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The Photo-Electric Measurement of the Penetration of Light of Various Wave-Lengths into the Sea and the Physiological Bearing of the Results

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V. *The Photo-Electric Measurement of the Penetration of Light of various Wave-Lengths into the Sea and the Physiological Bearing of the Results.*

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Introduction.

The chemical examination of sea water had shown that, as the spring advanced, the surface water became more alkaline and its phosphate content much reduced. These changes were shown to arise from the action of the phytoplankton, and the fact that they were, in these latitudes, mainly limited to the upper fifteen or twenty metres suggested that lack of light hindered growth at greater depths.

It was natural to seek for quantitative information on this subject, and as alternatives the photographic and photo-electric methods presented themselves. The former had been used to a considerable extent, notably by Grein (1913, 1914). It is specially suited for detecting very feeble illumination and for showing the depths to which light of various colours can penetrate. The difficulties and limitations of the method are obvious when quantitative results are required at lesser depths with relatively intense light, such as is wanted for photosynthetic processes to be carried on at a rate great enough to preponderate over respiration. Not the least of such difficulties is imposed by the condition that the light of the sky, including the sun if uncovered, is normally very variable, and that the surface of the sea is rarely at rest. Furthermore, the obtaining of a large number of measurements necessitates the exposure and development of many plates, and becomes very tedious. Moreover, the transmissive exponents calculated from Grein's results are highly irregular.

At the time when we first considered the problem, in 1924, Shelford and Gail (1922) had already carried out photo-electric measurements of the penetration, into the calm waters of Puget Sound, of the blue light, to which their sensitized gas-filled potassium cell was sensitive. The method had great advantages, the readings being obtained very quickly while the work was in progress, so that the extent of the absorption was shown at the time. In minor details the arrangements used were naturally open to improvements and to some criticism, but both methods and results are still worthy of consideration.

The use of a galvanometer as a component part of the apparatus could not be

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considered for our work, which had to be carried out in the English Channel on the steam drifter-trawler *Salpa*, belonging to the Marine Biological Association and working from Plymouth.

Accordingly, a potentiometer method, using a telephone as a null point indicator, was developed by one of us (Poole, 1925).

The Current-measuring Apparatus and Measurements.

The current is measured by noting the drop in potential across 100,000 ohms, or some convenient sub-multiple, using a potentiometer, with a telephone as a null-point indicator. An interrupter, made from a "Meccano" motor with slowing vanes, is included in the telephone circuit—in its final form—for the interrupter used initially proved unsatisfactory. The circuit is shunted by a condenser, and the sensitivity is increased by the use of a two-valve amplifier. For a detailed description reference should be made to the original papers (Poole, 1925, Poole and Atkins, 1928, 1931), but the general outlay of the apparatus may be seen by reference to fig. 1, which is reprinted by permission of the Marine Biological Association.

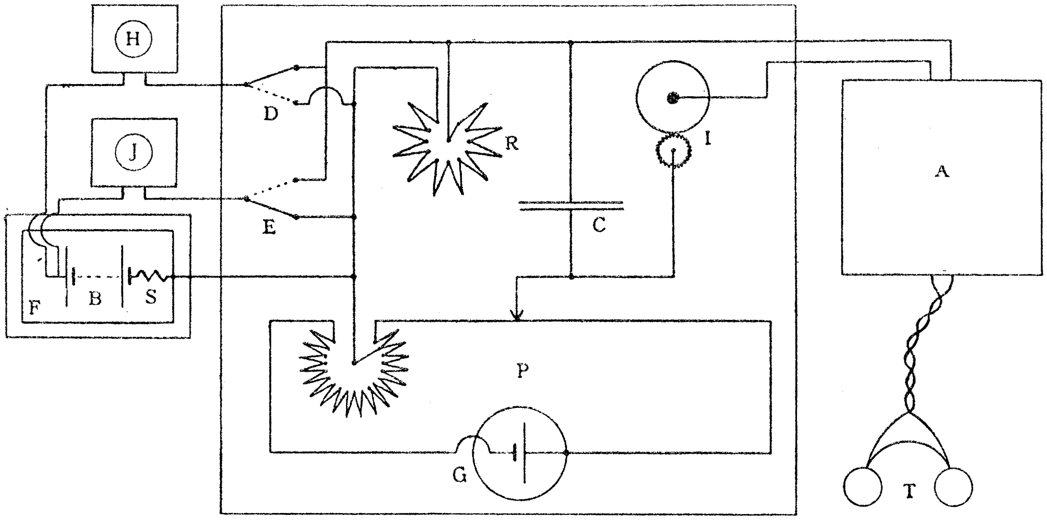

Fig. 1.—Circuit of potentiometer-telephone apparatus for measuring photo-electric currents. A, two-valve amplifier. B, anode battery. C, mica-insulated condenser, capacity 1 μF. D and E, two-way switches. F, insulated metal box. G, potentiometer battery on insulated guard plate. H and J, photo-electric photometers. I, interrupter, toothed wheel rotated by clockwork against smooth wheel. P, potentiometer. R, 100,000 ohm resistance. S, safety resistance. T, telephones.

In reproducing the apparatus for oceanic work, Gall and Atkins (1931) introduced a metal sheathing inside the box to aid in minimizing leakage currents ("dark currents"), and in cutting out capacity effects which interfered with the attainment of a sharp minimum under certain conditions. The whole of the outside of the main apparatus case in use at Plymouth and of the amplifier box was accordingly sheathed with thin copper foil. The position of the operator's body then ceased to be of importance as an "earth." Furthermore, the insulated metal box containing the H.T. batteries and connected to the negative pole, as shown in fig. 1, was earthed to a nut on the iron tube carrying the steering chain. Finally, when any "dark current" did appear, in damp weather, a portable electric heater was suspended in the main instrument case below the switches D and E, and adjacent to the high resistance and potentiometer terminals. Since there was no current supply on the ship the heater consisted of a 6-volt, 18-watt vacuum lamp carried in a socket fixed in a cocoa tin, with lid, to prevent accidental breakage. It was supplied from a Tungstone 6-volt, 40 ampere-hour accumulator. These precautions rendered it possible to work even in very damp weather.

With this apparatus and with the high-tension batteries applied throughout to the photo-electric cells, it is possible to carry out the measurements, in the air and under water alternately, with great rapidity, a rate of six to eight readings per minute being attained when the illumination was not varying too rapidly. Under steady conditions it sufficed to take four, or possibly three, readings under water and one less in air. With variable light, however, from twelve to twenty readings might be made under water and the mean taken, or perhaps the mean of a shorter and tolerably uniform run of readings, if such could be found within the longer series. The position of balance was always determined with the eyes shut. With the apparatus working at its best, it was possible to read to $0 \cdot 5$ scale division or 5×10^{-10} ampere, and it was usually sensitive to 10^{-9} ampere. For this the potentiometer plug is set in the $\times 0 \cdot 1$ position, viz., to read to $0 \cdot 1$ mv. and $R = 100{,}000$ ohms. With variable light, however, it was found advisable to follow the fluctuations using only the potentiometer dial, which meant either inserting the $\times 1$ plug or taking $R = 10{,}000$, giving, in either case, 10^{-8} ampere per scale division. With brighter light both reductions were employed, so that the readings were 10^{-7} ampere per scale division. It was, of course, frequently necessary to use one setting for the air and another for the under-water measurements. These points have been stressed as only by suitable manipulation of the scale used can high working speeds be obtained, and these are essential for determinations near the surface, or just above it, both in rough weather and in bright sunlight.

Owing to the difficulty of making measurements at depths less than 5 metres in bright sunlight, our original practice was to compare the photometers on the deck-house roof, and to assume that the sub-surface value was 85 per cent. of the simultaneous roof illumination. The submarine photometer was lowered from a spar lashed so as to extend the main boom outwards, but even so it was not possible to handle the heavy photometer case if suspended much more than one metre beyond the projecting ledge of the stern. The shading due to the ship was at first rather under-estimated and became relatively more important in dull weather, for in bright weather the stern was always directed towards the sun.

To ascertain the magnitude of such shading and immersion losses, we made use (1931) of J. H. J. POOLE's (1928) neon lamp device, as assembled by H. H. and J. H. J. POOLE (1930) for work in Lough Bray, as well as the potentiometer outfit; but in view of certain reflection losses, which were at that time left out of consideration, the values obtained require modification. The necessary corrections are considered further on. It was obviously desirable to measure, in each series, not only the illumination on the roof (r), but also that just above the water (a) and just below the surface (b), for which the neon lamp device, being an integration method, is specially suitable. The making of several depth series, to compare the penetration of light of different colours, is in itself a heavy piece of work in one day, and it was quite impossible to include a separate set of shading and sub-surface measurements with the neon lamp. Furthermore, the manner in which we have the neon lamp assembled at present does not, for various reasons, do the method full justice, and its sole use could not be considered on account of leakage losses and inadequate sensitivity. The assembly of Gall and Atkins (1931) was identical in principle, but insulation was much improved.

For the reasons just given determinations were made in positions a, b, and usually also at 1 metre, by the ordinary potentiometer method; reliance was placed on a high speed of operation, suitable manipulation of the scale, and a large number of observations, to obtain values of a reasonable degree of accuracy in spite of the rapid fluctuations in illumination experienced at times (though by no means always) in these positions; the variability at a was, of course, due to the swinging of the photometer. Furthermore, it must be added that the use of a very efficient opal glass diffusing filter with the photo-electric cells rendered such measurements far easier than in our earlier work with less efficient diffusing surfaces, several of which were tried. It is, nevertheless, realized that these measurements are probably not as accurate as those obtainable with the neon lamp at its best.

The Photo-electric Photometers.

For measurements on the roof of the deck-house our old photometer H, containing a G.E.C. unsensitized vacuum potassium cell mounted under surface-flashed opalized glass (opal), was used. This had been standardized as previously described (1928) against an open carbon arc, and had been found to give 10^{-9} ampere for a vertical illumination of 40 metre candles. For light from a uniformly illuminated hemisphere, the increased reflection loss for oblique rays decreased the sensitivity, so that a vertical component of 42·4 m.c. produced 10^{-9} amp. The latter figure was taken in calculating illumination at sea, since the diffuse light reflection loss factor gives a nearer approximation to the correct value than does that for vertical illumination.* By means of a test lamp, previously described, it was established that the sensitivity of the cell had remained constant, or had at the most decreased by only a small percentage.

Photometer H was used in conjunction with the submarine photometer J, previously described and figured, which contained a potassium hydride argon-filled cell made by

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* If necessary, a more accurate value of this factor may be calculated, as previously explained (1926), from the known proportions of direct sunlight (of known altitude) and diffuse skylight, but the correction is generally negligible compared with other sources of uncertainty.

the General Electric Co. This was maintained in its most sensitive condition by the glow-discharge method. For measurements in air or at moderate depths it was operated at 6 or 12 volts anode potential, values below that at which an increase in sensitivity occurs owing to ionization by collision. It was standardized against photometer H before each series. For greater depths it was operated at 60 volts, and the alteration in sensitivity was determined from its ratio to H, when submerged. This is preferable to determining the ratio J_{12}/J_{60} directly, since this necessitates alteration of the H.T. plugs and soakage effects occur in the cables; these last for several minutes, during which, of course, the illumination has probably altered. J_{12}/J_{60} is thus obtained from J_{12}/H_{60} and J_{60}/H_{60} at the same depth.

These two cells are sensitive only to the blue end of the spectrum, H showing a maximum close to 400 mμ, and J probably near 440 mμ as shown for a similar cell, K in fig. 2 of our 1928 paper. These wave-length sensitivity curves were determined as there described, using a Moll vacuum thermopile and a sensitive Kipp und Zonen type Zc galvanometer.

To cover the whole of the spectrum the General Electric Company's new thin-film cæsium vacuum cells, type C.M.V. 6, were used. The wave-length sensitivity curve for the one used on the roof was found by us (1931) to show a well-marked maximum at about 720 mμ and a minimum at about 500 mμ, beyond which it again rises. The curve is shown in fig. 3 where cited, the values having reference to the cell as mounted under opal glass. The same figure shows how this curve is altered by the interposition of a 4·2 mm. thickness of Corning "heat-absorbing glass, G. 392H, medium shade." It may be seen that between 440 and 640 mμ the response for equal amounts of energy is very approximately the same. The curve rises somewhat at about 420 and falls regularly to a very low value near 760 mμ.

The cell used in the submarine photometer case was not examined by us, but it is probable that its response did not differ markedly from its fellow, though small variations are to be expected.

