and *C* are predominantly hardwood; *B* is dense pure pine. In 1922–23 an additional area to the south of *A*, *B* and *C* was clear cut, and an area to the south of this was thinned. The rest of the stand was untouched. These operations gave rise to four classes of reproduction, all with eleven growing seasons in the autumn of 1925. They were: (1) those which received full insolation for eight summers; (2) those which received full insolation for three summers; (3) those which had been under a 40 per cent canopy for three summers; and (4) those which had been under a moderately heavy canopy, estimated at 85 per cent, since establishment.

The records were taken in each of three sites: (1) in the open under full light (Station **A** in the map, Fig. 10); (2)

under a canopy which, as estimated by the eye, obscured 40 per cent of the sky (Station **B** on the map); and (3) under an 85 per cent shade, which is nearly maximum density for a pure white pine stand (Station **C** on the map).

The crown relations of the trees comprising the canopy at the time of the radiation measurements can best be seen from the map (Fig. 10). The trees were about 70 years old, averaged 80 feet in height, and were spaced about 20 feet apart after the thinning in 1911–12. The crowns had spread, but had not developed symmetrically. They were approximately fifteen feet deep.

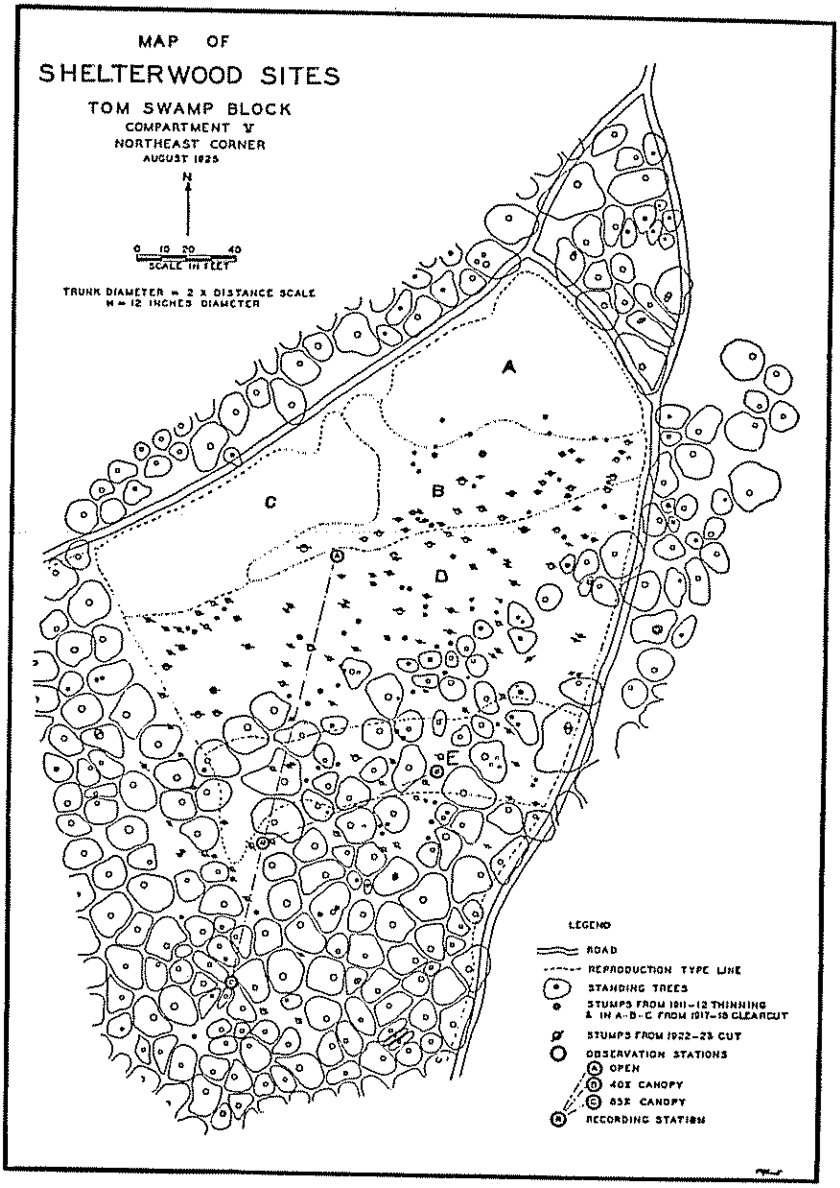


FIG. 10. MAP OF THE 1925 EXPERIMENTAL AREA

Setting up the thermopile and recording apparatus was comparatively simple. For each station three thermopiles were wired in series, joining the negative to the positive terminals. A variable compensating resistance was in each circuit and made it possible to adjust it so that the deflections of each of the groups of three units were equal to one another under a given radiation intensity.

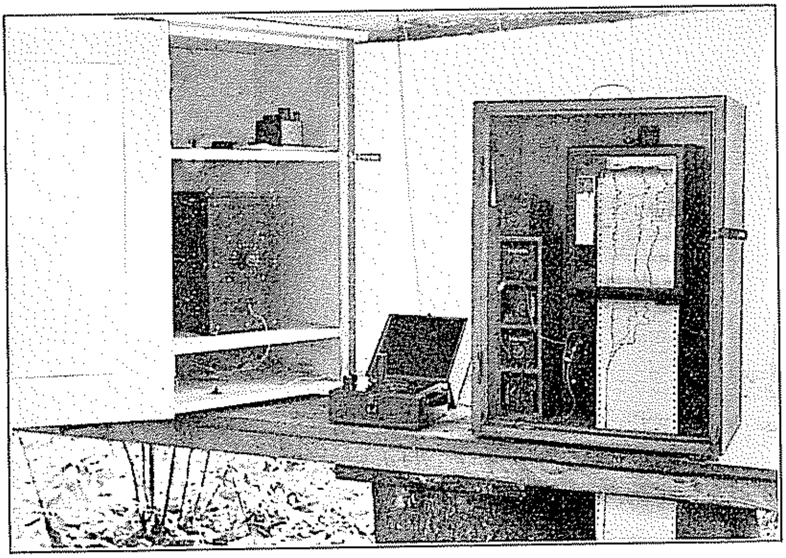


FIG. 11. THE RECORDING GALVANOMETER IN THE FIELD
Records are to be seen on chart

The thermopile galvanometer recorded automatically, demanding attention only for the daily removal of the record, winding, and similar attention to the mechanical operation once a week. The apparatus set up in the field is shown in Fig. 11; in the same figure the printed records are clearly seen. The chart as obtained from the recording galvanometer shows the variation of radiant energy intensity in each of four stations at intervals of four minutes. The chart is shown in Fig. 11.

If the daily record is viewed as a graph, with the intensity laid off along the axis of the ordinates and time along the axis of the abscissae, the area "underneath" the curve (between zero intensity and the plotted reading) is the total radiation received during the day.

Because of the acute angles and long reaches from point to point produced by the lag of the cold junction, it was considered better to get the areas by an indirect method rather than by planimetering. The curves were therefore traced on to a bond paper, cut out, and weighed. The weight of the paper for equal surface areas did not vary by more than 1.5 per cent. All the weighings were done in a dry, warm laboratory within a short period, and it is believed the error due to the method of obtaining area is negligible. The relative ratios of the weights of the cut-outs are the relative ratios of the total radiation. However, the areas on subsequent studies with spherical hot-junction thermopiles have been obtained by a planimeter.

