Polarization Patterns in Submarine Illumination

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ALTHOUGH the polarization of sky light has been known since 1809 and widely studied (*1, 2*), the comparable phenomenon in natural waters has scarcely been considered. The possible importance of this unexplored field has recently been emphasized by the discovery that polarized light has significant behavioral and physiological effects on a variety of arthropods. First demonstrated by von Frisch (*3*) in the honeybee, striking sensitivity to polarized light has since been found in a variety of insects and their larvae, crustaceans, and chelicerates.

Not only have these animals been shown capable of detecting polarized light, but also some of them have been found to use the natural polarization of the blue sky in navigating from one place to another. These facts have opened up a whole new field of visual physiology and behavior (*4*).

Among aquatic animals also polarized light sensitivity has proved to be widespread in the arthropods. The compound eye of *Limulus* was discovered to be sensitive to plane-of-light polarization, although so far the behavioral or ecological significance of such ability in this animal is unknown (*5*).

Behavioral reactions to polarized light have, however, been found by Baylor and Smith (*6*) in a number of fresh-water aquatic forms. Most interesting was their discovery that the swimming of cladoceran crustaceans like *Daphnia* could be predictably oriented by vertically or horizontally directed beams of plane-polarized light. Swimming was predominantly at right angles to the direction of the *e* vector in a vertically incident beam and could be repeatedly changed when the polarization plane was rotated. In a horizontal beam of polarized light, the crustacean's swimming direction was similarly related to the plane of polarization, being upward in a horizontally polarized beam and lateral, with the animals swimming on their sides, in vertically polarized illumination.

That polarized light of natural origin can have similar orienting effects on populations of these crustaceans was also demonstrated by these same workers, who briefly reported appropriate orientation of Cladocera exposed to the polarized light of the blue sky at sunset or sunrise. Homing on polarized shafts of penetrating light around shadows was predicted, too. The present data, however, indicate the importance for underwater polarization of the directionality of daylight illumination everywhere in the water. This presumably applies not only to the sea, where these observations were made, but also to any other extensive body of water, fresh or salt.

In view of these facts, then, the occurrence and pattern of light polarization in aquatic environments becomes a subject of wide potential relevance to various problems in oceanography and limnology. The basic principles of light polarization by scattering in gases and liquids have been well known since the pioneer work of Tyndall and Lord Rayleigh. Brief mention of the occurrence of polarized light in natural waters has been made (*7–10*), yet few if any, actual data are available.

The present observations on submarine illumination were, therefore, undertaken to outline the major characteristics of its polarization. The results indicate that to an even greater degree than terrestrial animals, aquatic forms of the photic zone are surrounded by a complex pattern of polarized light. For those that have eyes sensitive to it, this pattern may provide significant cues for orientation and migration.

The observations made so far have been carried out visually by the author, skin diving in the sea around Bermuda. Most of the data were taken in the surface 5 to 6 m, but a few measurements were made down to 15 m. Stations investigated included shallow turbid water in Ferry Reach, deeper more transparent areas in Castle Roads and the North Shore of St. George's Island, very clear oceanic water beyond the 2000-m contour of the South Shore, and cave waters of Harrington Sound. A face plate was employed for clear vision, and a special hand-held polarization analyzer was employed in examining the light from all directions. This device indicates by inspection the presence and plane of polarized light and at the same time allows an estimate of the degree of its polarization.

The polarized light detector utilized makes use of an interference pattern well known to crystallographers. The light being examined first passes in a convergent beam through a suitably thick plate of a uniaxial crystal cut perpendicularly to its axis. The light emerging from this is then circularly analyzed through a quarter wave plate and a disk of Polaroid film. The whole optic sandwich is cemented together and protected with glass covers.

If unpolarized light is viewed through this instrument, nothing is observed except a decrease in light intensity. If, however, plane-polarized white light is examined, a brightly colored interference pattern consisting of concentric, broken rings appears at the far point of vision. This figure subtends a visual angle of about 15° in the unit used. In partially polarized light, the intensity of this pattern and the number of concentric rings observable vary with the percentage polarization. Thus with strongly polarized, moderately intense light, 30 or more rings can be seen. With weakly polarized light of the same intensity, only a few rings, perhaps 6 to 8, are visible. This device, then, provides a rough but ready estimate of the degree of polarization. So far no precise method of calibration has been attempted.