It had been our custom to operate all our vacuum cells at 60 volts anode potential, since this is sufficiently close to their saturation voltage to give a voltage sensitivity coefficient of 0·3–0·5 per cent. per volt. It was, therefore, rather a surprise to find that these C.M.V. 6 cells were nearly saturated at 6 or 8 volts. They might certainly be used with safety at 10 volts. The advantage lies in being able to use a smaller, and far lighter, high-tension battery, where portability is important, and in the fact that "dark" currents become of much less importance with such a low voltage. In this work they were, however, operated at 60 volts, like photometer H, to avoid altering the plug, since the use of the heater prevented any dark current.

The results for ultra-violet radiation, Series 76 and 81, were obtained by the use of a Burt sodium vacuum cell of thin soda glass and a G.E.C. potassium vacuum cell respectively. The cells were embedded in vaseline, as recommended by SHELFORD and GAIL, and covered with special filters, below which sea water was admitted. No opal was used, since this glass cuts down ultra-violet heavily. The losses on immersion are vitiated by an error, present also in the first work of SHELFORD and GAIL, owing to the curvature of the surface of the cell in contact with the water. The Burt cell developed a leak when lowered beyond 5 m., and was thereby destroyed. The motion of the waves gave rise to an electrical leak between the vaselined terminals of the potassium cell. This method of mounting, adopted to save the cost of a photometer with quartz window, enabled us to obtain measurements to 6 m., but is unsuitable for work in the open sea.

The Characteristics of the Light Filters.

We have already (1931) described the method whereby the transmissions of the filters at various wave-lengths were obtained and the behaviour of several is shown in fig. 1, where cited. Those used at sea are as follows.

The heat-absorbing glass, G. 392H, has already been mentioned. It is of a greenish colour, 4·2 mm. in thickness, and reduces the response of C.M.V. 6 to 17 per cent. under conditions of sunshine, blue sky and some clouds. The uniformity of the response of C.M.V. 6 under this filter has been described, but it was thought that thinner specimens and the light shade might give a larger response in the red and in the visible spectrum generally, and yet eliminate the infra-red. Such attempts were, however, unsuccessful, since too much infra-red came through. It is desirable to eliminate the infra-red from our measurements, since it is not directly used in photosynthesis, though it may affect the process by raising the temperature. Further, it must be cut off from the deck photometer, since its parasitic presence in the blue filter would cause a serious error in such an infra-red sensitive cell as C.M.V. 6 ; in any case, the water quickly cuts it off.

Corning " dark blue, G. 54," marked " H lantern blue " (H denoting a heat-resisting glass for projection purposes), is said to be useful when a pure blue is needed (GAGE, 1924). Though eliminating green well, its red transmission begins at 600 mμ, and rises to 14·5 per cent. in the near infra-red. G. 392H should, therefore, preferably be used along with it. Its red transmission may be appreciated by viewing a gas-filled tungsten lamp through it and a red glass combined. Schott and Gen B.G. 12 is to be preferred, as it is opaque to red and is said to be so to infra-red. Its transmission curve approximates to the wave-length sensitivity curve of a sodium photo-electric cell, whereas Corning G. 54 is nearer to that of a potassium cell. The Corning glass, having been used in previous work in woodlands, was retained for this year's sea work ; the thickness was 2·96 mm.

Corning " sextant green," 3·81 mm., was found to be a pure green without infra-red transmission. It may, therefore, be used without G. 392H, though it was also used with it.

Corning " H.R. yellow, green shade," 2·96 mm., gives a high transmission with a fairly sharp cut off. It transmits freely in the infra-red, so should be used with G. 392H.

Corning "selenium red," G. 24, 3·23 mm., has a very sharp cut off at about 610 mμ, but transmits infra-red freely. Schott and Gen R.G. 5, 1·97 mm., is a dark red, and cuts off sharply at 650 mμ. It transmits infra-red freely.

Corning red-purple Corex A, ultra-violet transmitting glass, unpolished, was used in 10·2 mm. thickness to give ultra-violet around 340 mμ as a flat maximum. We are indebted to Messrs. Chance Bros. for a transmission curve for this glass, which agrees well with that recorded by the Corning Works, U.S.A. This glass transmits also in the red and infra-red, so cannot be used for ultra-violet with C.M.V. 6. It was used with the sodium cell. This combination, since the cell has a maximum sensitivity at 360 mμ, coinciding approximately with the maximum transmission of the filter, gave large readings; its use to very considerable depths was only hindered by the leak.

With the potassium vacuum cell, Chance's ultra-violet transmitting glass, 3·2 mm., was used. This has maximum transmission at 355 mμ, and we found the cell (L) to have maximum sensitivity at 410 mμ (fig. 2, 1928). The combination is less sensitive accordingly, the more so because the potassium cell was smaller than the sodium cell; its measurements relate to light of rather longer wave-length than the sodium cell combination.

Comparison of Photometer Readings in Air and in Water.

The submarine photometer is standardized by direct comparison with the "deck" photometer on the deck-house roof, where the shading by the mast and rigging is small; illumination in this roof position is shown opposite "*r*" in tables. Unfortunately, as already mentioned, the shadow of the ship may cause an appreciable reduction in the under-water light. Some allowance might be made for this by taking the light just above the water (position "*a*" in tables) as 100 per cent., this position being also somewhat shaded. Unless the sea is very smooth, however, the photometer in this position is inclined to swing violently, and measurements are difficult and not too satisfactory. Moreover, the shading is not the same as it is lower down, so there is little advantage in this attempt at compensation, except in smooth water, when an attempt can be made to measure the surface loss of light.

A determination of the illumination a few centimetres below the surface (position "*b*" in tables) would be of interest, but is seldom possible owing to the motion of the ship. It is also affected by shading. Thus, the measurements of the percentage of light transmitted by the surface, and of the opacity of the upper metre, or so, of water are not easy. Interpretation of the results is also complicated by the reflection effects discussed below.

Before using the reading of a submerged photometer as a measure of the light under water, it is necessary to consider carefully the effects of reflection at the various surfaces. We always work with water in the spaces between the opal, any colour filters that may be used, and the window of the submarine photometer, when the latter is in air. Accordingly, these surfaces may be disregarded, except for a secondary effect discussed below. We have also generally tried to maintain a layer of water over the opal also, when the submarine photometer was being standardized on deck. This may not be possible, however, in rough weather. From the fact that wet patches on the opal are almost indistinguishable visibly from adjacent dry areas, showing that the light scattered back is almost identical, we would not expect the presence or absence of a very shallow layer of water to have much effect on the reading. That this is true was shown by some tests carried out on shore with steady daylight and sunlight, altitude 32–33°, which gave an increase of 0·7 per cent. (mean of 14 measurements) when four millimetres of water were present. As this is negligible for our purpose, the presence of the water is immaterial.

Two important factors must, however, be considered which we may designate the "external reflection factor" and the "internal reflection factor," respectively. We have always allowed for the first, as explained below. We are deeply grateful to Mr. T. Smith, F.R.S., for calling our attention to the second, which had hitherto escaped our notice.

The "external reflection factor" allows for the effect on the readings of the change in the reflection losses for the direct light caused by the submergence of the photometer. About 9·5 per cent. of the diffuse daylight falling on a horizontal glass surface (refractive index 1·51) is reflected, 90·5 per cent. being transmitted. For a water surface the transmission is 93·5 per cent., of which 99·5 per cent. would penetrate a submerged horizontal glass surface. Thus we have always multiplied the submerged readings of a photometer which is standardized wet by 0·935 to allow for the reflection loss at the water surface which occurs during the standardization, but is absent under water (since we wish to deduce the light *in the water* from the photometer reading). Experiment has shown, however, that the "wet" air reading is very little greater than the "dry," for which the factor should evidently be 0·905/0·995, *i.e.*, 0·91. This is due to the effect of even a few millimetres of water on the scattered light, as explained below. Evidently we may take 0·915 as the "external reflection factor" for diffuse daylight without serious error, whether the photometer be wet or dry.

The "internal reflection factor" is necessary in order to allow for the effect of the water in reducing the downward reflection of light which has been scattered upwards by the opal. As the scattering occurs beneath the surface of the glass, much of the scattered light strikes this surface so obliquely as to undergo total reflection, thus again reaching the diffusing layer and contributing to the reading. A thin film of water produces little effect, as the effective critical angle remains the same, though most of the reflection now occurs at the water surface. For deeper layers some of the totally reflected light misses the opal, all of it being lost for any depth exceeding 0·9 of the radius of the opal. The effect of partially reflected light at smaller angles is much less important, but this also decreases rapidly with depth, falling to about 0·1 per cent. at a depth equal to the diameter. For greater depths only the very oblique light totally reflected at the glass-water surface again strikes the diffusing layer.

A similar effect occurs at the lower surface of the opal. If there is a film of water between the opal and the window most of the reflection occurs at the inner surface of the window, and, as the latter is some 9 mm. thick, much of the light is lost round the rim. Experiments both with daylight and with a vertical beam of electric light show that the reduction in the illumination of the diffusing layer owing to this loss is more important than the increase in the transmission for rays of moderate obliquity between the opal and the cell, so that the net effect of the water film below the opal is to reduce the reading by a few per cent., the exact value depending on the geometrical arrangements. With our submarine photometer in daylight the loss was 2·1 per cent.

It is worth noting in this connection that bubbles of air in the water film of a submerged photometer form conspicuous bright patches, quite unlike drops of water on the upper surface of an opal in air.

We cannot calculate the magnitude of these effects without making assumptions, which may differ appreciably from the truth, as to the angular distribution of the scattered light within the opal. The effect of layers of distilled water of various depths was, therefore, directly measured in a dark room for light from a gas-filled lamp, run at constant voltage, mounted about 2·5 metres above the opal. Diaphragms and screens were used to cut off almost all diffuse light and to limit the direct beam to an area only slightly greater than the 3 cm. hole in the bottom of the water vessel, which was closed by the opal plate. This was placed in contact with the under side of the bottom, the joint being made watertight with plasticine. Thus no direct light fell on the walls of the vessel, and very little on any part of the bottom except the opal. The interior of the vessel was carefully blackened with waterproof dead black enamel, or, in one test, lined with black paper. A Siemens cuprous oxide photronic cell was mounted just below the opal, the current being measured with a sensitive galvanometer. This cell is sensitive chiefly to blue and green, and not to infra-red. For the very small illuminations used the current is very nearly proportional to the light.

The results showed that a film of water 0·5 mm. deep produced no appreciable effect, but with deeper layers the current decreased, rapidly at first, and more slowly as the depth approached the diameter of the opal, 3 cm., from which depth up to 24 cm. the rate of fall was constant, and was evidently due to absorption. The absorption coefficient of the distilled water was surprisingly high—0·6 to 0·8 per metre in different experiments. This may possibly be due to the absorption by the water of a trace of soluble colouring matter from the black paper or from the enamel, though no darkening was visible to the eye even in a test-tube in which a sample of the paper was soaked for a week. The absorption was not reduced by filtering.

The effect of even this rather rapid absorption is, however, small in the first 3 cm., and when it has been allowed for we obtain the total reflection-effect of the water surface. Three tests with slightly different arrangements gave 0·808, 0·795 and 0·805 as values for the ratio submerged reading/dry reading. The first two results were obtained with the opalized surface upwards, and the last with the clear surface upwards, showing that the difference, if any, is inappreciable; they all refer to tests with the lower surface of the opal dry. When a sheet of glass 4·5 mm. thick was placed below the opal, and the intervening film filled with water, the reduced reflection from the lower surface, by decreasing the total light scattered upwards by the opal, reduced also the relative effect of overlying water. A test under these conditions gave 0·850, and a previous test in which the elimination of the effects of extraneous reflection was less complete gave 0·846 for the ratio submerged reading/dry reading. The ratio of the thickness of the sheet of glass used in above to the effective diameter of the opal differs but little from the corresponding ratio for the submarine photometer, so we may take the value 0·85 as being correct for the latter. The use of colour filters below the opal should cause a further reduction in the effect of overlying water, but we may probably neglect this.

In the above tests with vertical light the "external reflection factor" was 0·96/0·995, *i.e.*, 0·965, since the losses at the air-glass and water-glass surfaces were 4 per cent. and 0·5 per cent. respectively. The loss at the air-water surface was 2 per cent. Hence the "internal reflection factor" by which the reading should be multiplied to correct for the internal reflection effect is 0·98/(0·965 × 0·85), *i.e.*, 1·195. This factor, unlike the "external reflection factor," is the same for vertical as for diffuse light. If, therefore, we combine it with the value of the latter for diffuse light, 0·915, we obtain the factor 1·09, by which the readings of a submerged photometer should be multiplied to correct for both reflection effects. As we have hitherto neglected the "internal reflection factor," and used the factor 0·935, all the results obtained with diffusing or opal glasses (Series 1 to 6 (1926), 23 to 46 (1929), and 47 to 54 with N1–N4 (1931)) should be multiplied by 1·17. For Series 7 to 22 (1928), in which only a ground-glass window was used, the correction would be considerably smaller. This correction is evidently of great importance in connection with estimates of the light loss at the surface or of the absorption coefficients of shallow layers obtained from one submarine measurement and an assumed surface loss, but does not affect the values obtained for the absorption coefficients of deeper layers.