There is a source of error in the results because the recording galvanometer was not the ideal type but has been the best to be obtained. The printed central divisions on the chart are closer together, the central third of the record is approximately 10 per cent smaller in area for a given electrical power increase than the two outer thirds. So the total radiation values obtained by planimetering the area of a record extending into the middle third or the outer third may be from 10 to 5 per cent too low. This causes an error in that the percentage records relating the intensity under the canopy to the intensity in the open are 1 to 3 per cent greater than their probable true value. Since the percentage records range from 30 to 60 per cent this error of 1 to 3 per cent is comparatively insignificant, and in any case is less than the probable error in the tree growth data.

This area multiplied by an appropriate conversion factor becomes the value of the gram-calories of radiation per square centimeter for the day, and is thus given in units of work.[1]

The data for the summer are given in the form of graphs

[1] For discussion of the relative advantages of the heat units, gm. cal., and of the electrical units, watts, see Ångström (1927) and Shaw (1927).

The *work* equivalents are

1 gm. cal. per sq. cm. = 1.162 kilowatt hours per sq. dekameter.
0.8606 gm. cal. per sq. cm. = 1 kilowatt hour per sq. dekameter.

rather than in the less convenient form of tables. In Fig. 12 are given the summer's records for 1925. The days of the month are laid off along the abscissae and along the ordinates are the total intensities of radiation for the day in gram-calories per square centimeter.

The radiation has been totaled for the entire summer in the three sites. For 105 days from May 12 to September 13, one square centimeter in the open received 47,280 gram calories, under the 40 per cent canopy 26,850 gram calories, and under the dense 85 per cent canopy 12,870 gram calories. For the period over which the measurements were taken in 1925 the radiation under the 85 per cent canopy averaged 123 gram calories per square centimeter per day. For the period of 69,300 minutes in which the intensity was greater than 0.01 gram calories per square centimeter per minute under the 85 per cent canopy, it averaged 0.186 gram calories per square centimeter per minute.

The data are given in another form in Fig. 13. The total intensities in the open are read downward along the ordinate scale with the zero at the top of the graph. The daily intensities under the canopies are expressed in percentages of the daily intensities in the open. These values are plotted along the ordinate scale with the zero at the bottom of the graph.

The moving averages for a ten-day interval are also plotted in Figs. 12 and 13. This average is the arithmetical mean of a ten-day period plotted on the fifth day of that interval.

The appropriate *power* units are

1 gm. cal. per sq. cm. per minute or 1 gm. cal. $cm^{-2}/min.$ or 1 gm. cal. cm^{-2} $min.^{-1}$ = 69.73 kilowatts per sq. dekameter or 697.3 watts per sq. meter or 0.06973 watts per sq. centimeter

The use of the term "light" for radiation has led to the statement of the radiation environment in terms of "foot-candles." These units are properly associated only with the intensity of a *source* or of *illumination* for the stimulation of the human eye. Only selective instruments with the photosensitivity curve of the human eye can be calibrated in terms of candle power. A thermopile or any selective instrument which is not modified to the photosensitivity of the human eye cannot be calibrated to measure variation in foot-candle power. Since a device modified to the photosensitivity of the human eye loses any intrinsic value it may have for the integration of radiation for plant physiological research, the worthlessness of a statement of radiation environment in terms of foot-candles is apparent.