The interference pattern further indicates the planes of the *e* and *h* vectors of the polarization. As mentioned in the preceding paragraph, the concentric rings are broken. The interruptions occur in quadrants and establish a right cross, the arms of which define the orientation of the polarized light traversing the analyzer. At the center of the pattern two diametrical quadrants are dark, and two are light, This relationship provides a ready means of discriminating the *e* and *h* vectors, since the position of these quadrants is specifically related to the plane of polarization and the kind of crystal plate used.

Most of the time no close measure of the polarization angle was made. However, in a few cases, the analyzer was used with a plumb line for zenith reference and a protractor for measuring the angle. Even so, accuracies greater than ± 2° to 3° would not be expected, because sights were all taken while swimming freely. At least for exploratory purposes the superiority of the present analyzer to a complicated prismatic polarimeter or a Savart plate should be obvious. Rapid, convenient, reproducible estimates of degree and plane of polarization were thereby accessible for inspection or photography.

In general the daylight reaching any observed submarine point from almost all possible directions was found to be partially polarized. The pattern of this polarization, described in detail in the following paragraphs, is shown diagrammatically in Fig. 1. There were at least two major components of this polarized light.

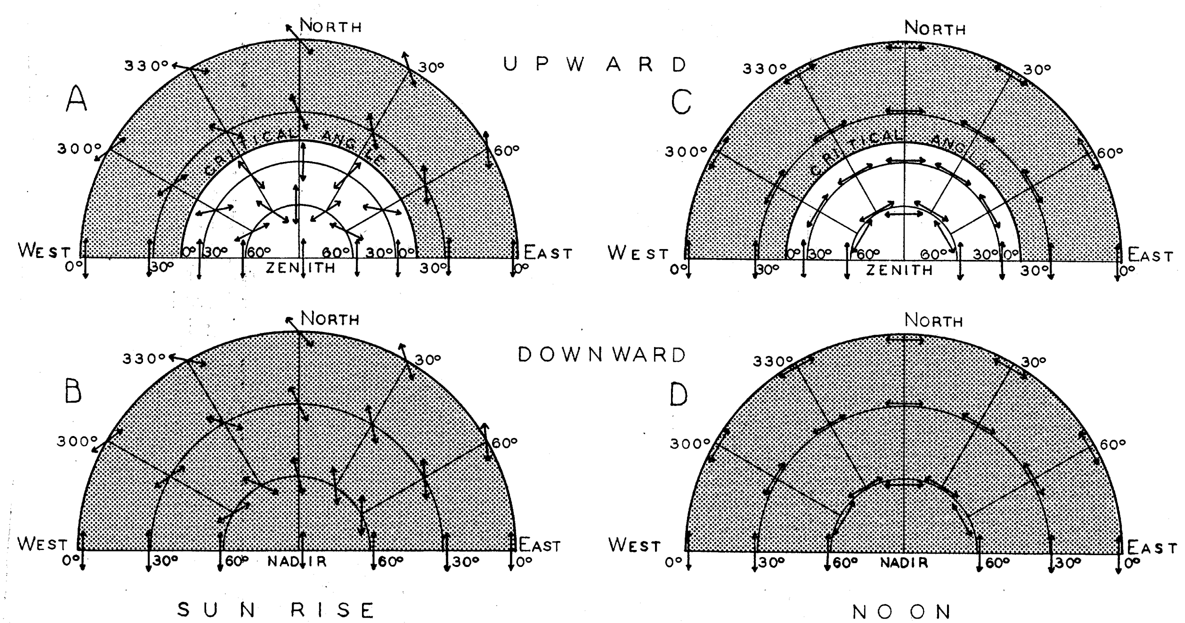

Fig. 1. Polarization planes of submarine illumination as seen from a point a few meters under water at two different times of a clear cloudless day (diagrammatic). In *A* and *B* the pattern shown is that observed at sunrise with the sun on the horizon directly east. In *C* and *D* the pattern is that observed at noon with the sun directly overhead in the zenith. The diagrams are plotted on polar coordinates with azimuths represented by radii, and elevation or depression of the observer's line of sight as concentric circles. The outermost circle (0°) in each case is the underwater horizontal—that is, the edge of a plane passing through the observer and normal to the vertical. Diagrams *A* and *C* show polarization appearing when the line of sight is raised upward toward the zenith; *B* and *D* show polarization planes seen when it is depressed downward to the nadir. In looking upward, when the critical angle (about 42° elevation) is reached, the sky and its polarization are seen, as they are at all greater elevations. The areas showing sky polarization as seen underwater are unshaded; those where the polarization is produced by sunlight in the water itself are gray. The numbers labeling angles between the critical angle and the zenith are altitudes in the sky measured from the water-level horizon (0° inside the semicircles). These are distorted by refraction, as the plot shows. In all cases the polarization planes are represented by vectors whose angular relationship to the azimuthal radius that they intersect is the same as that between the *e* vector of the polarized light and the vertical at the point plotted. The pattern of light polarization in the observer's other visual hemisphere would be a mirror image of that in the hemisphere diagramed. Intensities of polarization are not represented in this figure but vary markedly as described in the text.