If a sheet of clear glass is mounted above the opal with an intervening air film, total reflection of scattered light is not affected by overlying water, which now only reduces the partial reflection of light scattered upwards at moderate angles. Thus the "internal reflection factor" is now only slightly greater than unity. A laboratory test gave 1·03. Such an arrangement is, however, not entirely suitable for marine work, as it is quite insensitive to any light in the water making an angle with the normal greater than 48·5°, the light being totally reflected at the lower surface of the upper glass. This also applies to any photometer with a clear window, and, to some extent, to one with a window ground on its lower surface, as used in Series 7 to 22, since the diffusing properties of the ground-glass surface are rather low.

Such a photometer is quite unsuited for measuring the effect of the sea surface on the light, as it ignores all light scattered downwards, by waves, at angles beyond 48·5° with the vertical, and all light totally reflected by the surface, which may be appreciable in shallow water over a light-coloured bottom. That the wave effect is important is shown by the fact that the presence of an opal with its under surface wet renders the readings obtained just below a disturbed water surface very much steadier.

Measurement of the Opacity of the Water.

The opacity of the water is indicated by the quantity which we have called the "vertical absorption coefficient" (termed the "vertical transmissive exponent" by some workers*), and denoted in the tables by the symbol μ_v. This is defined as being equal to $2 \cdot 3\ (\log_{10} p_1 - \log_{10} p_2)/\delta$, where p_1 and p_2 are the percentage illuminations at two points differing in depth by δ metres. Before we can take its values at different depths as true measures of the opacities of the various layers we must consider the following possible sources of error.

(1) The shading caused by the ship, which has already been mentioned, must vary in a somewhat complex way with the depth, probably increasing slightly for the first metre or two, and subsequently decreasing. Even within 10 m. of the surface it would seem to be an extreme assumption to take the error in the ratio p_1/p_2 due to differential shading at depths 5 m. apart as 10 per cent. This would cause a logarithmic difference 0·0414, as compared with a difference 0·380 for the interval 5 to 10 m. in Table II. It would appear, therefore, that the error is unlikely to be much in excess of 10 per cent. at any depth. The value should be raised for the first couple of metres and reduced for greater depths, the reduction, after passing through a maximum (probably about 5 to 10 m.), decreasing with depth.

(2) It is generally impossible to ensure that the whole of a series is made in the same water, whether the ship be anchored or drifting. Any change in the opacity of the entire water column above the photometer between two readings will be attributed to absorption in the layer between the two depths. The resulting error is difficult to estimate, but is probably small or quite negligible for stations 10 or more miles off the shore, though it may not be so at 2–3 miles in shallower water. It evidently increases with the depth.

(3) With unscreened cells, sensitive to a considerable spectral range, the variation of μ_v with wave-length will cause a decrease with depth, the more absorbable wave-lengths being filtered out. This effect is of great importance close to the surface, if a cell sensitive to infra-red is used without a filter. It is probably not very important with potassium cells whose comparatively short range of sensitivity is close to the region of minimum absorption.

(4) As the average length of path of the light in the water exceeds the vertical depth, μ_v evidently always exceeds the true absorption coefficient. This would not affect its

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* For a discussion of the various expressions termed the absorption coefficient, see GIBSON (1925), who introduced the term transmissive exponent.

use as a measure of the relative opacities if the average obliquity is the same at different times and at different depths. There is ample evidence, some of which is described later, that, for a given date and station, the percentage illumination at any depth is very little affected by changes in the angular distribution of the surface light, or by the presence or absence of direct sunlight. Moreover, comparisons of Series 15 and 16 (1928) and of 24 and 25 (1929) agree in giving approximately constant values for the ratio of the horizontal to the vertical illumination at different depths, though, as in the earlier series, the photometer being without an opal was almost insensitive to light making an angle exceeding 48·5° with the normal, the values of the ratio differ widely in the two pairs of series. It would seem, therefore, that, except within a few metres of the surface where the obliquity must obviously depend to some extent on that of the light in air and on the condition of the water surface, the average obliquity must depend chiefly on a balance between the effects of absorption and scattering, the latter tending to increase it, and the former to decrease it by the more rapid removal of the more oblique rays. As absorption and scattering increase together, we would expect variations in obliquity to be small compared with the changes in opacity to which they are due.

(5) Even if we assume the obliquity to be constant, however, another related effect must be considered. Since suspended matter scatters back some of the incident light, some of the downward illumination at any point is caused by the downward scattering or internal surface reflection of upward illumination which was itself due to upward scattering or to reflection from the bottom. It can be shown that in uniform deep water, where bottom reflection is negligible, the ratio, u, of the upward to the downward illumination should be independent of the depth, and that the effect is to increase the apparent absorption in the ratio $(1 + u)/(1 - u)$. Series 16 and 17 (1928) gave 1·3 per cent. as the average value of u. A recent test at Station E1 gave 1·8 per cent. In both cases the results were independent of the depth within the limits of error, which are rather wide, since the results involve the comparison of two series with a considerable time interval. In deep water, then, this correction only amounts to about 3 per cent., and, being independent of the depth, need only be considered if an attempt is to be made to correct also for obliquity, and so to deduce the value of the true absorption coefficient.

(6) Near a light bottom, however, u is no longer constant, being increased by reflection from the bottom. This will also increase the downward illumination. Thus the value of μ_v, which is slightly increased in the upper layers by back scattering, is reduced near the bottom. Just below the water surface, also, the illumination is increased by the internal reflection of light scattered back by the opal and the surrounding photometer case. As we have seen, however, this effect becomes negligible at a depth equal to the diameter of the case, and so may be disregarded. It is worth noting that in shallow water over a very light bottom more light may be gained by internal reflection of oblique light scattered upwards from the bottom than is lost by surface reflection, so that the illumination just below the surface may exceed that in the air

above—an effect similar to the increase in the illumination of the diffusing layer in an opal glass by internal reflection. Laboratory tests with water in an inverted white enamelled conical lamp shade, the central aperture being covered by the photometer opal, showed that reflected light from the shade, which formed a sloping bottom to this model pool, increased the illumination by about 25 per cent. As this was with vertical light, the loss of direct light at the surface was only about 2 per cent. With daylight this loss would be some 6·5 per cent., which might easily be exceeded by the gain owing to a light bottom. Such conditions, however, have not occurred in our work.

Summarizing the various corrections considered above, we see that for off-shore measurements below 10 m. with photometers sensitive to only a limited spectral range we are unlikely to make an error greater than a few per cent. in using μ_v as a measure of the opacity. Within a few metres of the surface the possible effects of varying obliquity, of the ship's shadow, and of the variation in μ_v with wave-length, may cause larger errors, as may want of horizontal uniformity of in-shore waters for greater depths. Close to a light bottom a small error might be caused by reflection. It seems very unlikely, however, that any appreciable fraction of the large variations which occur in μ_v could be attributed to the above causes, and hence it appears to be reasonable to take μ_v as a measure of the opacity of the water.

Submarine Measurements, 1931.

The object of the measurements was two-fold. Firstly, it was desired to extend the previous photo-electric measurements with blue-sensitive cells to include the remainder of the spectrum. The red end is of special importance in view of its influence upon photosynthesis, and the ultra-violet is concerned in the activation of the precursor of vitamin D. Now cod-liver oil is one of the main sources of both vitamin A and vitamin D, though other fish liver oils may be equally rich. The cod is usually found at a considerable depth, and in any case presents but a small surface. It seemed probable that the source of the vitamins was to be found in the plankton, vitamin A being of vegetable origin. Miss Leigh-Clare (1927), however, showed that diatoms, grown in pure culture, contained no vitamin D. The zooplankton had, therefore, to be considered, chief among which, as a source of food for fishes, stand the copepods. These, being small, present a large area for the absorption of radiation.

Secondly, F. S. Russell (1925–32), engaged in studying the depth distribution of the zooplankton, had found the copepods to be mainly at a moderate depth, regulated by light intensity. The *absolute* value of the illumination was, accordingly, of importance in this connection, as well as the percentage transmission of ultra-violet. Measurements were therefore made at the station east of the Eddystone in which Russell's plankton hauls had previously been taken. Further plankton hauls were made by Russell either just before, or just after, the submarine determinations of the illumination, from which the percentage transmissions were calculated. During the hauls, which usually

TABLE I.—Vertical Illuminations, V, in thousands of metre candles, at the depths, in metres, at which the six nets were fishing. The depth of the water was 50 m., near Eddystone, summer of 1931.

Date.	July 21.		July 21.		July 22.		July 29.		August 5.		August 12.		August 12.	
G.M.T.	2.24–2.54.		5.54–6.24.		11.11–11.41.		11.39–12.9.		11.19–11.39.		10.55–11.25.		3.7–3.32.	
Reference Series.	55		55*		60		61		67		75		75*	
Net.	*d.*	V.	*d.*	V.	*d.*	V.	*d.*	V.	*d.*	V.	*d.*	V.	*d.*	V.
In air	*r*	88·6	*r*	27·1	*r*	91·5	*r*	50·0	*r*	26·9	*r*	35·4	*r*	45·8
1	0·5	80·8	0·5	24·7	0·5	72·8	0·5	45·4	0·5	22·0	0·5	24·4	0·5	31·6
2	7·2	34·4	7·9	9·36	8·1	19·7	7·1	16·4	7·2	7·05	7·5	11·5	7·0	15·7
3	14·3	13·2	15·7	3·32	16·1	6·63	14·4	6·55	14·3	2·42	14·9	4·34	13·8	6·65
4	21·4	5·18	23·5	1·24	24·1	2·78	21·7	2·22	21·4	0·88	22·3	2·07	20·6	3·11
5	28·5	2·39	31·3	0·54	32·1	1·39	29·0	1·29	28·5	0·47	29·7	1·08	27·4	1·66
6	35·6	1·03	39·1	0·16	40·1	0·43	36·3	0·53	—†	—	37·1	0·58	34·2	0·91

* Had drifted a little further in.

† One net lost.

lasted 30 minutes, the deck-house photometer was used to measure the air illumination, a mean value being taken. From this the submarine illumination was calculated for the six depths at which the six nets were fishing. The fishing depth was maintained as uniform as possible by keeping the angle of the warp nearly constant against a weighted protractor; the depths were obtained from the tracing on the Admiralty recorder, attached to the warp, as described by RUSSELL. Since the nets were fishing in the open and quite clear of the shadow of the ship, the illuminations shown in Table I were obtained by plotting the percentages at various depths, taking the readings in the "*a*" position as 100 and finding the appropriate values for the depths of the nets; such percentage values were then multiplied by the quite unshaded "*r*" readings. In Table I the metre candle has been used to express submarine illumination, since absolute, not comparative values are required. Owing, however, to the alteration in the quality of the light, this is no longer strictly accurate; but as green light, to which the eye is most sensitive, penetrates well, the error is probably not very great, but its presence should be borne in mind—also the fact that while the colour sensitivity of the fish-eye is not very different from our own, yet the sensitivity of the eyes or bodies of invertebrates is not so well known.

The series referred to in Table I are plotted with other results in fig. 2, and provide a measure of the blue transmission of the water for comparison with previous results for blue, and with results obtained on the same days for other colours, as plotted in figs. 2, 3 and 4.

Table II illustrates the method of work, d representing the depth in metres, V the vertical illumination in air in metre candles, and p the percentage reading of the immersed photometer as compared with that for the same photometer on deck, allowance

TABLE II.—Series 68, on 6/8/31. Photometers with C.M.V. 6 cells and Corning heat-absorbing filter under opal, on each. In Whitsand Bay, 1½ miles West of Rame Head, depth 32 m. Very calm, water glassy, with ripples. Sun hot in blue hazy sky. $\beta = 4\cdot5$ to 5 about 11.20—11.50.

G.M.T.	d	V_a	V	p	μ_v
	m.	k.m.c.	k.m.c.	Per cent.	
10.39	*r*	85·8	85·8	100	—
10.46	*a*	88·6	82·8	93·4	—
10.54	*b*	89·0	57·0	64·1	—
11.6	1	91·5	29·1	31·7	—
11.9	5	91·6	14·2	15·4	0·181
11.14	10	92·2	5·92	6·42	0·175
11.17	15	92·9	2·37	2·55	0·185
11.20	20	92·7	1·11	1·19	0·151
11.23	25	93·4	0·51	0·55	0·152
11.26	30	93·9	0·26	0·28	0·140
11.31	20	94·3	1·17	1·24	0·150

being made for any variations in the daylight that may have occurred in the meanwhile (as measured by the " deck " photometer), and for the reflection effects already discussed.