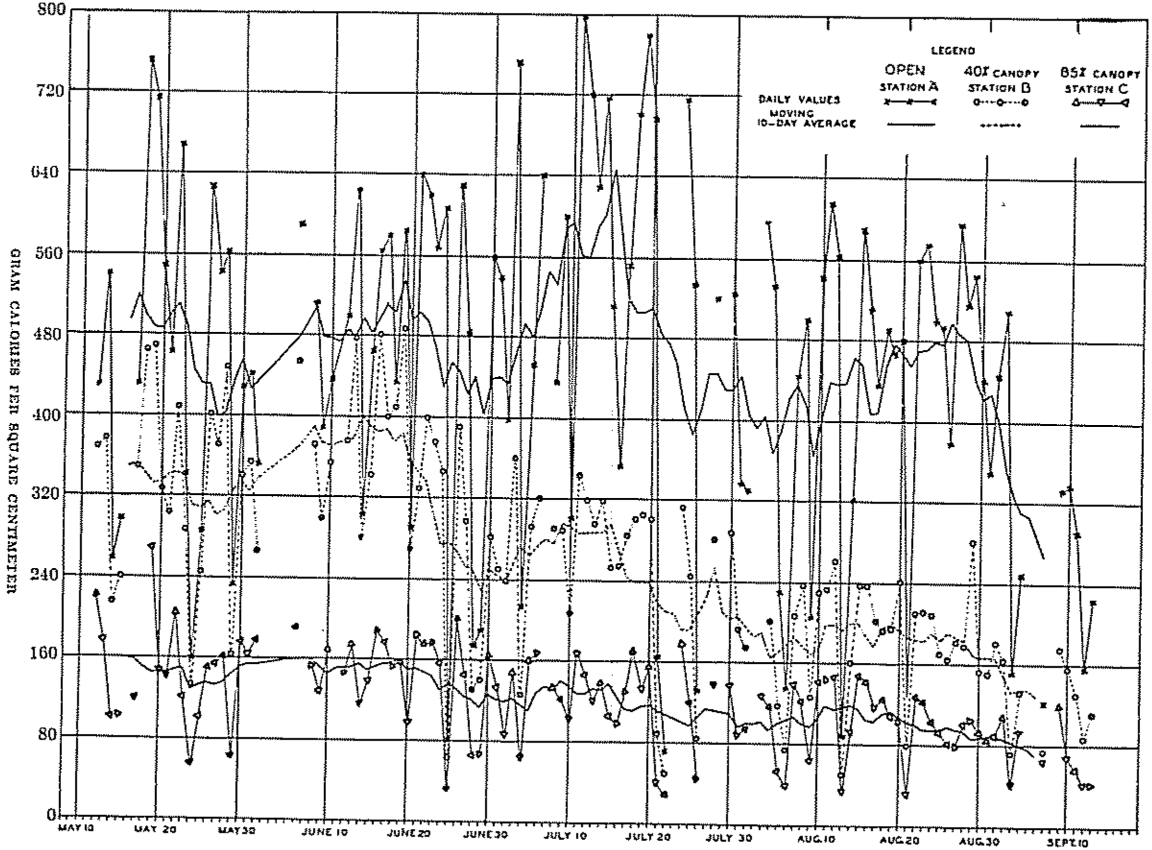


Fig. 12. THE DAILY TOTALS OF RADIATION FOR 1925 IN THE SHELTERWOOD SITES

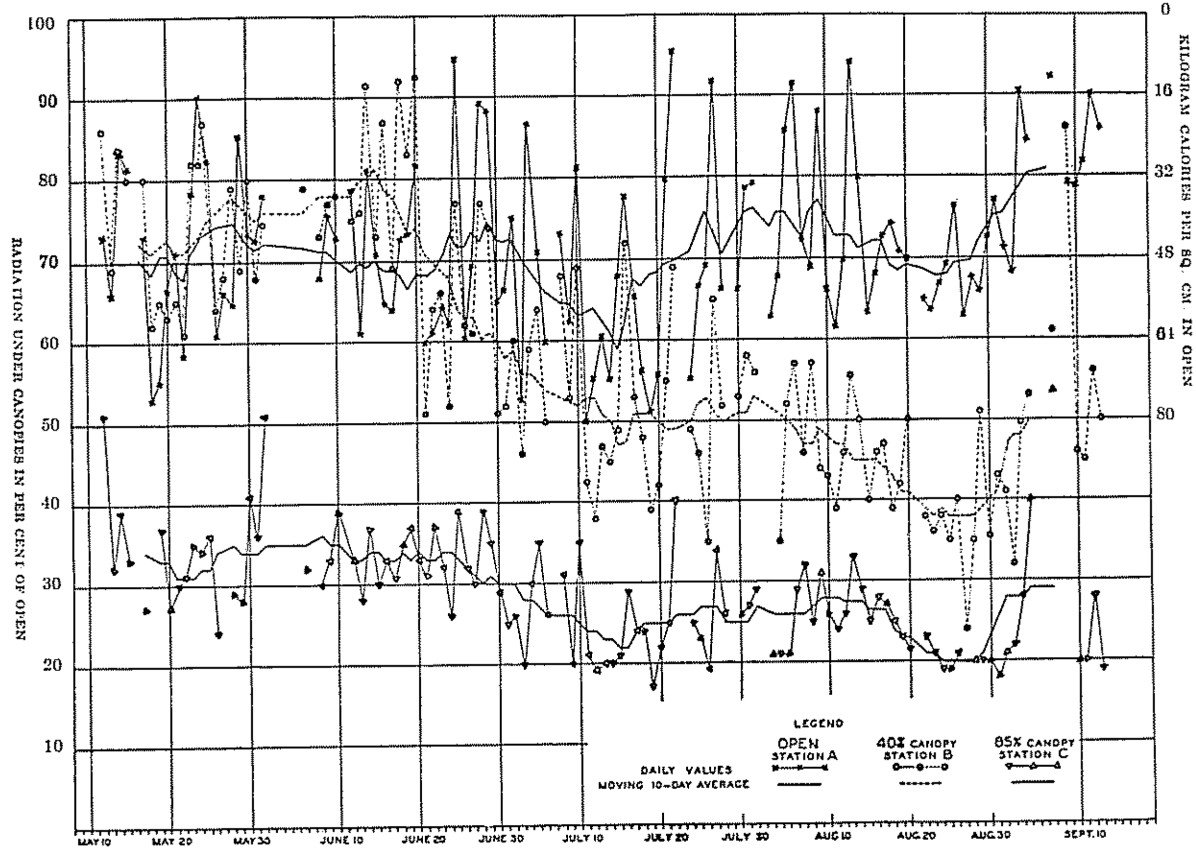


FIG. 13. THE 1925 DAILY TOTALS OF RADIATION UNDER THE CANOPIES IN PER CENT COMPARED WITH THE RADIATION IN THE OPEN

8. DISCUSSION OF THE 1925 THERMOPILE DATA

ALTHOUGH the individual day-to-day observations exhibit great differences, the moving ten-day averages show several well marked facts. In the first place it may be noted that the maximum total daily values are obtained in July and August. This is not in accord with the calculations of Kimball (1919) whose data indicate the probability of maxima in May and June. The explanation of the difference is apparently due to Kimball's use of vapor pressure and not relative humidity in determining the probable transmission of the atmosphere. The use of vapor pressure as a criterion predicts the probability of clear skies; the use of relative humidity predicts the probable duration of cloudy weather and the probable radiation absorption in the clouds. A study of the data presented by Piipo (1928) confirms this analysis.

The radiation under the 85 per cent white pine canopy, as shown in the graph (Fig. 13), runs very close to but above 30 per cent at times of lower radiation in open, and a bit below 30 per cent at times of higher intensity in the open. If the day-to-day radiation values are followed more closely it will be noted that this inverse relationship between percentage penetration through canopy and the relative intensity in the open is even more strongly marked.

That the percentage transmission of the canopy is less when the intensity in the open is greater is quite different from what might be expected. There is a two century old law [1] commonly designated as Lambert's Law, relating absorption to thickness of the absorbing medium, which states that the absorption is independent of the intensity of the incident light. But this law applies only to homogeneous, continuous absorbing media. The canopy of a coniferous forest is in effect a discontinuous medium in which tree

[1] This law was originally due to Pierre Bouguer, Essai d'Optique, Sur la Gradation de la Lumière (1729) but it was later restated by J. H. Lambert in his Photometria (1760) and has since borne his name. See p. 66.

crown and opening alternate. The direct radiation from the sun in passing through the crown is diminished to approximately 10 per cent of its intensity in the open. High intensities are received on the forest floor when the sun is visible through an opening, but otherwise most of the radiation comes from the sky light penetrating the openings. The sky radiation is relatively greater on a hazy day although the total intensity of direct and sky radiation is diminished because the light is scattered by the water in the atmosphere. Therefore, the percentage penetration through the canopy is greater on hazy days than on bright ones.

That the percentage penetration and relative intensities in the open are inversely related does not mean that less light penetrates the canopy on bright days (see Fig. 12). The net result is toward an equalization of the radiant energy underneath the canopy because the higher percentage penetration on the cloudy days makes for a more even daily radiation environment. In this paper this effect will be called the "equalization effect" of the forest canopy.

The radiation record under the 40 per cent canopy shows the same equalization effect to a less marked degree than does the heavier 85 per cent canopy. But in general, the brighter days show a smaller percentage penetration. It is notable that in June occurs the maximum percentage penetration at a value of approximately 80 per cent. During the summer the percentage penetration gradually falls off to 50 per cent in July and 40 per cent in August. This falling off is attributed to two causes. The first is the relative increase in radiation intensity during the summer months with the resulting operation of the equalization effect. The second is the gradual increase in the zenith distance of the sun. The sky brightness about the sun varies inversely as the distance from the sun. Lines of equal brightness of sky may be drawn around the sun as center. Thus the whole radiant source alters its position with relation to the canopy as the declination of the sun decreases with the increasing elapsed time after the summer solstice. The sparse canopy — looking through it at the sun and the immediate surrounding sky — is effectively more dense due to a "shingling" effect of the individual crowns as the zenith distance of the sun increases. The additive effects of the equalization relationship and the shingling phenomenon are considered to account for the decreased percentage under the 40 per cent canopy in July and August. Under the 85 per cent canopy, this falling off in intensity during the season is not as marked as under the 40 per cent canopy.

The operation of the equalization effect makes it absolutely impossible to secure precise results from discontinuous observations of the light intensity. Obviously, the effect depends upon the character of the crowns — their diameter, depth, and spacing — and upon the character of the clouds — formations of a stratus type give a different scattering from cumulus clouds.

Since all previous measurements of the penetration through canopies implicitly assumed that the canopy acted as a continuous filter, it is apparent that the probable error of the earlier determinations based on short discontinuous observations is high. Also, since the data have been taken mostly on bright, clear days (at least such are recommended in the literature) it is also apparent that the percentage determinations are lower than the average of the summer.

From these data it is apparent that the longer the record the more nearly will the average approach a true figure. In the case of dense even canopies a comparatively short period of observation will suffice. For open, thin canopies a longer period must be used. At least twenty days consecutive readings in June and an equal period in September would give a good working value. If this is impossible, three or four shorter periods may be satisfactory. It would seem that a minimum of forty days of total daily radiation values, well distributed through the growing season, must be set up as the minimum for a significant figure.