1) One of the components originated in the blue sky and was readily visible at depths of 5 to 6 m or less. As is well known, the surface of the sea acts as a wide-angle lens which provides about a 180° aerial field of view to an underwater observer. The whole water-level horizon and the celestial hemisphere are seen restricted within a circular area subtending an angle of just over 96° centered around the vertical. Within this area, determined by the angle of total reflection, any atmospheric polarization was readily detected and found to be the same as when observed in air except, of course, that apparent elevation was distorted by refraction and surface roughness.

For this reason then the pattern of polarization reaching any submarine point (at least within a few meters of the surface and from directions included by a 96° to 97° angle symmetrical around the zenith point) will be determined by factors the same as those influencing the sky's polarization. These primarily are relative position of the sun and amount of overcast but secondarily include distance of the point observed from the zenith, the earth's albedo, amount of atmospheric dust, multiple scattering and depolarization owing to anisotropy of air molecules (*2, 11*). In addition, these rays may be modified by scattering and absorption at the surface and by the water itself. However, in the present measurements, none of the numerous secondary factors had sufficient effect to be noted.

In the few observations made at 15 m, neither the sky nor its polarization was visible in the turbid water concerned.

2) The other major component of polarized submarine light, under the conditions stated, was found to arise outside of the angle of total reflection and to originate from the water itself. In depths of 5 to 6 m, this underwater polarization could be observed in all directions not included within the critical angle and a small transition region immediately outside this where some elliptical polarization appeared to be present. At 15 m this component of the polarization was seen in all directions.

This strictly aquatic polarized light was found in turbid shallow water containing much suspended matter and in the far clearer oceanic water, where the absorption coefficient would be intermediate between that of the clearest known sea water and that typical of western North Atlantic continental slope regions (*12*). In these highly transparent waters the degree of polarization was found to be considerably greater than in the shore areas under the same conditions of illumination. With the sun close to the zenith at the deep-water oceanic station, the water's polarization in a horizontal direction was even appreciably greater than the polarization of the sky near the horizon in the same azimuth (*13*). The blue of the oceanic water, however, appeared far more luminous and brilliant than that of the sky, so that quantitative comparison was not feasible by the visual method described.

Besides being influenced by the clarity of the sea water, the intensity of submarine polarization was found to be affected by the position of the sun relative to the line of sight. When the sun was close to the zenith maximum polarization was found in the water observed horizontally. Depressing the direction of vision downward toward the antisun decreased the amount of polarization to zero at the latter point which lay within the observer's underwater shadow directly below. Raising the line of sight toward the angle of total reflection also decreased the polarization to a fraction of the total light.

When, on the other hand, the sun was close to the horizon at sunrise or sunset, the distribution of polarized light intensities was quite different. Maximum polarization then was found directly downward and along an arc outside the critical angle and at all points 90° from the bearing of the sun. Minimum polarization with level lines of sight occurred in the sun's azimuth and also toward the antisolar point. Therefore in sweeping the direction of view around horizontally, the percentage of polarization varied continuously passing through minima in the bearings mentioned and maxima at azimuths 90° from the sun.

In addition to its intensity and its degree of polarization, the plane of the light's polarization was discovered also to vary systematically with the relative position of the sun and the point observed underwater. When the sun was near the zenith, the electric vector of the polarized light was horizontal and the same at all azimuths.

At sunset, on the other hand, the plane of polarization in the sun's azimuth was horizontal. As the direction of view made an increasingly large angle with the sun's azimuth the plane of polarization tilted more and more toward the west. When it was observed 90° from the sun this tilt was about 45°. Turning still farther from the sun, the westward tilt decreased to zero 180° from the sun's bearing. At sunrise a similar pattern of polarization was found, except that the slant of the polarization plane was toward the east. At either sunrise or sunset, when the observer looked directly down in the water, the magnetic vector of the polarization coincided with the great circle through the sun, the point observed and the antisolar point.