V_a, being defined and measured by a potassium cell (or by a cell standardized in daylight against a potassium cell), is chiefly a measure of the blue and the blue-green light present, as compared with that obtained from the crater of a carbon arc. V in Table I measures the submarine illumination on the same scale, a potassium cell having been used. In Table II, however, the submarine light is measured by a cell sensitive also to green, yellow and red. It is obvious that the two are not strictly comparable, but the values have none the less been given for V in water as they illustrate the effect of the absorption upon what is approximately white light ; this is so because we have shown (1931) that the heat-absorbing filter gives, with the wave-length sensitivity curve of the photo-electric cell used, a line which is approximately parallel to the wave-length axis between 440 and 640 mμ.

The " vertical absorption coefficient," μ_v, has already been defined. In our earlier papers it was calculated for 10 m. intervals, the value for the range 5 to 15 m. being printed opposite the depth 10 m., and so on. In our 1931 paper and here, however, the value printed opposite to a given depth is that for the interval between it and the reading next above, the use of shorter ranges being rendered desirable by the large absorptions for certain colours.

In measuring p there is a choice of three possible values to be taken as 100 per cent. Firstly, as in all our previous work, the illumination on the deck-house roof may be taken, this being a near approximation to the true air illumination, since the shading by funnel, mast, and rigging is but small. Moreover, this value can be measured with a considerable degree of accuracy ; it is accordingly used for calculating the percentages tabulated under p, save in Table I, as previously explained.

Ideally the illumination in position a, just above the water, should equal that at r. Actually there may be a considerable difference, so that percentages p and p' (taking illumination at $a = 100$) differ appreciably. It is obvious that the surface loss is measured by the value of p' just below the surface rather than by that of p, but at greater depths the difference becomes less important, especially as, for example, at 40 metres the influence of the shading of the ship is much reduced. Furthermore, measurements cannot be made with as much accuracy at position a, in which the photometer is swinging above the water, as they can at r, where the deck photometer is mounted on gimbals and compared with the submarine photometer, unmounted, side by side. Both p and p' were given in our 1931 paper.

Finally, it is of interest to calculate how much of the light that actually enters the water penetrates to any given depth. For this it is necessary to determine the illumination at b, which is never an easy measurement owing to the motion of the water and the ship. Its determination, however, gives the surface loss, and under p'' one might tabulate percentages with illumination at $b = 100$. Usually a one-metre value has been included as a check upon b.

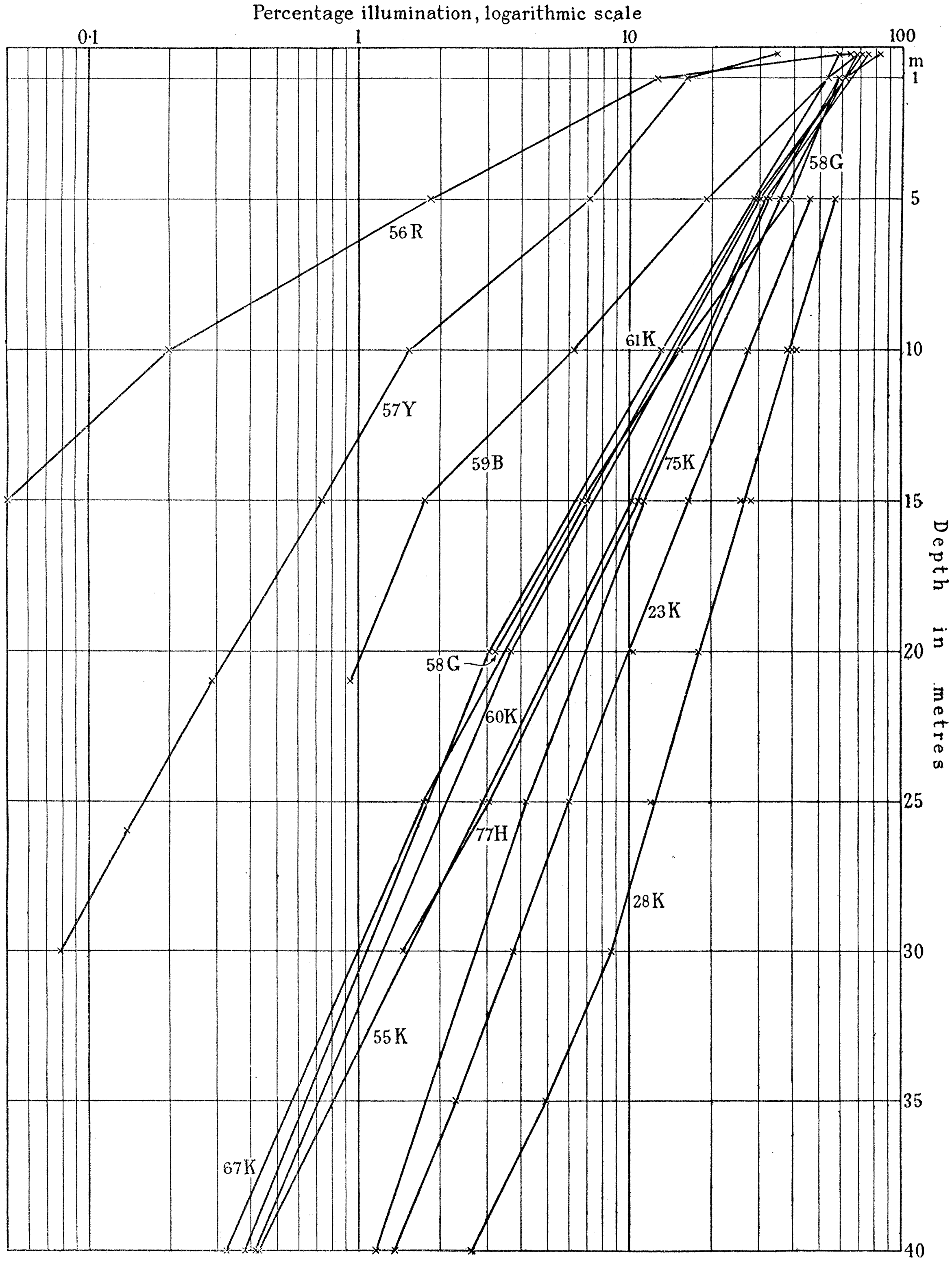

FIG. 2.—Percentage illumination (plotted on a logarithmic scale) at various depths. Series 23, 28, 55, 60, 61, 67, 75, marked K, were obtained with gas-filled potassium cells under diffusing filters. Nos. 23 and 28 were at Station E1, depth 73 m., 20 miles from land on 1.3.28 and 19.4.28, respectively. All the others in this figure were got about 1–2 miles E. of the Eddystone, depth about 50 m., and about 10 miles from land.

Series 55, 60, 61, 67, 75 relate to July 21, 22, 29, August 5 and 12, 1931, respectively. Series 56, 57, 58 and 59 followed 55 immediately, using a type C.M.V. 6 cell with red, yellow, green, and blue filters, under opal, respectively, and marked R, Y, G, and B. A heat-absorbing screen, H, under opal, was used with this cell for Series 77, which followed Series 75 after $2\frac{1}{4}$ hours, during which the ship drifted about 2 miles towards shore.

Secchi disc visible 14 m. on 1.3.28 and 18 m. on 19.4.28; 8 m. on 29.7.31, 10 m. on 5.8.31, 15 m. on 12.8.31.

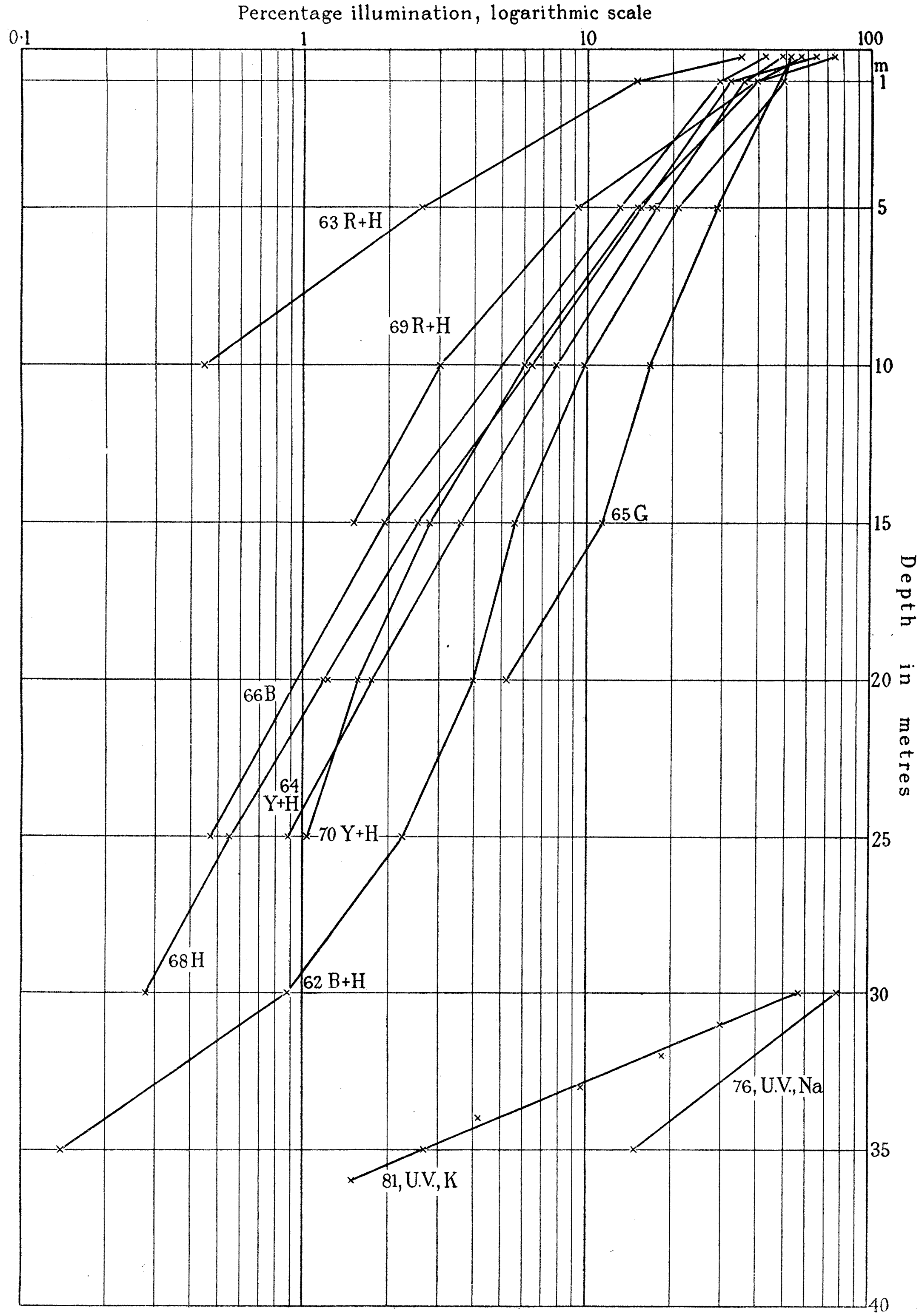

Fig. 3.—Ordinates and abscissæ as in fig. 2. All curves originating near right-hand top corner of diagram were obtained using type C.M.V. 6 cell, in fairly calm water at positions in Whitsand Bay, in open sea to W. of Plymouth Sound. Series 62–66 were obtained on 31.7.31 about 2 miles S.W. of Rame Head, depth 35 m., using for Series 62, 63 and 64 blue, red and yellow filters respectively, under heat-absorbing and opal filters; lettering as before. Series 65 and 66 were under green and blue filters, under opal only. Note heavy absorption of blue, near bottom, in Series 62.

Series 68, 69 and 70 were obtained on 6.8.31, about $1\frac{1}{2}$–2 miles W. of Rame Head, depth 32 m., using heat-absorbing filter under opal, alone, with red, and with yellow filters respectively.

For Series 76 and 81 the abscissa, 30 m., must be taken as the surface. They relate to ultra-violet radiation—Series 76 as measured with a Burt sodium vacuum cell and 10 mm. Corex red purple filter, and Series 81 with a potassium vacuum cell under 3·2 mm. Chance's ultra-violet transmitting glass (Wood's glass), no opal in either case. Series 81 was obtained on 18.8.31, about $2\frac{1}{2}$ miles W. of Rame Head. Series 76 was obtained near Eddystone, between Series 75 and 77.