9. RELATION OF SEEDLING GROWTH TO RADIATION INTENSITY

That the young pines are affected by the degree of removal of the older stand under which they were growing is apparent

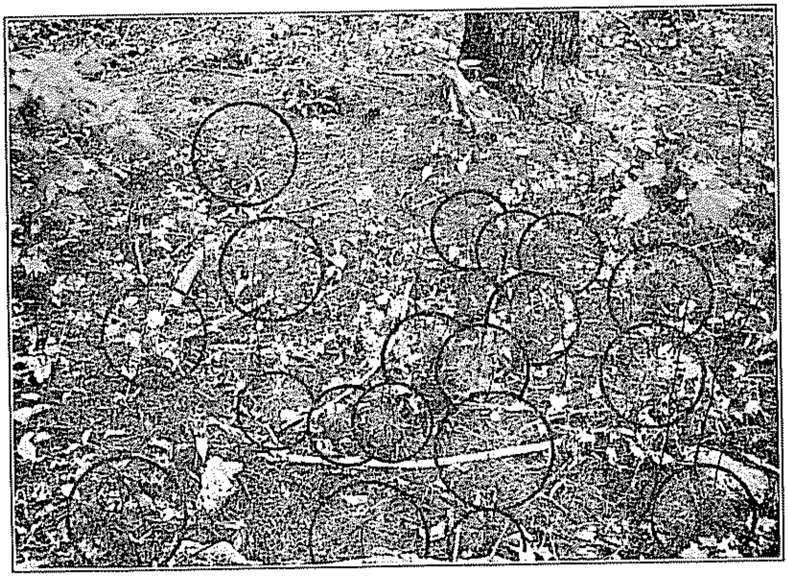


Fig. 14 ELEVEN YEAR OLD WHITE PINES UNDER THE 85 PER CENT CANOPY IN 1925

Compare also the photograph of a single tree in Fig 19, p. 58

from a casual observation of the large differences in the annual growth of the central shoot and lateral branches, the size and appearance of the needles, and the root development (Figs. 14, 15, 16, 17 and 19).

The pine reproduction in the three sites has been measured for annual height growth. By comparison of the average percentage radiation intensities through a summer and the annual leader growth, some idea of the effect of various amounts of radiation intensity on the growth and development can be obtained.

The pines to be compared were all eleven years old and had passed the first eight years under what was up to 1922 an 83 per cent canopy. Those in the open were exposed by the removal of the entire stand in the winter of 1922–23,

FIG 15 ELEVEN YEAR OLD WHITE PINES WITH THREE GROWING SEASONS UNDER THE 40 PER CENT CANOPY IN 1925

when those under the 40 per cent canopy were but partially exposed. The soil was a uniform stony fine sandy loam, site quality II, and the ground sloped off very slightly to the west. The whole area from which the seedlings were taken was not more than 100 feet by 200 feet.

For each tree the leader growth for 1922, 1923, 1924 and 1925 was measured, as were the needle lengths for 1925. In the following computations each tree was treated individually. As a base the leader growth of each of the trees for the summer of 1922, before the area was cut, was taken as 100. The leader length for each of the following summers was divided by the leader length during the summer of 1922. In this way were obtained the individual annual height growth rates relative to the 1922 growth. The data for the individual trees were then combined to give the growth data

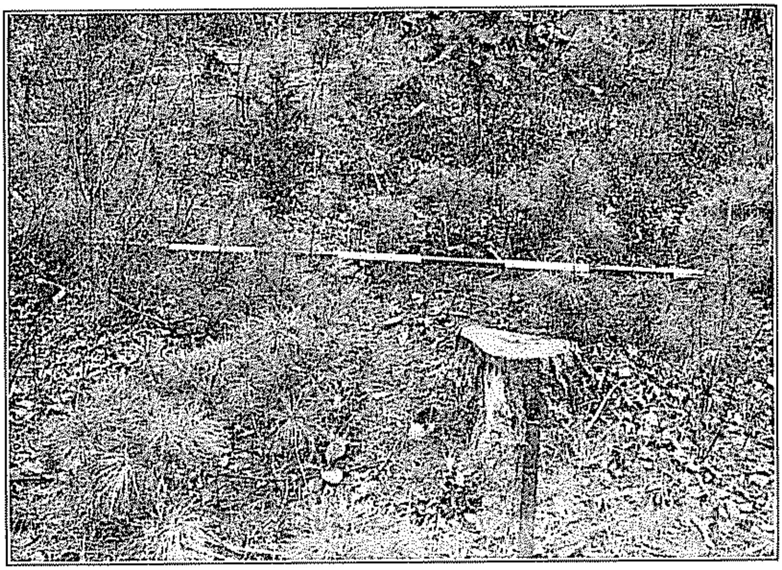


Fig. 16. ELEVEN YEAR OLD WHITE PINES WITH THREE GROWING SEASONS IN OPEN (NO CANOPY) IN 1925

for the year. The averages and probable errors (the probable error equals .67 times root-mean-square deviation) of the respective height growths and the needle lengths are given in Table 1. The growth ratios are represented in Fig. 18.

Trees eleven years old should be entering upon a "grand period" of growth, and the annual height growth should be greater for each succeeding year.[1] But the annual height growth of the leaders of the trees under the 85 per cent canopy

[1] The eleven year old trees (see Fig. 17) from which the over-topping trees were removed in 1917–18 are making 18 to 30 inches annual growth. They have had eight growing seasons in full solar radiation, and are to be compared with those which have had three growing seasons in full solar radiation and are making 6.3 to 8.9 inches annual growth.

(Fig. 14) have been practically equal during the last four years — 1922 to 1925. It is believed that this results from a limiting radiation intensity. Hence, apparently a total radiation of 27 per cent of that in the open is very near the minimum. The trees under the 40 per cent canopy (Fig. 15)

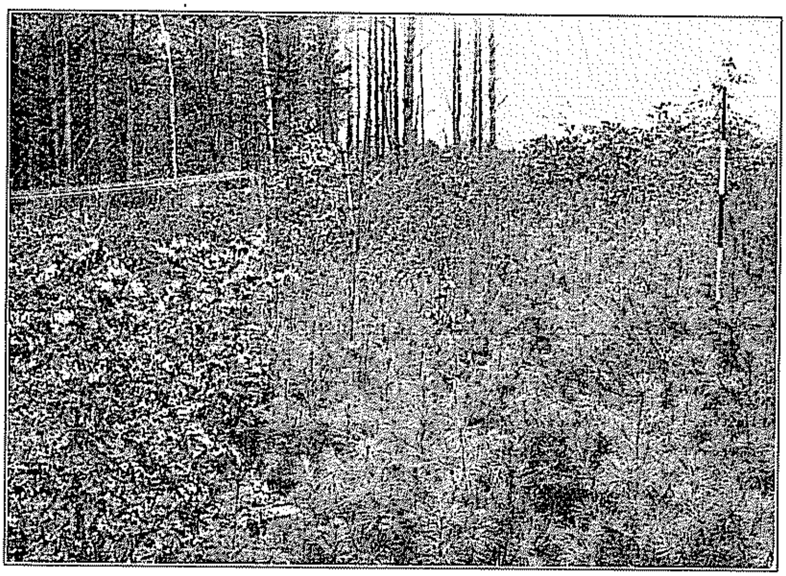


FIG. 17. ELEVEN YEAR OLD WHITE PINES WITH EIGHT GROWING SEASONS IN OPEN (NO CANOPY) IN 1925

Taken along south edge of area B looking toward area C (compare the map, Fig. 10). The range pole is eight feet tall and is marked in foot divisions

are not making the same height growth as those in the open (Fig. 16); they too are not receiving as much radiation as they could profitably use; so a percentage as high as 60 per cent does not make for the greatest possible growth.