On the basis of the data reported, it seems obvious that the polarization of light underwater is primarily determined, as one might expect (*8*), by factors similar to those that determine the underlying pattern of sky polarization (*14, 15*).

In this case the degree of polarization, assuming it all to be due to isotropic molecular scattering, is given by the relationship, $P = \frac{\sin^2 \theta}{1 + \cos^2 \theta}$, where P is the fraction of total light polarized and θ is the angle between the sun's direction and the line of sight. Obviously P varies from 0, when $\theta = 0°$, to 1, when $\theta = 90°$. Similarly, the e vector of the scattered light is at all points normal to the direction of the impinging light rays.

Note, however, that superimposed on these fundamental similarities to sky polarization the pattern of polarized light in natural waters will show an important difference—namely, as long as the light originates out of the water, the direction of the primary rays, which are to be scattered, will be altered by refraction. The resultant amount of deflection varies with the angle of incidence. Thus with a flat calm the refractive effect at the sea surface is nil for vertical incidence. It is maximum near sunrise and sunset when the angle of incidence is 90° and, according to Snell's law, the angle of refraction is only 48°20′ (estimated at Bermuda salinities and temperatures).

There are a number of specific observations, in addition to the general facts already presented, which give further support to the scattering theory for the origin of the primary pattern of polarized submarine illumination. Most instructive was the examination of polarized light distribution in caves and under deep overhanging ledges, Here it was possible to compare the plane of polarization in water that was illuminated by direct sunlight and water that was illuminated by an aperture lighted generally by sky and clouds but not directly by the sun. In suitably chosen areas, it could be demonstrated dramatically that the direction of the penetrating illumination was the main determinant of the plane of underwater light polarization.

Thus, in one particular case, this was shown directly by my swimming a few feet from open water into water overhung by a large rock ledge. In the open sunlit water the plane of polarization, as seen looking north and horizontally, was tilted about 35° toward the west. This tilt corresponded with the angle of refraction of the sun's rays and the direction of view. In the shaded water, where the rock overhead cut out all illumination except from the eastern third to half of the sky, there was a tilting of the *e* vector toward the east by 30° while the line of sight was still level and to the north. Therefore, the plane of polarization differed by 65° in these differently illuminated areas, although the sun's position and the line of sight were the same. This is a crucial observation in support of the scattering hypothesis.

Somewhat similar effects have been seen underwater on several instances when heavy overcast of limited extent obscured the direct rays of the sun. For example, on one occasion in moderately clear water, the following was observed in a horizontal direction 90° from the sun's azimuth. The sun was close to the horizon, and the plane of submarine polarization was tilted west by about 40°. While this was being observed a dense cloud drifted in front of the sun, although most of the rest of the sky was clear. At this time the tilting of the *e* vector became less pronounced by 10° to 15°. A return to the initial condition, when the sun again came out from behind the cloud, provided a good control.

Clearly the alteration in net direction of the total incident illumination produced a concomitant shift in the polarization. This is also supported by observations under a thick general overcast when the plane of submarine polarization was found to be horizontal in all azimuths. When the cloud cover was thin or incomplete, the obliquity of the polarization plane depended on the position of the sun and the contribution of its direct rays to the over-all underwater illumination.

Finally, some more quantitative measurements of the actual orientation of the polarization plane in the water under different specific conditions should be mentioned. At sunset the deviation of the polarization from horizontal was 48° toward the west, 90° from the sun. This is well within the observational error of the theoretical value obtained with the foregoing assumptions. Similarly, when the sun's zenith distance was 35°, the measured displacement of the interference pattern was 28°, while the predicted value on the basis of simple refraction would be 25°, again within the experimental error.

The observations described in foregoing paragraphs demonstrate that submarine illumination, at least at the depths observed, is highly polarized in patterns primarily related to the directional incident light from the sun and sky. Several additional points of interest arise from these findings. These relate, on the one hand, to problems in physical oceanography and, on the other, to the biological implications of the data.

At first glance one of the most surprising aspects of the pattern of submarine illumination is the lack of evidence that surface reflection plays any primary part in it. On the basis of simple refraction and reflection at the air-water interface, one would expect strong vertically polarized components, particularly when the sunlight is incident at Brewster's angle (53°15′ at Bermuda salinities and temperatures).

Vertical polarization has, in fact, never been observed underwater. The only possible part of the polarization pattern that does not seem directly related in its origin to scattering of the incident light occurred, as mentioned earlier, in an annular area near the angle of complete reflection. Here the interference pattern gave evidence of elliptical polarization of the light. This may have been related to polarization by refraction and reflection at the surface.