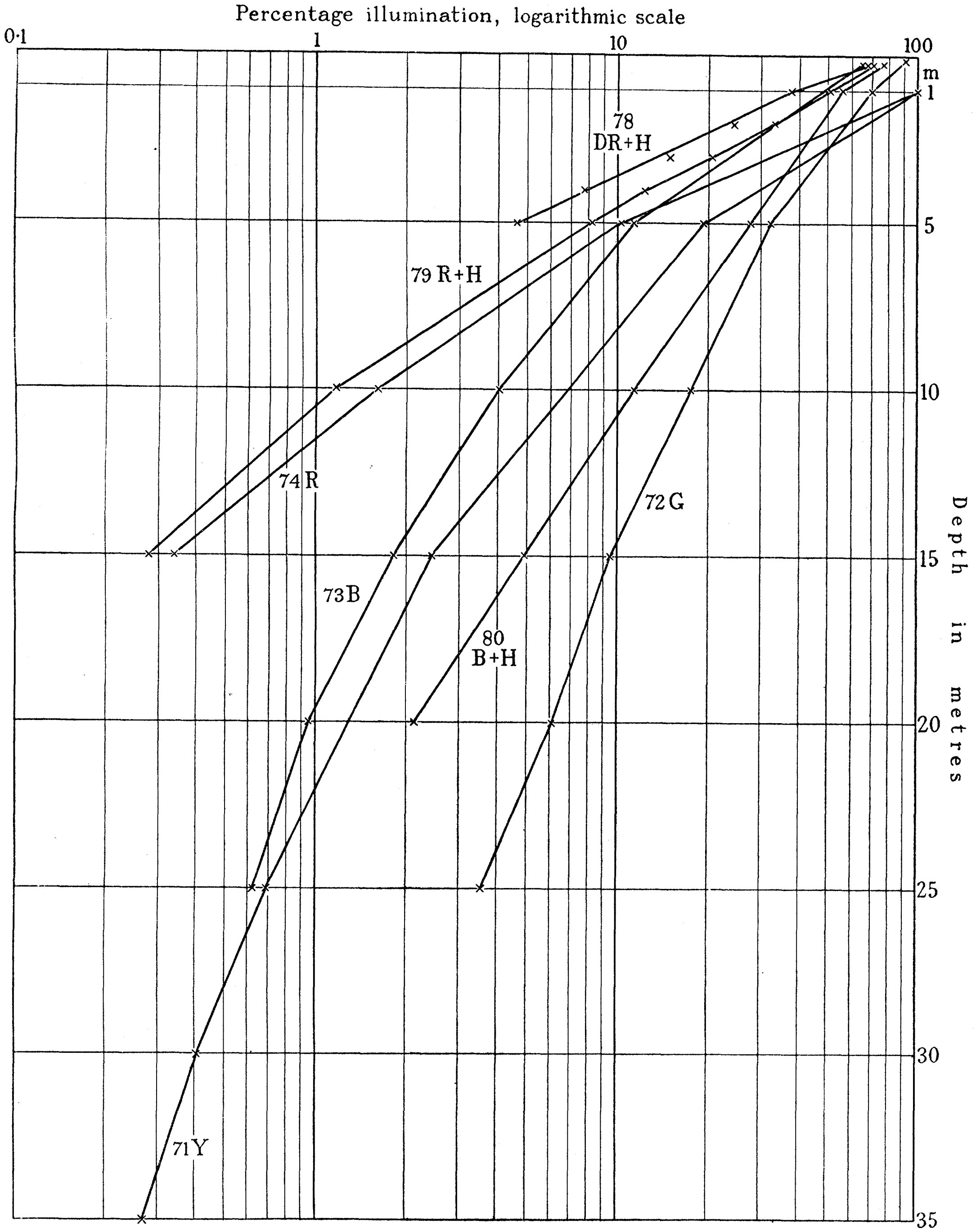

Fig. 4.—Ordinates and abscissæ as before. Type C.M.V. 6 cell used throughout with filters under opal, in Whitsand Bay, 1$\frac{1}{2}$–2 miles from land, depth about 35 m., water fairly calm.

Series 71–74 were obtained on 6.8.31 with yellow, green, blue, and red filters, respectively. In this locality yellow penetrates better than blue. Series 78, 79 and 80 relate to 13.8.31, using dark red, red, and blue filters, respectively, under heat-absorbing glass and opal, but the heat-absorbing filter was removed at 5 m. in Series 79 and at 10 m. in Series 80. Note increased penetration of blue on 13th, partly due to combination with green heat-absorbing filter.

Secchi disc visible 7–7·5 m. on 6th, and 10 m. on 13th, water green.

Note that Series 71 and 74 originate from 1 m. depth, as 1 m. of water was used instead of the heat-absorbing filter, though it lets through more red.

For economy of space and also because of the uncertainty attaching to determinations in the *a* and *b* positions, only *p* has been shown in the table.

When all corrections have been made it appears that the actual loss at the water surface is small, as determined by taking illuminations at *a* and *b*, calculated as a percentage of *a*, and using only sodium or potassium cells so that the cutting off of infra-red does not affect the readings. Thus at Station E 1, with a flat calm and glassy water, the surface losses were, in Series 48 and 50, 1 and 2·3 per cent. respectively. Near the Eddystone, Series 55, 60, 61 and 67, with light wind, gave respectively, 2·6, 16·9, 5 and 5·5 per cent., and Series 75, with moderate wind, gave 25·5 per cent. loss.* Such losses, of course, include any increase in the shadow effect that may occur owing to the lowering of the photometer, and to its swinging in towards the ship when rolling. In heavy weather one has also to consider the loss due to foam, which, since it appears white to the eye in air, must darken the water beneath. Near land, too, floating particles near the surface may conceivably cause a quite appreciable obstruction.

General Discussion of Results of figs. 2, 3 *and* 4.

As regards the determinations with photometer J, all at the same station, as shown in fig. 2, the results of Series 55, 60, 61 and 67, are in good agreement. The concordance is a test of the reliability of the cell, which was in Series 55 worked with 6 volts anode potential to 15 m., and at 60 volts from that down to the bottom and up again to 15 m. In Series 60 it was kept throughout at 6 volts, as also in Series 61, and at 12 volts in the remaining two series. In Series 61 the zone of less transparent water, $\mu_v = 0{\cdot}173$, is found at 5–10 metres, instead of 0–5 m., and the percentage illumination *p* at 40 m. has remained almost the same, 0·39 to 0·47, in the three series, falling to 0·33 per cent. in Series 67, and rising to 1·47 in Series 75, which shows high transmission throughout.

It is, of course, possible that a part at least of the decrease in absorption usually found with increasing depth may be apparent rather than real, owing to the fairly wide range of sensitivity of the potassium cell, extending from the green into the ultra-violet, in which it is considerable. Since the latter has a high absorption coefficient, it follows that the violet and blue, which remain, will be progressively less cut down by each 5-metre interval, as has been pointed out in an earlier section. In spite of this, the evidence of, for example, Series 58, in which only a narrow zone of pure green was studied, is in favour of a real decrease in absorption with depth. This lack of vertical uniformity appears, however, to be often accompanied by a lack of horizontal uniformity, so that the drift of the ship during a series may produce appreciable effects. In summer the phyto-

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* Some of these values are actually below the theoretical losses for a smooth water surface, *i.e.*, 2 per cent. for pure vertical light or 6·5 per cent. for diffuse light. The differences are too large to be entirely due to the internal reflection of upward-scattered light, and must be partly ascribed to experimental errors in a rather unsatisfactory measurement. The results show, however, that the surface loss is small with a smooth surface but is appreciably increased by wind.

plankton has multiplied in the upper 15 or 20 metres to an extent limited by the exhaustion of the nutrient salts, and the existence of a marked thermocline in this region cuts off the upper water and its phytoplankton very sharply. Thus, for example, on one occasion in August the water at 20 m. was found to contain 0·2 mg. nitrite nitrogen per cubic metre, whilst at 25 m. 38·3 mg. was found. Across this thermocline only the motile zooplankton can pass, and many of them do so freely under the stimulus of a varying light intensity.

One may, however, obtain a linear relationship between the depth and the vertical illumination (the latter being plotted on a logarithmic scale) if the water be uniform ; this has frequently been found, especially when the water is, from the temperature readings, known to be homogeneous. Series 2 in fig. 3 of our 1926 paper shows a straight line for 5–35 m., its end, as does also Series 16 in fig. 3 (1928), down to 50 m. Series 23, shown now in fig. 2, is straight to 40 m., and Series 28 to 30 m., also Series 55 to 40 m., from 10 m.

Measurements at the same spot, at 9.22, 10.28 and 12.6 G.M.T., over the range 0–40 m., gave $\mu_v = 0 \cdot 121$, $0 \cdot 121$, and $0 \cdot 124$, respectively, while the sun's altitude varied from 24° to 31° and 35°. It seems, therefore, that, for comparatively great depths, the sun's altitude has but little effect upon the length of the mean path of the light in the sea. For the lesser depths, under 10 m., at which determinations of the absorption of the longer wave-lengths have of necessity to be made at sea, the altitude might be expected to influence the path, but the data of Series 28, for the range 5–15 m., which are quoted in the next section, are in favour of the opposite view.

The degree of accord obtainable in these submarine measurements may be illustrated by examples from Series 55. In this the deck-house roof illuminations, r, being taken as 100, the photometer swinging just above the water gave at the beginning of the series at 12.29 G.M.T., 77·6 per cent., and at the end, at 1.59, it gave 78. For 40 metres' depth the values at 1.19, 1.29 and 1.32 were respectively 0·47, 0·42 and 0·42 per cent., though the air illuminations, V_a, had varied from 115 thousand metre candles to 75·9 and 114·6 respectively ; at 15 m. the percentages were 10·3 and 9·2 at 12.57 and 1.36 respectively, while at 5 m. the values were 31·9 and 37·4 at 12.37 and 1.52. The difference here is due to the fact that at such a small depth the angular distribution of the light in air may make an appreciable difference to the length of the mean path in water, and the sun was, at 12.37, visible through clouds, but was perfectly clear at 1.52 ; moreover, during this long period the ship had not remained in the same water.

Ratio of Total to Diffuse Vertical Illumination in Air.

In this connection it is of interest to consider the ratio of the total vertical illumination to the diffuse vertical illumination in air. Such values, denoted by β, have been shown in the records of the series of submarine measurements. The operation of screening the sun's disc, and no more, is not easy in a small ship rolling heavily, so the tendency is for the deck-hand who performs this screening to shade the photometer rather too heavily, thus reducing the value of the diffuse light and raising β fictitiously. Even with very different values of β, however, the values of μ_v for the range 5–15 m. may remain unchanged. Consecutive measurements were made when the sunlight was reduced in intensity by a light cloud, when it was nearly clear, and quite clear, the values of β being 2, 3·5 and 4, respectively, for the blue light affecting a vacuum potassium cell; the corresponding values of the vertical illumination in air were 49, 81 and 121 thousand metre candles; the values of μ_v were identical, 0·077 in each case (data of Series 28, 19/4/1928). The sun's altitude was 51°, the determinations were made between 12.20 and 12.40, under a clear sky with white clouds. It is obvious that the values of β are much greater for the longer wave-lengths, since the sky is predominantly blue. The data of August 17, 1931, obtained with due precautions on land, may be taken as typical of conditions during the sunny days at sea, with sun at 51°–53° altitude, and clear blue sky with a few white clouds.

For the deep red (710 mμ) and infra-red, β equals 5–5·9; the infra-red is cut off almost entirely by one metre and probably altogether by two metres of sea-water. When the visible red is included, values of β = 4–5. With such intense direct sunlight, errors due to the shadow cast by the ship become, in the standard position, of little importance. With yellow filter, β = 3·3, and for green and blue β = 2·7 and 2·5. For the ultra-violet β = 2·2–1·8, as determined without opal.

The Transmission of Light of Various Wave-lengths.

We may now consider the absorption coefficients, selecting for each colour the values which seem to be most accurate. It may be noticed in fig. 2 that the first metre shows very high values of μ_v, with red and yellow filters, also a lesser effect with the impure Corning blue filter, owing to the infra-red being absorbed heavily. Thus, since the yellow filter transmits also infra-red and red, the true coefficient for yellow can only be found by its use at depths sufficient to cut off these regions of the spectrum. Such results have been collected in Table III.