The competition for soil moisture has been spoken of as a factor in the ability of trees to endure under a canopy. The low value for the leader growth under the 85 per cent canopy in 1924 raised a question as to possible variation in rainfall. A number of different ways of identifying a relation

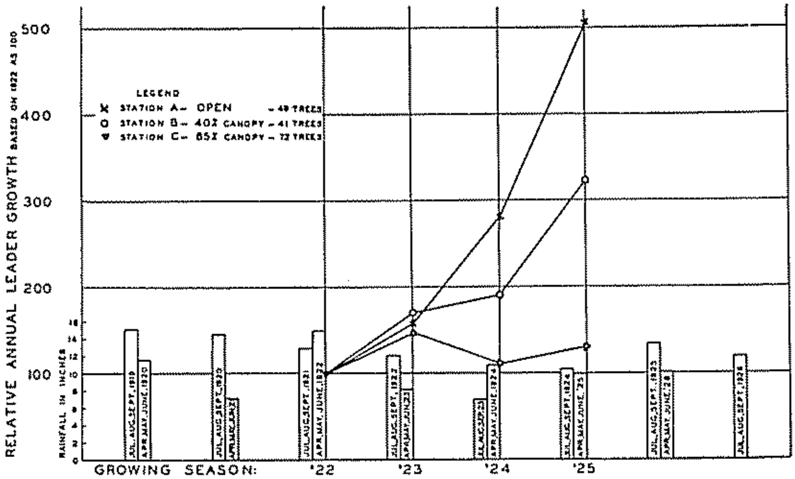


Fig 18. THE AVERAGE ANNUAL LEADER GROWTH IN THE THREE SHELTERWOOD SITES

The 1922 growth under a uniform canopy before the area was cut was taken as 100. The rainfall of the preceding summer (July, August, and September) is plotted with the spring rainfall (April, May, and June) against the height growth of that year

TABLE 1

RELATION BETWEEN GROWTH AND RADIATION PASSED BY DIFFERENT CANOPIES

	85 per cent Canopy	40 per cent Canopy	Open
Total Radiation in gram cal. per sq. cm.[1]	12,870	26,850	47,280
Number of Trees	72	41	49
Leader Growth Ratios, 1922	100 ± 32[2]	100 ± 32[2]	100 ± 32[2]
1923	147 ± 28	170 ± 18	157 ± 39
1924	110 ± 27	190 ± 62	280 ± 62
1925	130 ± 31	323 ± 64	505 ± 85
Average Leader Lengths in inches, 1925	2.0 ± 0.5	4.9 ± 1.0	7.6 ± 1.3
Average Needle Lengths in inches, 1925	2.1 ± 0.2	2.8 ± 0.4	3.1 ± 0.3

[1] 105 days from May 12 to Sept. 13, 1925.
[2] The probable error of the trees in the three plots, if grouped as a single plot is ± 32.

between seasonal rainfall and growth have been set forth. In the diagram (Fig. 18) the rainfall in the previous summer months (July, August, September) is coupled with the spring (April, May, June) rainfall. This does not satisfactorily explain the dip in the 1924 growth; it might have been better to use only the six months of 1923.

In any case, it is quite evident that the low growth in 1924 occurs shortly after a summer precipitation which is the smallest in eight years. The effect of rainfall enters as a minor factor in the thriftiness of young growth which, in addition to being affected by the absorption of radiant energy by the superior canopy, is in competition with older trees for water. No satisfactory method for the measurement of the moisture available to the plants exists, since the measurement of available water by subtraction of the wilting point gives no idea of the dynamic rate at which that water is available. That the drought of 1923 did not cause the 1924 growth of the seedlings under the 85 per cent canopy to drop below the 1922 growth is interpreted as showing that the water was not the limiting factor.

With full realization of the possibility of underestimating the importance of the relatively decreased competition of roots for water in those places in which the trees have been removed, the growth rates may be examined for their relation to the radiation intensity.

The trees did not suddenly increase to a higher rate of annual growth after increased insolation because the amount of leaf area presented also determines the amount of carbohydrate a tree elaborates. Hence we find a gradually increasing annual height growth, as the products of the previous year's photosynthesis become available for needle, branch and root development.

But after two years' exposure to full solar radiation (and whatever added moisture supply might have been available due to removal of competing roots) the growth of the pines is found to be related to the radiation intensity as seen in the following ratios:

	85 per cent Canopy	40 per cent Canopy	Open
Relative Leader Growth	130	323	505
Total Radiation Intensity, 1925*	12,870	26,850	47,280
Ratio: $\frac{\text{Relative Growth}}{\text{Radiation}} \times 100$	1.01	1.20	1.07

* Total radiation in gm. cal. per sq. cm. for 105 out of 125 days from May 12 to September 13, 1925.

The leader growth is apparently proportional to radiation as measured by the thermopile used, up to the intensity of full solar radiation.

It has been stated above that 27 per cent seems to be very near the limiting tolerance intensity for white pine. This may be questioned on the basis of the experiments of Bates and Roeser (1928) who have determined the minimum theoretical intensity as 2 per cent. That they used in their experiments radiation from electric lamps containing an even greater percentage content of red and infra-red radiation [1] than the sun (compare Figs. 3 and 4) makes the discrepancy the more serious. However, it is not possible to check their values and these in terms of absolute units, which is the only real basis of comparison. They used the noon radiation intensities on clear days for the determination of the 100 per cent value of sunlight. Had they used the average of all days, and all times of the day it is evident from Fig. 12 that the percentage values would have been larger, and the discrepancy would have been decreased. Parenthetically, one remarks that here is a case which demonstrates the need of

[1] There is a suggestion both in the work of Bates and Roeser cited above and this reported here that infra-red may be more important in photosynthesis than has been demonstrated. It would seem that possibly infra-red may be important in producing a high order temperature coefficient effect. To illustrate: let the rate of photosynthesis be determined for a plant illuminated with a known intensity of visible monochromatic radiation (λ 0.66 μ): then irradiate with a series of increased intensities of λ 1.3 to 1.7 μ only. It would be interesting to watch for any alteration in the rate of photosynthesis.

calibration in absolute units for the inter-laboratory comparison of results.

The value of 27 per cent for the limiting tolerance intensity for white pine is, in absolute units, 123 gram calories per square centimeter per day, or 0.186 gram calories per square centimeter per minute. This may be compared with the value of 60 gram calories per square centimeter per day for beech (Fagus silvatica L.) as determined by Odén (private communication). For forcing the growth and development of this species, which is considered one of the most tolerant, this minimal quantity is required over a period of about thirty days of continuous exposure. For continuous exposure the minimal radiation intensity is therefore 0.0416 gram calories per square centimeter per minute. It is to be questioned whether the shorter photoperiod in temperate latitudes would not require a higher minimal intensity. For comparison with the results of Bates and Roeser the noon radiation intensity used for standardization may be estimated as between 1.4 and 1.6 gram calories per square centimeter per minute. A 2 per cent intensity would be between 0.028 and 0.032 gram calories per square centimeter per minute, which would be the theoretical minimum for the growth of white pine as determined by their study.

If the attempt is made to compare the minimum radiation requirements as determined by the thermopile with the values obtained by selective photographic, visual, etc., methods another difficulty is encountered. There is a difference in the kind of energy registered, and these various regions are differently intercepted by the crown canopy. The "equalization effect" noted above is very important in dealing with the shorter wave lengths because the absolute values of blue, violet, and ultra-violet radiation are considerably altered by variation in the atmospheric humidity. Measurements have been made under this same 85 per cent canopy by a chemical method continuously integrating the ultra-violet radiation (λ 0.35 to 0.30 μ) at normal incidence. These showed that the

85 per cent canopy which passes about 25 per cent of the total radiation transmits on the average 6 per cent of this "near ultra-violet" (unpublished work of the writer).

Again, it is to be recalled that these pines were eleven years old, and it is believed that the tolerance of white pine decreases with age.