The variation of absorption coefficient with wave-length, shown by these results, is the combined effect of several factors. Firstly, the water, as such, is most potent in absorbing the longer wave-lengths. This is known from the results of laboratory investigators, and from the work of Birge and Juday (1931) upon the waters in certain American lakes. Secondly, the ultra-violet near the limit of the solar radiation falling on the water, namely, 320–290 mμ, is heavily absorbed by the sulphates of calcium and magnesium, and, to a lesser extent, by the chlorides of potassium and sodium (Hulburt, 1928). Thirdly, suspended matter in the water will, if the particles be large compared to the wave-length of light, stop and scatter non-selectively; if relatively small the action will be selective, with a preponderating effect upon the shorter waves. Pietenpol (1918), working upon water from the Wisconsin lakes, considered that the action was non-selective, though there was superimposed a selective reduction of the violet and blue owing to a yellow tint in the water. Such tints are entirely absent from the water of the open sea, but may be very intense in the water of peaty lakes. Thus it was found in Lough Bray, Co. Wicklow (Poole and Poole, 1930), where the water is deeply stained and highly acid, p_H 4·8—as against sea water, p_H 8·2—that the light to which a sodium cell is sensitive is very heavily absorbed, values of μ_v being 5·1, 2·6, and 1·25 for 0–1, 1–2, and 2–3 m., respectively; the ultra-violet, to which the cell is specially sensitive (maximum sensitivity 360 mμ), is obviously absorbed first. The white window of the photometer was just visible at 1.75 m. From this value, using the approximate relation we found to hold (1929) between μ_v and the depth of visibility of the white Secchi disc at sea, namely, $\mu_v = 1 \cdot 7/D$, it may be seen that the value for the light by which the

Table III.—To show the vertical absorption coefficients for light of different colours at stations in the English Channel: E, near Eddystone; W, various positions in Whitsand Bay (see legends of figs. 2 and 3).

Series.	Cell.	d	Spectral region measured.	μ_v	Date, etc.
56	C.M.V. 6	1–10	Red and shorter infra-red	0·460	July 21, E.
57	,,	10–20	Yellow only	0·164	,,
58	,,	10–20	Green only	0·155	,,
59	,,	10–20	Blue and violet	0·189	,,
63	,,	1–5	Red only, H.*	0·435	July 31, W
63	,,	1–10	Red only, H.*	0·380	,,
64	,,	10–20	Yellow only, H.	0·149	,,
65	,,	5–15	Green only	0·103	,,
62	,,	5–15	Blue and violet, H.	0·132	,,
66	,,	5–15	Blue and violet	0·189	,,
66	,,	15–25	,, ,,	0·139	,,
68	,,	5–15	Orange to violet evenly, H.	0·180	August 6, W.
68	,,	20–30	Yellow ,, ,, H.	0·145	,,
74	,,	1–5	Red and shorter infra-red	0·567	,,
69	,,	1–5	Red only, H.	0·359	,,
70	,,	10–20	Yellow only, H.	0·135	,,
71	,,	15–25	,, ,,	0·126	,,
72	,,	5–15	Green only	0·137	,,
72	,,	15–25	,, ,,	0·098	,,
73	,,	10–20	Blue and violet	0·146	,,
73	,,	15–25	,, ,,	0·108	,,
78	,,	1–5	Dark red only, H.	0·556	August 13, W.
79	,,	1–5	Red only, H.	0·455	,,
80	,,	1–10	Blue and violet, H.	0·178	,,
81	KV	1–6	Near ultra-violet, Wood's glass*	0·598	,,
76	NaV	0–5	,, ,, Corning filter*	0·328	August 12, E.
77	C.M.V. 6	1–10	Red to violet evenly, H.	0·132	,,
75	KG	0–5	No colour filter, blue and violet	0·117	,,
75	,,	25–40	,, ,, ,, ,,	0·084	,,
55	,,	0–15	,, ,, ,, ,,	0·142	July 21, E.
55	,,	15–40	,, ,, ,, ,,	0·123	,,

H.—Greenish heat-absorbing filter used. * No opal at the depth considered.

apparatus was seen comes out as $\mu_v = 1$, which is in accord with the 2–3 m. value for the residual region of the spectrum where the sodium cell is still sensitive. The strong absorption of this water is in keeping with the observation that, in diving into such a lake, the darkness encountered is quite startling as compared with similar experiences in sea water.

It may be seen, therefore, that in sea water one would expect the absorption due to the properties of the water and dissolved salts to remain constant from place to place, whereas the variation in the absorption due to matter in suspension may be—and indeed is—quite considerable, both selectively and non-selectively. An attempt to compare the absorption coefficients is shown in Table IV. It may be seen that the red and infra-red are more heavily absorbed from sunlight than from diffuse light, because the infra-red has already been cut out of the latter. Also, in the shallower inshore water the yellow and green are of relatively greater importance.

TABLE IV.—Ratios of the absorption coefficients for light of different wave-lengths, taking that for blue light as unity. The data refer to coastal waters.

Approximate position :	Whitsand Bay.	Eddystone.	Whitsand Bay.	Eddystone.	Whitsand Bay.
Light :	Sunlight.	Weak sunlight.	Diffuse only.	Diffuse only.	Sunlight.
Series	68–74	55–59	62–66	75–77	78–80
Red with near infra-red	5·25	3·43	—	—	—
Dark red	—	—	—	—	4·21
Red	—	—	3·30	—	3·45
Yellow	1·17	1·17	1·13	—	—
Green	0·91	0·96*	0·78	—	—
Blue	1·00	1·00	1·00	1·00	1·00
Near ultra-violet	—	—	—	2·80	4·53
Red to violet	1·23	—	—	1·13	—

* Taking mean of Series 55 and 59 for blue.

Though the green is shown in Table IV as less absorbed than the blue, yet other values might be selected with the blue penetrating better. Indeed at Station E1, 10 miles farther out to sea, the value of μ_v taken for blue in Table IV would be rather a high one; accordingly the value which is more representative of deep water conditions has been used in the calculations plotted in fig. 5, which shows the percentage illuminations at a series of depths calculated from the following values of μ_v: 0·567, 0·480, 0·435, 0·164, 0·155, 0·140, and 0·390, corresponding to the respective approximate mean wave-lengths; 760, 700, 660, 580, 520, 440, 360 mμ, transmitted by the filters and the water about 10 miles off the land. These percentages have been calculated, taking the illumination just below the surface as 100, viz., they refer to p'', previously mentioned.

From fig. 5 it may be seen that even at 10 m. there remains only a little orange with the green, blue, and violet; at 20 m. the spectrum extends from the yellow to the violet.

It may be seen from the values, shown in the legend of fig. 5, that nothing but blue and violet penetrate to 80 m. In clear ocean water this is known to be the case from the interesting visual observations of BEEBE (1930) in his bathysphere. Thus, in his log for Dive No. 10, he records that at 152 m. every colour except violet had gone from the field of his spectroscope, and that though large print could still be read his colour chart colours were indistinguishable. At 244 m. the spectrum appeared a pale greyish white, and was lightest at 520 mμ, namely, where the eye is most sensitive. The observations made by BEEBE during such dives are of great interest.

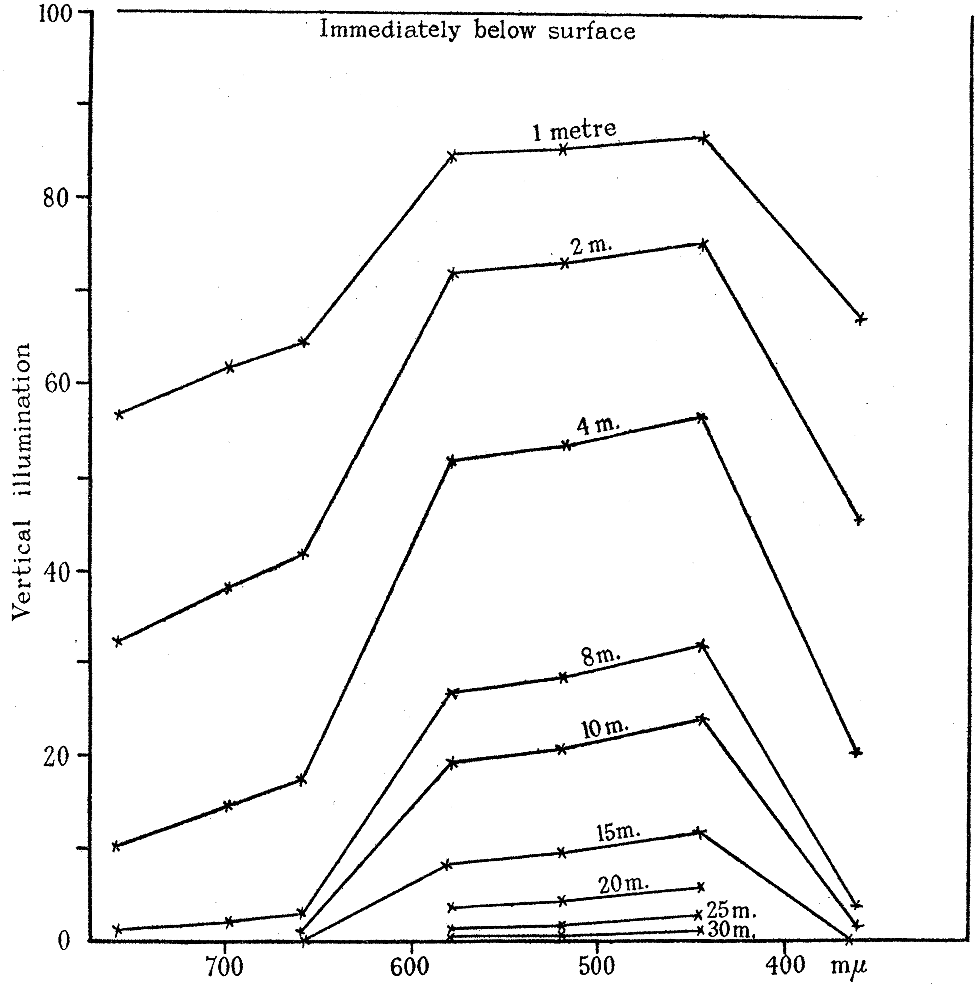

FIG. 5.—The ordinates show the percentage vertical illumination. The abscissæ denote wave-lengths. The curves relate to depths of from 1 to 30 metres, taking, for each colour, the illumination immediately below the surface as 100. The figures plotted are for clear sea water in the English Channel, about 10 miles from land. For the wave-lengths 760, 700, 660, 580, 520, 440, and 360 mμ, and the absorption coefficients used in constructing the curves, the sub-surface light would be reduced to 0·001 per cent. of its value at the following approximate depths, respectively, 20, 24, 26, 70, 74, 82, and 30 m.

The clearest column of water we have ever found was at Station E1, 10 miles S.W. of the Eddystone on April 19, 1928. Using a gas-filled potassium cell, values of μ_v were determined for 10 m. intervals, 5–15, 10–20, 15–25, and 20–30 m., and were respectively 0·077, 0·078, 0·079, and 0·075, mean 0·077. Taking this value, and assuming a uniform column downwards, the light would be reduced to 0·001 per cent. only at $2\cdot3 \times 5/0\cdot077$, namely 149 m., according to the formula already given. We are indebted to Dr. G. L. Clarke for the information that when crossing the Atlantic from Plymouth in the *Atlantis* he was able to make measurements down to 175 m., the limit of his 200 m. cables, allowing for drift. His gas-filled potassium cell, as standardized against our potassium vacuum cell, gave at 85 volts anode potential a current of 1 μa for 151 m.c., vertical illumination, or 0·15 m.c. per 10^{-9} ampere, corresponding to 1 scale division of the potentiometer. Taking $\mu_v = 0\cdot05$, which seems quite a possible value, the percentage illumination at 200 m. would amount to 0·0045. The greatest depth of visibility of the Secchi disc, which we have been able to find in records of oceanic expeditions, is 66 m. in the Sargasso Sea; the disc used was of sail-cloth and 2 m. in diameter. For various reasons the Sargasso Sea is peculiarly free (Schott, 1912) from suspended matter. Our approximate formula, $\mu = 1\cdot7/D$, obtained with the standard white disc, 20 c.m. diameter, cannot be expected to apply in this case. It would give $\mu_v = 0\cdot026$ (which is probably too low a value),* giving 0·55 per cent. of the sub-surface illumination at 200 m.

Comparison with Laboratory Measurements of Absorption.

It is interesting to compare the above values of μ_v with the results obtained by other workers for μ, as found in the laboratory, for pure water and also for samples of sea water. Some of the latest determinations have been made by Sawyer (1931), whose paper also contains an interesting summary of earlier work. It will be seen that, although there are considerable discrepancies between the values of the absorption coefficient of pure water obtained by various workers, there is little reason to doubt the approximate accuracy of his figures. According to these, μ for pure water decreases from 0·84 for a wave-length of 310 mμ to a minimum 0·015 between 460 and 490 mμ, rising again at 650 mμ to 0·21, which is the value given by Aschkinass for 620 mμ. Aschkinass gives μ as 0·28, 0·55, and 2·41 at 660, 700, and 750 mμ, respectively.

Thus, the lowest value obtained by us for μ_v in the English Channel is about five times the minimum value of μ for pure water, while, if our approximate formula connecting μ with the limit of visibility of the Secchi disc is to be trusted for such an extreme extrapolation, the value of μ_v for the clearest sea water ever recorded is about 1·7 times the minimum. So far as it goes, this agreement is satisfactory if we assume that this very clear water contained very little matter in suspension, since the path of the light

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* Through the courtesy of Dr. G. L. Clarke we are now able to state that at the northern edge of the Sargosso Sea he found the value to be $\mu_v = 0\cdot031$ down to 170 m.

in the ocean is certainly greater than the vertical depth, and there seems to be some evidence that for the blue part of the spectrum the transparency of sea water free from suspended matter is not very different from that of pure water.

This does not appear from SAWYER's work, as his two samples of salt water, taken from localities not far from the land, namely, the St. Croix River and Bay of Fundy off Head Harbour, and tested within an hour before the suspended matter had time to settle, naturally gave values of μ differing greatly from that for pure water and from each other. His clearer water gave results for blue light which could readily be matched in many of our series, while the river sample was rather more opaque than any that we have found.

The evidence for the transparency of pure sea water is really derived from HULBURT's (1926, 1928) work in the ultra-violet region. His values for pure water are some 25 per cent. lower than those found by SAWYER for the same wave-lengths, an agreement probably as good as could be expected, whereas sea water samples, taken far from land and tested two months later, ranged from 3·9* at 303 mμ to 0·3 at 366 mμ, showing a rapid approach to the value for pure water as the visible spectrum was approached. His absorption cells were too short to give reliable measurements of the very small absorption coefficients found for both pure water and sea water in the visible spectrum.

The Physiological Bearing of the Results.

(*a*) *The phytoplankton.*—As previously mentioned, information as to under-water illumination was, in the first instance, sought in connection with the desire to know the conditions under which diatoms could carry on photosynthesis effectively. Several workers had measured the rate of photosynthesis of plants lowered to various depths in water. In particular, MARSHALL and ORR (1928) made a careful study of the oxygen given off by diatom cultures in bottles lowered in a horizontal position to various depths in the sea; controls gave the oxygen used up in respiration, this amount being added to the oxygen found in the illuminated bottles gave the true result. By this means they found that the point at which evolution of oxygen is balanced by absorption, the "compensation point," lies, for the waters of Loch Striven, at a depth of 20 to 30 metres in summer. Were the coefficient of absorption known for this region, one could ascertain the daylight factor for the compensation point; but the figures given by MARSHALL and ORR enable one to calculate an approximate value for the absorption coefficient, on the assumption that the rate of photosynthesis is proportional to the mean illumination over the period. The values given are for volumes of oxygen per million diatoms. Thus on sunless March days, 18–19, the data for a one-day period give in Loch Striven for 0–5 m. $\mu_v = 0·149$, and for 5–10 m. $\mu_v = 0·128$. For a bright day, March 28–29, 0 and 5 m. gave almost identical results for oxygen, as obviously the illumination

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* This figure is quoted as 13·9 in SAWYER's paper.

at the surface was too great to be used completely ; for 5–10 and 10–20 m. the absorption coefficients come to 0·113 and 0·144, respectively. The value 0·113 is probably too low, and indicates that the illumination at 5 m. is still too bright for maximum photosynthetic efficiency. The water appears to have cleared somewhat by March 31–April 1, as on a bright day, with surface evolution of oxygen far below the 5 m. value, $\mu_v = 0{\cdot}104$ for 5–10 m. and 0·107 for 10–20 m. Again for a bright day, May 18–19, $\mu_v = 0{\cdot}184$ from 2–7 m. The results for a very sunny day on June 13–14, with 16 hrs. 5 mins. sunshine, are especially instructive. Down to 7 m. the photosynthetic efficiency was reduced by the high illumination, so that $\mu_v = 0{\cdot}027$, a fictitiously low value. Even over the 7–10 m. range the excessive intensity of the light is shown by the value $= 0{\cdot}100$, as against $\mu_v = 0{\cdot}196$ and 0·179 over the ranges 10–20 and 20–30 m., respectively. One can thus use the calculated value of μ_v as an indication of the level above which the mean illumination over the period is so great that the light energy is not the chief factor limiting photosynthesis, even though increase of light does produce an increase in oxygen evolution. One could not ascertain this from inspection of the percentages—1 m., 100 ; 7 m., 84·8 ; 10 m., 62·8 20 m., 8·8 ; 30 m., 1·46—yet the values of μ_v calculated therefrom bring out the relation clearly, since it appears to be highly improbable that the low apparent values found near the surface on bright days can be attributed to very clear water overlying water of average opacity lower down. These values of μ_v, based upon MARSHALL and ORR's data, lie between 0·1 and 0·2 (and chiefly between 0·15 and 0·2), and are very similar to those we obtained in Cawsand Bay or Whitsand Bay, or even further out towards the Eddystone for yellow, green and blue light, but are quite unlike our values—or even the values given by pure water—for red light. It is accordingly obvious that, even in the upper 5 m. of Loch Striven, red light can play only a minor part in diatom photosynthesis. This is what one would expect from the data of Table VII, but its confirmation by means of an entirely different line of investigation is not without interest in view of the great importance formerly attached to red light by workers on photosynthesis. In this connection the conclusions drawn by Miss STANBURY (1931) may be recalled, namely, that, for a low intensity of radiation, diatom growth is roughly proportional to the energy received, irrespective of its wavelength within the visible spectrum, and that, when grown under selective filters, the cultures tend to show chromatic adaptation, assuming colours which are complementary to those in which they are growing, *e.g.*, a rich dark brown shade under the green and blue screens, and a decided green colour under the red and yellow. The filters used were identical with those used in the determinations of μ_v for different colours at sea.

If it so happened, however, that throughout the experiments quoted the light was supra-optimal, the proportionality between photosynthesis and light would not hold, and the above calculations of μ_v would be valueless. It appears improbable that this was so, because the compensation point may be no deeper than 20 m. With light halved for each 5 m. it penetrates, the illumination x at 20 m. would only be $8x$ at 5 m. It must also be borne in mind that when the submarine illumination is given as, say, 10 k.m.c., as against 100 k.m.c. in air, the energy of the radiation is not reduced in the proportion of 10 : 1, but the reduction is far greater ; this is so because, firstly, all the infra-red has been cut out by the first metre of water and, secondly, all the red has been absorbed by the first 10 m., so that what is left is roughly one-tenth of the original yellow, green and blue, which is probably near one-thirtieth of the total energy in air, as pointed out later. Furthermore, the illumination can hardly have been supra-optimal for a sunless day in March—18–19—which gave $\mu_v = 0\cdot149$ for 0–5 m., as against $\mu_v = 0\cdot184$ from 2–7 m. on a bright May day, 18–19 ; the value of μ_v in May shows that if March was not supra-optimal as regards illumination, May could not have been so, unless the true value of μ_v were higher than 0·184 in May.

Taking the value 0·15 for μ_v, as calculated from the oxygen evolution and 20 m. as the compensation point, the percentage of the sub-surface light is 5·0 ; for 30 m. this is reduced to 1·3. With $\mu_v = 0\cdot20$, these values become 1·8 and 0·25, respectively. The diatom outburst is usually at, or past, its height by the end of April, so it seems legitimate to take our data for April 27, 1930, as the basis of an approximate calculation of the light requirements of diatoms. This was a bright day, with 15 hours' daylight and a maximum illumination as high as 170 thousand metre candles (k.m.c.) carbon arc standardization. The area of the curve marked out by our daylight recorder (1930), with sodium photo-electric cell, was measured ; from it the mean illumination was found to be 70·2 k.m.c., or 1,053 k.m.c. hours. For $\mu_v = 0\cdot15$ it follows that the mean illumination at the compensation point, 20–30 m., lies between 3·5 and 0·77 k.m.c., corresponding to 52·7 and 11·5 k.m.c. hours. With $\mu_v = 0\cdot20$ these values become, respectively, 1·28 and 0·17 k.m.c., *i.e.*, 19·2 and 2·5 k.m.c. hours.

From observations made on a clear, almost cloudless evening, it was found that the vertical illumination in air was 620 m.c. when the disc of the sun had just vanished, the illumination then being 0·36 per cent. of the maximum or about 0·5 per cent. of a less brilliant day's maximum. It seems probable, therefore, that the compensation point illumination is rather greater than the sundown illumination.

It is of interest to try to arrive at an approximate value for the intensity of the radiation received by the sea water at the levels of the optimum and compensation points for diatom growth. Even though it seems impossible to ascertain the amount actually absorbed by the diatoms themselves, the radiation-climate under which they thrive may be studied with profit.

(*b*) *The heating of sea-water by light absorbed.*—According to CORLESS (1912), the vertical component of the radiation at South Kensington, London, from sun and sky, during a cloudless day, September 1, 1911, amounted to 450 gramme calories per square centimetre. It so happens that our own photo-electric records show that September 1 and 2, 1930, were similar cloudless days, giving regular ascending and descending intensity curves.

From the areas marked out it was ascertained that the days received respectively 590 and 641 k.m.c. hours. The 2nd was rather clearer than the 1st, and had a higher maximum. From these figures, since South Kensington and Plymouth are in nearly the same latitude, 51·5° and 50·4° respectively, it follows that the energy received from an illumination of one thousand metre candle hours is 0·763 cal./cm.^{2} or 0·702 cal./cm.^{2}, according as we calculate from the data for September 1 or 2 respectively. Since London atmosphere probably approaches more nearly to the less clear day, the first value seems to be preferable and may be rounded off to 0·75 g. cal./cm.^{2}

Table IV and fig. 5 make it clear that nearly the whole of the light reaching 20–30 m. lies in the region between 580 mμ and the blue end of the visible spectrum. The energy penetrating to any such depth must, therefore, be calculated, not from the total vertical component of sunlight plus skylight, but from the energy of the spectrum below 580 mμ. Data given by ABBOT, FOWLE, and ALDRICH (1922) enable one to plot arbitrary energy values, k_λ, for each wave-length. Data for f, the transmission factor of the atmosphere, are also given, so where z is the zenith distance of the sun, the energy received normally is $k_\lambda f^{\sec z}$, or $k_\lambda f^{\sec z} \cos z$ for a horizontal surface. This is for pure sunlight. Taking the proportions of each colour as equal in light from a grey sky, we have found blue sky light to contain blue 100, green 90, yellow 60 and red 50, but the proportions vary somewhat. Clear blue skies are not the normal in this country, so it seems probable that no very serious error will be made in assuming that the sky light is sunlight diffused non-selectively. Taking the curve $k_\lambda f^{\sec z} \cos z$ when $z = 60$, we find the proportion of energy below 580 $m\mu$ to be 33 per cent. of the total. This gives, as a rough estimate, that of the 450 cal./cm.^{2} received on September 1, only 150 cal./cm.^{2} would have been conveyed by radiation under 580 $m\mu$. Allowing 20 per cent. for surface loss and scattering, which is intentionally above our figure for calm weather determinations, the sub-surface energy received on September 1 would be 120 cal./cm.^{2}. Taking $\mu_v = 0{\cdot}15$ and the corresponding percentages at 20 and 30 m., the energy received would be 6 and 1·3 cal./cm.^{2}.

In each case the difference in the energy received at 20 and 30 m., namely 4·7 cal./cm.^{2} per day, has been used up in warming the 10 m. water column and in providing the diatoms with energy for photosynthesis. If we assume for the moment that this is all used up in warming the water, since we cannot determine the proportions, and that used in photosynthesis is relatively small, the rise in temperature is 0·0047°. If it be taken as an approximation that this amount is received daily for the six months during which the sea is warming up each year, the rise amounts to 0·84°. Actually at Station E1, 10 miles S.W. of the Eddystone in the English Channel, the mean temperature rise in 1926, in the 53 days between June 24 and August 16, was 0·86° C. In this region μ_v may have been as low as 0·12, though on the average 0·15 seems a better value, and 0·20 too high a figure. It seems probable that the value taken for the sub-surface energy, 120 cal./cm.^{2} per day is too low for the period between mid-summer and August, and that in reality the slow rise in temperature observed at 30 m. during summer is due to the absorption of light. The demarcation between the upper warm layer and the cooler water beneath is often sharp. Thus on September 22, 1926, the temperatures at 0, 20, 23, 25 and 30 m. were, respectively, 16°·75, 16°·23, 13°·76, 13°·76 and 13°·61.