The root systems of pines grown under a canopy of older trees show an extreme development of a lateral root, and a little or no tap root (Fig. 19). The lateral root runs along in the organically enriched layer of the soil profile, and feeding coralloid mycorrhizal rootlets develop into the humus layer. This sort of root system is interesting in that it corresponds to what has been found to be the relative root and shoot growths in plants grown with a minimal supply of light and with adequate nitrogen (Reid, 1924). But the work of Hesselman (1927) showed that the leader height growth is directly proportional to the nitrogen availability. The increased temperature of the organic horizons due to the increased insolation may well cause an increased nitrogen availability. Since Reid (1929) has shown that exposure to radiation may cause an increase in the assimilation of nitrogen, it is probable that the larger growth in the specimens receiving the greater insolation is the result of increased photosynthetic activity, increased nitrogen availability, and increased nitrogen assimilation. The character of the luxuriant needle production and increased root development also closely parallels the reaction of pine and spruce seedlings to increased nitrogen mobilization in the substrate as found by Hesselman (1927). It is apparent that the effect of increased insolation is not the result of the effect of increased radiation intensities upon the mechanism of photosynthetic activity only.

The work of Grasovsky (1929) demonstrated that there is sufficient "light" under most forest canopies of New England forests to maintain photosynthesis at the minimum rate necessary for survival. But it would seem that such a minimum radiation intensity fails to provide for adequate trans-

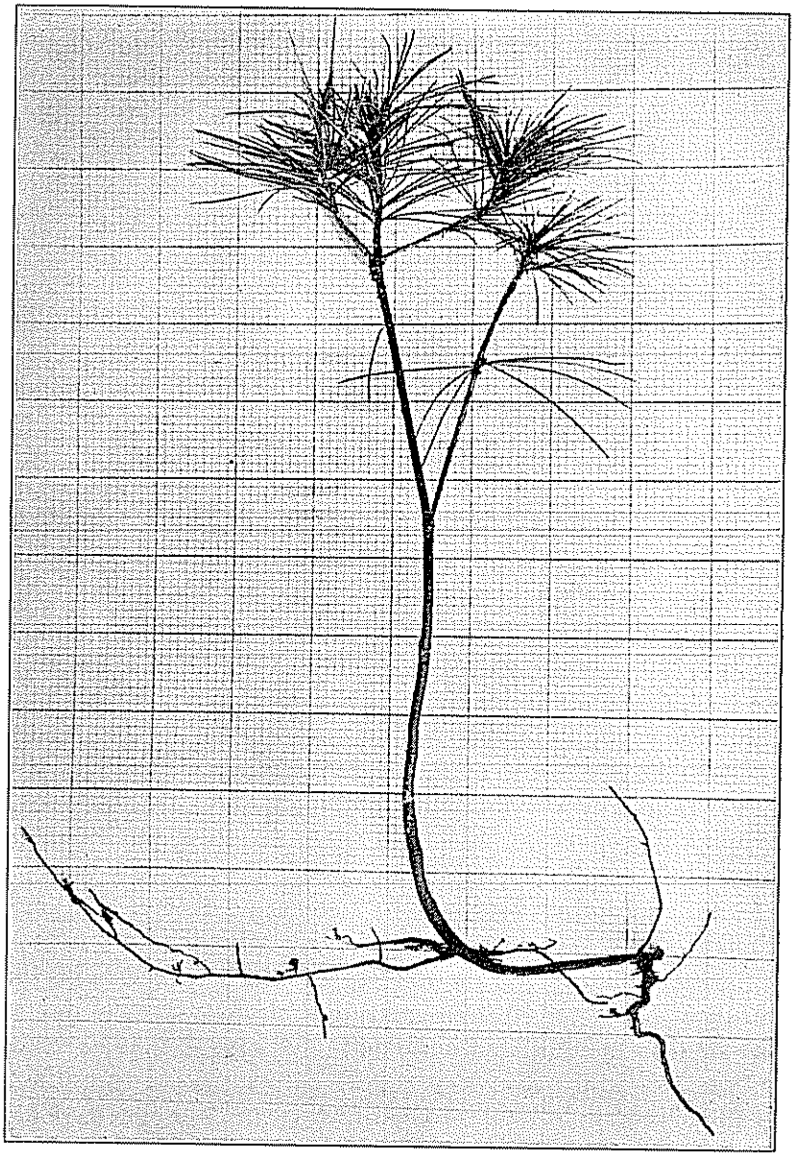


Fig 19. ELEVEN YEAR OLD WHITE PINE FROM UNDER THE 85 PER CENT CANOPY

Note the small root as compared with size of shoot, also the strong mycorrhizal development. The cross section paper is divided in inches and tenths formation of the humus with a consequent lack of nitrogen. That trenching experiments on sandy soils (Toumey, 1928) are not conclusive in showing that the moisture relation is the single factor is shown by experiments on the Harvard Forest. Here under a pine-hemlock stand on a coarse sandy loam soil the burning of litter and duff horizons produces the same result as does trenching.

This series of experiments is therefore interpreted to mean that the effect on growth of the partial removal of the canopy is due to increase in insolation and not to increase in moisture availability. Unfortunately the proportionate effects of the increase in radiation intensity on the carbohydrate metabolism of the plants and the nitrogen metabolism of the plants have not been distinguished.

CONCLUSION

It appears that there has been a sound physical reason for empirical attempts to develop scales of tolerance. While "light" has for many years been stressed as the important factor in silvicultural operations, looking to the regeneration of the forest, the recent decade has seen the pendulum swing far in the other direction. Foresters in the United States have tended to minimize the importance of radiation.

This tendency was doubtless because most of the intensive fundamental research has been in regions where the small yearly precipitation or the low summer rainfall pointed to available soil moisture as the limiting factor (Bates and Zon, 1922).

But where rainfall is well distributed and on the less meagre soils in New England, it is possible to over-emphasize the importance of soil moisture in the growth and development of trees. Several years' observations with an apparatus which gives a truer record of the total radiation than any previously used show that over and above the deviations in growth which are due to seasonal water supply the relation of growth to total radiant energy remains constant and conspicuous.

Therefore the attempt to develop successful methods of controlling natural reproduction must continue primarily to consider the reaction of germination, growth and development to the total radiation that reaches the forest floor.

APPENDICES

APPENDIX 1

Wave Length

Wave length is the distance from crest to crest of two successive waves. In the cartoon two figures are represented as riding the crests of successive waves toward a bell buoy, one wave length ahead of the front rider. By the time he reaches it, the buoy will have made a complete vertical displacement to the bottom of the trough and a return to the top of the swell. This we may call a

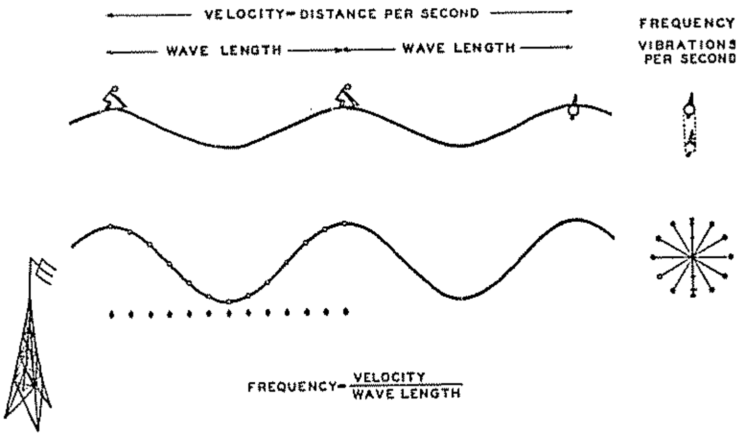


Fig. 20

vibration. The *frequency* of vibrations is the number of completed vertical movements per second. It may be calculated by the formula

$$f \text{ (frequency)} = \frac{v \text{ (velocity)}}{\lambda \text{ (wave length)}}$$

If we use 10 feet for a wave length of water waves and for their velocity a distance equal to two wave lengths, or 20 feet per second, then

$$f = \frac{v}{\lambda} = \frac{20 \text{ feet per second}}{10 \text{ feet per second}} = 2 \text{ vibrations per second}$$

When the rear rider reaches the buoy in one second of time it will have made two vibrations. (The analogy is rather forced since water waves do not travel so fast!)