Again, on August 16, 1928, the nitrite nitrogen, expressed as milligrammes per cubic metre, was at 0, 20, and 25 m., respectively, 0·2, 0·2 and 38·3. One is, therefore, led to the conclusion that the heating of the water can be accounted for by the absorption of the radiation that penetrates below the thermocline.

Since the foregoing was written we have found a similar calculation by HELLAND-HANSEN (1931). Using the value 360 g. cal. per $cm.^2$ per day for the radiation falling on the North Atlantic in summer, together with the absorption coefficients for pure water, he concludes that the temperature at 50 m. in spring and summer on an average rises about 0·004° C. per day as a result of the absorption, at this depth, of radiation from sun and sky. It corresponds to an increase of about 0·7° C. from April to September. The rise of temperature at 100 m. is about 0·0013° C. per day, or 0·2° C. from April to September. In these calculations it was taken that about 60 per cent. of the total heat energy of the normal spectrum at sea level is due to non-luminous rays, and about 40 per cent. to the visible.

In order to test whether the proportion of the total incident radiation used up in photosynthesis is or is not likely to be relatively small, an approximate calculation may be made as to the maximum thickness of diatom cells traversed by a light-ray in passing through 10 m. of water. Measurements (1923) of the annual phosphate consumption have shown that 30 mg. per m^3, reckoned as pentoxide, is used up by the phytoplankton annually and regenerated during winter. From counts made on a pure culture of *Nitzschia closterium* it was ascertained that complete exhaustion of the 30 mg. per m^3 produced 27 diatoms per cubic millimetre, or 27×10^6 per litre. Taking the average length of the Nitzschia cell, excluding the horns, as 30μ and the width as 8μ, the area exposed by the given number comes to 64·8 $cm.^2$ in the litre volume of the column 10 m. by 1 $cm.^2$ Obviously the area is covered 65 times over. Taking the thickness of the cells as 4μ, the total average thickness traversed by the beam is 0·25 mm. Since on the average a ray passes through 65 cells in 10 metres, screening is bound to occur, but this does not affect the above argument in any way. The fact that the path of the ray is not vertical will, of course, increase the thickness traversed. Obviously the number of cells taken, 27 million per litre, is a major limit. Ordinarily there might be only one-tenth as many, though LOHMANN has reported as many as 77·8 million per litre of *Skeletonema costatum* found at Kiel, where probably the water was initially richer in phosphate than in the English Channel. MARSHALL and ORR (1930) also report this diatom as occurring in Loch Striven in quantities of from 5×10^5 chains per litre early in the spring outburst, up to 25×10^5 at its height. Taking 10 cells per chain, and average values for the diameter and thickness of the disc-shaped cells as 12μ and 6μ, respectively, the total area covered by the cells when at their maximum number comes to 18 $cm.^2$ when the filaments are viewed sideways. Thus, for this diatom the light would have to traverse, on an average, 18 cells, the depth being the diameter, 12μ, so the total thickness works out as 0·22 mm., which is probably a fortuitously close agreement with the value calculated for Nitzschia, 0·25 mm. There can, however, be no doubt that the maximum thickness of the diatom screen is of this order of magnitude. Since this is so, it is hardly surprising that the spring diatom outburst does not produce the increase in absorption which we had expected. Phosphate, as pentoxide, was on January 31, April 19, and May 2, 1928, found to be 35, 23, and 10 mg./m.^{3} at 5 m., respectively, whereas on March 1, 27, April 5, 19 and May 7, the water column gave μ_v as 0·123, 0·144, 0·121, 0·096, and 0·094, respectively. The clearing of the water was apparently due to the inward movement of water of similar phosphate content from about 20 miles further out to sea, as indicated by salinity analyses.

(*c*) *The zooplankton.*—Since little or no red light is transmitted beyond 10 m. for inshore waters, it would seem probable that the eyes of deep water fishes would be insensitive to such wave-lengths, except so far as they may be present in the phosphorescence of deep water fishes themselves. As regards fish inhabiting shallow waters, BULL (1928) gives an example of a positive conditioned response being evoked by a red light. This implies not only that the fish could distinguish between the unscreened light from a 60-watt " Fullolite " gas-filled lamp, and the same light as modified by the interposition of a Wratten No. 70 (red) light filter, as BULL had shown by other experiments, but also that it could recognize the red light as being light. Had the response been positive to the unscreened light and negative to the red light in other experiments cited, one could only conclude that the fish could distinguish light from a less bright light or from one that, to it, was darkness.

According to G. M. SPOONER (private communication), herring larvæ under a fortnight old move towards diffuse daylight, but, in a room illuminated only by a photographer's lamp with a Wratten red light filter, they move away from even this weak source of red. This observation, repeated several times with the same result, seems conclusive evidence that such larvæ can recognize red light as being light, namely, it does not fail to affect them as infra-red fails to affect us. The amount of energy conveyed as heat would have been altogether negligible in this experiment, so the red perception could not have been a mere heat perception.

It would be foreign to our aim in this paper to enter further into the vexed question of the colour vision of fish. Reference may be made to the admirable survey by WARNER (1931), though some of his evidence is of a conflicting nature. It seems possible that a better agreement may in future be obtained by paying more attention to the origin of the fish ; thus it should always be stated whether the fish tested lived at a depth of less than 10 m., or at a greater depth, due regard being paid to both larval and adult habitat. Furthermore, it should be stated whether the fish, even though belonging to a shallow water species, is a member of a genus which is predominantly an inhabitant of deeper water.

It remains to consider the penetration of the anti-rachitic portion of the ultra-violet in relation to the production of the vitamin D stored in fish liver oils. According to SAWYER (1931), the amount which penetrates is very minute for the Bay of Fundy, off Head Harbour, even with a depth of 90 m., and far less again in the St. Croix

River, 30 m. deep. SAWYER's laboratory values of μ (not μ_v) are 4·2 and 4·9 at 320 and 310 mμ, respectively, for the Bay, and $\mu = 12·8$ and 16 at 320 and 313 mμ for the River, respectively. For 360 mμ he gives for pure water, Bay water, and River water, $\mu = 0·281$, 2·34, and 5 respectively, as compared with our sea-water values $\mu_v = 0·60$ and 0·33 for positions 2·5 and 10 miles, respectively, from shore. SAWYER's specimens of salt water were evidently not very clear. HULBURT's (1928) measurements on water from the ocean are of interest. For pure water, tap water, and ocean water, HULBURT records values as follows: at 303 mμ, $\mu = 1·2$, 1·6, and 3·9; at 313 mμ, $\mu = 0·5$, 0·7, and 2·1; and at 366 mμ, $\mu = 0·2$, 0·2, and 0·3, respectively.

In Table V HULBURT's values have been used to show that, even in the pure water of the open ocean, the anti-rachitic portion of the spectrum is reduced to as little as 0·001 per cent. of its sub-surface value at from 2·9 to 5·5 m., according to wave-length, and only 1 per cent. is found at from 1·2 to 2·2 m. The radiation seems quite inadequate to produce the effects found, but it is possible that the explanation may lie in the fact that, as pointed out by RUSSELL (1928, 1930), species of the plankton, which normally occur at depths below 10–15 m. during April, May, and June, become abundant, as shown by the percentage depth distribution curves, right up to the surface in July, August, and possibly September also. In *Calanus finmarchicus* it was found that the females of the summer brood were always slightly higher up in the water than the males. The presence of vitamin D in zooplankton has been demonstrated by BELLOC, FABRE, and SIMONET (1930), also by DRUMMOND and GUNTHER (1930).

TABLE V.—Showing the depths in metres at which various percentages of ultra-violet radiation are found after traversing columns of pure, tap, and ocean water. The figures have been calculated from HULBURT's values, $\mu = 1·2$, 1·6, and 3·9 for 303 mμ, and $\mu = 0·5$, 0·7 and 2·1 for 313 mμ, respectively, for the waters.

Wave-length:	303 mμ.			313 mμ.		
Water:	Pure.	Tap.	Ocean.	Pure.	Tap.	Ocean.
Percentage:	m	m	m	m	m	m
10	1·9	1·4	0·6	4·6	3·3	1·1
1	3·8	2·9	1·2	9·2	6·6	2·2
0·1	5·7	4·4	1·8	13·8	9·9	3·3
0·01	7·6	5·8	2·4	18·4	13·2	4·4
0·001	9·6	7·2	2·9	23·0	16·4	5·5

It also seems possible that, though anti-rachitic action is but feeble at wave-lengths longer than 313 mμ, yet owing to their better penetration those somewhat longer than the limit given may be more effective in sea water.

The calculations from HULBURT's values of the absorption coefficient show conclusively that it would be profitless to attempt to determine penetration to such small depths at sea, since the error due to the movement of the ship would be far too great. It appears, however, that measurement of the absorption coefficient with a sodium cell and a red purple ultra-violet transmitting filter, as in Series 76, may provide a useful method for the study of the suspended matter in sea or fresh waters.

In conclusion we would add that no use has been made, in the foregoing discussions, of the valuable results of BIRGE and JUDAY (1929–31) on the penetration of total radiation and of the component colours, since these relate to fresh-waters and are being reviewed by one of us elsewhere. Their method would appear to be of value for marine work also.

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Summary.

1. Using a potentiometer method, with telephone and amplifier as a null-point indicator, measurements of photo-electric currents were made at sea. By means of sodium, potassium, and thin-film cæsium cells, together with appropriate light filters, the coefficient of absorption (transmissive exponent) was determined from the near ultra-violet to the deep red. In these measurements the depth was taken as the path traversed.

2. Our attention has been drawn to the necessity for correcting for the effects of internal reflection, as between water and opal diffusing filter, when comparing the readings of our photometers in air and in water. Laboratory tests have shown that most of our previous results for light under water should be multiplied by 1·17 in order to correct for this effect. This does not affect the values given for the absorption coefficient, which depend on the ratios of submarine readings.

3. Consideration of the various possible sources of error attending the use of the "vertical absorption coefficient" as an index of the opacity of the water shows that the errors, though appreciable and difficult to estimate, are very unlikely to be important compared with the large variations which are found in the value of the coefficient, which must imply corresponding changes in the opacity. The loss at the air-water surface appears to be small in calm water, being appreciably increased by wind.

4. For sea water in the English Channel, 10 miles from land, the following values may be taken as typical for near ultra-violet, blue, green, yellow, orange-red, red and deep

red, respectively : $\mu_v = 0\cdot390, 0\cdot140, 0\cdot155, 0\cdot164, 0\cdot435, 0\cdot480, 0\cdot567$. From these values it follows that the sub-surface illumination is reduced, for each spectral region, to 0·001 per cent. at the following depths : 30, 82, 74, 70, 26, 24, 20 metres, respectively.

5. For the clearest water found, 20 miles from land, $\mu_v = 0\cdot077$, for blue light.

6. The heating of the water, at depths of 20 to 30 m., namely, below the thermocline, may be attributed to the absorption of light, from yellow to violet.

7. The ratio of the total vertical to the diffuse vertical light, in air, increases with wave-length, being for the colours named in § 4, in the same order, 2·2, 2·7, 2·7, 3·3, 5·1, 5·4, 5·5, as determined under a clear blue sky with a few white clouds and the sun at 51°–53° altitude. Values up to 3·5 have been found for blue light, and up to 5·9 for deep red with infra-red.

8. Data, available from the work of Marshall and Orr, for the evolution of oxygen by diatom photosynthesis in Loch Striven, yield values for μ_v chiefly between 0·15 and 0·20, corresponding to that of light from yellow to blue.

9. The great increase in diatoms, which occurs in spring, was not found to decrease light penetration. Calculations show that, at a maximum, the mean thickness of diatoms traversed in a 10 m. water column only amounts to 0·25 mm., and is probably nearer one-tenth of that as an average value.

10. Measurements of submarine illumination were made almost simultaneously with plankton hauls, using six nets at various depths ; these will probably throw light on the vertical distribution of the zooplankton.

11. The absence of red light from the deeper water may be expected to have a bearing on the colour vision of fish dwelling under such conditions.

12. Hulburt's coefficients have been used to show that even in the clearest ocean waters the anti-rachitic portion of the spectrum is reduced to 1 per cent. of its sub-surface value at 1·1 to 2·2 m., according to wave-length and to 0·001 per cent. at from 2·9 to 5·5 m. This has an obvious bearing on the origin of vitamin D in fish liver oils.

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