For calculating the displacement of the buoy the geometrical construction to the right of the lower curve is used. The vertical displacement of a particle moving at the end of a radius which has a given angular velocity is plotted. The cross lines on the vertical diameter are thus obtained. These points are transferred to successive ordinates spaced at equal distances along the horizontal axis. By joining these points the sine curve is derived.

APPENDIX 2

Description of Fig. 2: the Great Electromagnetic Spectrum [1]

For the scale of lengths the metric system is used. The centimeter is taken as the unit of measure; each increasing or decreasing power of 10 (10^1, 10^{-3}, etc.) beside a heavy cross-line represents the appropriate number of centimeters. This is, therefore, a logarithmic scale. To the right of the scale the words underscored are the various units of length. The micron (0.001 mm.), the millimicron (0.000 001 mm.) and the Ångström unit (0.000 000 1 mm.) are used to indicate the length of waves in the vicinity of visible radiation,— "light." To the left of the scale the words in large type suggest distances which are of the same order of magnitude as the lengths represented by the places which the words subtend, e.g., known stars are from 1 to 10,000 light-years away (a light-year is the distance light is propagated in one year at the rate of approximately 300,900 kilometers or 186,000 miles per second); microscopical distances are from millimeters to microns in length; colloid particles are from microns to millimicrons in diameter; molecules are less than millimicrons in diameter, etc. The words to the right in heavy letters are the names of the various regions of the great electromagnetic spectrum. The names are placed with reference to the scale of measure of lengths so as to indicate the order of magnitude of their

[1] This figure and description are adapted from Bovie (1926) Houston (1920, p. 312) and Preston (1914, p. 414).

respective wave-lengths; e.g., wireless waves range from a few meters to some hundreds of meters in length. (The "S.O.S." wireless call is given in waves 300 meters long.) Visible light waves are some tenths of microns long. Gamma waves, from radio-active substances, have very short wave-lengths. As shown in the figure, one could place 1,000,000 of them end to end in a space only one micron long.

When we are dealing with the biological effects of electromagnetic waves we are concerned with vibration frequency, or the number of electromagnetic vibrations per second. Electromagnetic waves are all propagated through space at the same rate. Hence, the number of vibrations per second, the frequency, varies inversely as the wave-lengths. The number of vibrations per second is indicated by the small figures to the left of the wave lengths. An electromagnetic wave one light-second long obviously vibrates once per second. A wave 100 meters long vibrates 10^6 or 1,000,000 times per second. Light waves vibrate 10^{15} or 1,000,000,000,000,000 or some quadrillion [1] times, while X-rays (Roentgen rays) vibrate 10^{19} (10,000,000,000,000,000,000), or some quintillion [1] times per second. The gamma rays vibrate still faster.

APPENDIX 3

Description of Fig. 2. Solar Spectrum

In figure two arithmetic scales are used: the right hand scale from λ 0.25 μ to 0.75 μ is five times the scale on the left, which ranges from λ 0.60 μ to 3.0 μ.

In the right hand figure the various limiting and representative wave lengths of the different colors are given through the center. The frequencies corresponding to these wave lengths are found in the next column to the left. The energy of quantum — the unit of energy — for the given wave lengths is given in the next column; they are equal to the product of the frequency and Planck's constant (6.55 times 10 erg. sec.). The position of the various Frauenhofer lines frequently used for locating wave lengths is given in

[1] The names given above are the American name for these numbers. The English names are thousand billion and trillion respectively.

Ångström units equal to 0.1 $\mu\mu$ (see also Fig. 1). Between the limits of transmission of crown glass (see also Fig. 1) and the limit of sunlight is the biological band of anti-rachitic fame.

In the graph above, the visible colored spectrum, are given two different sorts of data. The heavy curve gives the relative brightness to the eye of equal amounts of radiant energy of different wave lengths, obtained by the step-by-step method (Gibson and Tyndall, 1923). Radiation at λ 0.555 μ in the yellow has the greatest visibility. The use of these data is best shown by an example. Assume two sources, the first emitting only yellow of λ 0.555 μ at a given intensity, and the second emitting the same amount of energy in gram-calories per square centimeter per minute, but of another wave length. The data indicate that the second source is only one fiftieth[1] as bright to the eye if it is red radiation of λ 0.67 μ. To obtain equal brightness the red source would have to emit energy fifty times the intensity of the yellow when both are measured in absolute units.

The dashed line connects the five values determined by Warburg and Negelein (1923) for photosynthetic efficiency of Chlorella. Complete absorption of the radiation was obtained, and the values indicate the relative CO_2 production for equal intensities of irradiation by the given wave lengths.

On the left hand graph are given the absorption and its complement, transmission, for the different wave lengths through three different thicknesses of water: 5.0, 1.0 and 0.005 cm. For any other thickness the value of the transmission can be computed by substituting the appropriate value of the extinction coefficient ϵ in the formula derived from Lambert's law.

$$T_n = T_o \cdot e^{-n\epsilon}$$

where T is the transmission through n thicknesses of water in cm., T_o = 100 per cent, e is the base of the natural logarithms. Example: at λ 1.30 μ, ϵ is 1.2 and through a layer of water 1 cm. thick the transmission is

$$T_{1cm.} = 100 \times e^{-1.0 \times 1.2} = 30 \text{ per cent.}$$

[1] There is an error in the datum for the value of relative visibility for λ 0.67 μ in Fig. 2: read 0.02 instead of 0.002!

APPENDIX 4

THE LAMBERT COSINE LAW

IN the figure, OP_1 represents a cross sectional view of a plane intercepting radiation from the source S at normal incidence; the perpendicular OL to the plane parallels the path of the radiation. If the plane is moved through the angle a to the position OP_2, using as an axis the edge through O which is perpendicular to the cross section, then radiation from S meets it at oblique incidence. To the plane OP_2 drop the perpendicular JO. Then by definition the angle i is the *angle of incidence* since it is the angle between the direction of the radiation and a perpendicular to the plane.

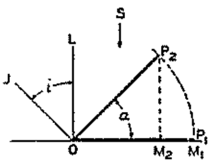


FIG. 21

On the plane OP_2 the intensity (I_{op2}) will not be as great as the intensity (I_{op1}) on the plane OP_1, since the plane OP_2 will intercept only a fraction of the radiation on OP_1. Let op_1 and op_2 be the lengths of lines perpendicular to the axis of rotation (the edge seen in cross section at O) in planes OP_1 and OP_2 respectively. The width of the illuminated area of the plane in position OP_1 is om_1, and om_1 is thereby equivalent to op_1. If the width of the shadow cast on OP_1 by OP_2 is om_2, the fractional intensity on OP_2 is $\frac{om_2}{om_1}$.

That is $$I_{op2} = I_{op1}\frac{om_2}{om_1} \qquad (1)$$

Since $$om_1 \simeq op_1 = op_2$$

$$\frac{om_2}{om_1} = \frac{om_2}{op_2} = \cos a$$

By substitution in (1)

$$I_{op2} = I_{op1} \cdot \cos a \qquad (2)$$

Since $$a = 90° - \angle LOP_2 = i$$

By substitution in (2)

$$I_{op2} = I_{op1} \cdot \cos i \qquad (3)$$

APPENDIX 5

Explanation of Figures 3 and 4. Black Body Radiation Curves

It is a familiar fact that as a body is heated the amount of energy radiated from it becomes greater. The laws governing this phenomenon have been the subject of much intensive study. It has been found possible to relate the spectral distribution of such energy to the temperature of the body. The data for these two sets of graphs were calculated by aid of the formula of Planck. For its statement any text on radiation may be consulted as well as Frehafer and Snow (1925) and the numerous contributions of Coblentz from the United States Bureau of Standards.

The values shown in these graphs are important in the calibration of all selective radiometers. Neglect of them may lead into error, as illustrated in the case of the use of photographic plates cited in the text. They are important in calculating the energy of the wave lengths emitted by a body at a given temperature.

The data in the two figures are identical. They differ in that Fig. 3 is plotted on an arithmetic scale, and Fig. 4 is plotted on a logarithmic scale. The essential similarity between the curves, which is not seen in Fig. 3 is revealed in Fig. 4. The temperatures are given on the absolute scale which has a zero at −273°C. and is usually designated as °K. (Kelvin).

The temperatures correspond to the following radiant bodies:

273° K	0° C
338	150° F: hottest ground temperature reached on the Harvard Forest.
748	Red heat (barely luminous)
866	Dull red heat
1000	Full cherry red heat
1140	Light red heat
1323	Light yellow heat
1423	White heat
2000	Tungsten filament
3773	Carbon arc
5000	Cloudless midday sun
6000	Blue sky (equivalent or "color" temperature)

It is to be emphasized that the last values indicate that the radiation received from these bodies is of such spectral distribution that a body at that temperature would give the same relative distribution. The sun is apparently at a temperature of 5,000°K.; we know that the sky is not. This index to spectral energy distribution is called the color temperature of a body. By plotting the relative spectral energy distribution, then moving it along the dotted line of maxima until it coincides with an appropriate curve, and then by following out to the left hand margin of temperature values it is possible to determine the color temperature.

A graphical aid, from which part of these data was plotted is a set of Tables and Graphs by K. Frehafer and Chester Snow (1925).

APPENDIX 6

Principle of the Thermoelectric Radiometer

The simplest thermoelectric circuit is formed as in Fig. 22, in which a short piece of constantan wire is shown joined to copper wire at the two points T_1 and T_2. The copper wire is interrupted

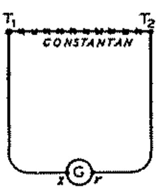


Fig. 22

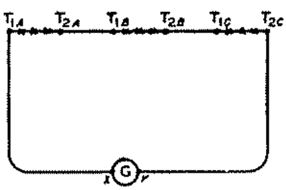


Fig. 23

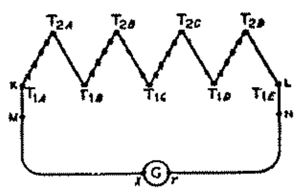


Fig. 24

by a galvanometer G inserted between x and y. If the two junctions are at different temperatures which may be designated as t_1 and t_2, an electromotive force will result which will be shown by the deflection of the galvanometer. The exact value of the voltage can be calculated from the equation:

$$\text{E.M.F.} = k(t_2 - t_1)$$

In this equation k is a constant which depends upon the two metals which form the circuit. A complete discussion of the calculation of k for a number of combinations of metals from a thermoelectric diagram is to be found in Brooks and Poyser (1920).

As T_2 or T_1 is at the higher temperature, the direction of the fall of potential and consequent current movement is reversed. Except for the reversal of the current, either junction serves equally well as the "hot" junction. For measuring instruments rather sensitive galvanometers or special potentiometric circuits are necessary. When two junctions only are used, the combination is called a thermocouple. By holding one junction at constant temperature, or by means of a circuit which corrects for its deviations, the variation in the temperature of the hot junction can be determined electrically. The thermocouple has been widely used as an extraordinarily sensitive thermometer where small temperature differences are to be determined and also where a thermometer of small volume and small heat capacity is desired.

A thermocouple is a kind of battery (electric generator) in which the heat is directly transformed into electrical action. Just as it is possible to increase the voltage by joining several chemical batteries in series, so is it possible to increase the voltage by joining several thermocouples in series, as represented in Figs. 23 and 24. For a few thermocouples the total voltage is increased approximately as the number of couples; but as the number of couples is increased indefinitely, a "diminishing return" due to increased resistance results.

Such a series of thermocouples is called a thermopile, and is the basis of the legion of radiometers devised in the last eighty years. The circuit as shown in Fig. 24 does not differ from the circuit in Fig. 23. What appears to be a difference is due only to the mechanical arrangement whereby the "hot" T_2 junctions are separated from the "cold" T_1 junctions to facilitate the difference in exposure to the radiation or to the environmental temperature of which a measurement is desired. The large number of thermopiles which have been built and projected vary in the details of construction, being different in the metals used in completing the circuit, in the manner of combining the metals at the welds, in the construction of the receivers, in the manner of shielding the cold junction or otherwise controlling its temperature, and in the relative masses of the hot and cold junctions and radiant surfaces.

When the thermopile is used as a radiometer, the usual practice is to blacken the hot junctions exposed to the radiation and by bright surfaces to shield the cold junctions from the radiation.

The blackened surfaces of the hot junctions by reason of their greater heat absorption maintain those junctions at higher temperatures than those of the cold junctions shielded with white or mirror surfaces. The two sets of junctions are thus in equilibria with the source of radiant energy, and the temperature difference between these equilibria is used as the measure of the intensity of the incident radiant energy. The accuracy of a given design of radiometer can be determined only by comparing its readings with the known values of radiant energy of the intensity the instrument was constructed to measure. It is difficult to predict beforehand exactly how modifications in design will alter the character of the device.

For a hot junction receiver to integrate radiation at normal incidence the writer has used a hollow sphere. It was anticipated that the conduction through the wall of the sphere and re-radiation from side to side within the ball would maintain a constant temperature throughout the metal. It was anticipated that thus the average temperature of the two points (Fig. 25, t_b and t_c) where the junction wires are welded to the metal of the ball would be maintained at a constant temperature under all exposures of the sphere. It was supposed that if t_a were the hottest point, t_b and t_c each 90° away from the t_a would be about equal; if t_c were the hottest point, then the average temperatures of t_c and t_b would be the same as the average temperature of the two points when t_a is the hottest. This does not seem to be exactly true. It was found that apparently reflection from the bright annulus underneath the spheres was essential to cause the approximately equal registration from normal incidence. While the practical advantage of such an approximate registration is of great advantage for ecological work over the plane thermopile exposed horizontally, the ideal thermopile is not achieved.

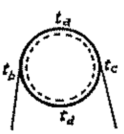


Fig. 25

The question may be raised as to what influence the temperature of the other parts of the ball may be. The answer is the same as that to a question as to the possible thermoelectric currents due to interposition of the nickel and the copper-clad iron lead wires *km* and *ln* which connect the iron-constantan pile proper with the leads external to the bulb. The rule governing such cases is that it is only the temperatures of *junctions* which count. That is, if in

Fig. 23 the junctions T_{1b} and T_{2b} are at the same temperature, it is as though the piece of constantan wire between them were missing. In effect one thermocouple is removed. And so with any intermediate conductor which may be inserted into the circuit, as long as such a conductor is kept at the same temperature as the original junction, no alteration of the E.M.F. in the circuit results.

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