The absence of a marked effect of the water surface on the submarine polarization may be the result of the complex nature of the reflection, refraction, and scattering that occur there. In the first place, the surface is not usually smooth, so that simple Brewsterian reflection may not be prominent. This kind of rough surface effect may be observed in model form by comparing the polarization of reflected light by a smooth glass surface and by a scattering-reflecting surface such as the cloth binding of a book. In the former case, as in a flat calm at sea, light reflected is highly polarized horizontally and follows Fresnel's formulas. In the case of the scattering surface the polarization plane may be tilted far from the horizontal and toward the source in highly directional illumination if this is not normal to the surface in the line of sight.

Furthermore, the light reflected from the sea surface is partly polarized by the blue sky which it reflects (*7, 16*). Thus the surface polarization of the total reflected light and, hence, that of the penetrating light will have at least three major sources whose relative importance will vary under different conditions and angles of incidence. The present observation that the surface polarization ordinarily has a small effect on the over-all submarine polarized light is consistent with the more general finding that surface scattering and reflection, except at high angles of incidence, have negligible effects on light penetration as a whole (*8*, *17*).

If these surface phenomena, or any other sources of polarized light than Rayleigh scattering, are significantly involved in the polarization of underwater illumination, they should be revealed by a more detailed study of the pattern of polarized light. Interaction between light rays polarized in different planes would produce idiosyncrasies in the pattern analogous to the neutral points and lines in the blue sky (*18*). As mentioned earlier, such have not yet been observed underwater with the present technique.

Another matter of considerable interest is the question of how penetration into deep layers affects the polarization of submarine light. If, as the present data indicate, polarized light underwater originates mainly by Rayleigh scattering of beams of penetrating light, one would expect polarization to occur as deep as significant directionality is present. Although scattering tends to decrease directionality, most of the scattered light in sea water is directed forward (*19*). Photographic measurements at 400 m in very clear water demonstrated that the ratio of total horizontal to vertical illumination was still 60 percent (*20*). It seems clear then that directionality of illumination is maintained to great depths, in terms of the total distance of submarine penetration of light. On this basis one would predict the presence of polarization produced by Rayleigh scattering at all depths where significant light from the surface is present.

From the known data on the directionality of light penetration in general, one would also predict that the polarization pattern would become simpler and increasingly stable in time in deep water. These differences from the polarized light patterns near the surface would arise from the antagonistic interaction of scattering and absorption which eventually should produce an equilibrium pattern of illumination centering around the vertical (*21*).

Actual observations have shown that, while directionality is maintained, average obliquity is reduced and the angular spread of the radiation is broadened with depth (*22*). Thus at some depth characteristic for the optical properties of the water column concerned, the directional pattern will center about the zenith and be independent of the sun's altitude. In the clearest water this equilibrium point, which is reached gradually, has been estimated by Jerlov (*22*) to occur at about 300 m. In less transparent water it would occur nearer the surface. One would expect, therefore, that as depth increases, the light polarization pattern would become, at all times when there was adequate illumination, increasingly like the pattern in the upper layers, when the sun is in the zenith, or even more like that with a completely overcast sky.

The physical optic problem of the precise origin of submarine polarization by scattering is also an interesting matter that needs further study. If the scattering is molecular, then the polarization and the brilliant blue color of very clear oceanic waters are linked together as they are in the sky (*9*, *23*). Upward scattering of daylight in highly transparent oceanic water has been found to have a maximum at 425 mμ (*22*). This is the value one would predict on the basis of molecular scattering by the water. On the other hand, the color of clear ocean water corresponds with the wavelength of greatest transparency, 467 mμ (*22*), and at least in inshore waters the scattering is predominantly the effect of transparent mineral particles (*19*). Perhaps the present findings on submarine light polarization may stimulate further work in this interesting and still somewhat controversial field (*7*, *8*, *24*).

Another area where further research is required relates to the whole question of the biological effects of a complex pattern of polarization such as actually occurs in natural waters. Not only is the region within the critical angle affected by sky polarization, but the water itself has a complicated pattern dependent on the obliquity of incident light. This pattern is omnipresent during the day in surface waters, and, as outlined in foregoing paragraphs, at least the part originating from scattering in the water itself probably extends with modifications into the lowest layers of the photic zone.

Since bathypelagic animals are orienting to light and undertaking extensive diurnal vertical migrations down to 600 to 800 m (*25*), the possibility that light polarization may be involved in cuing such activity should not be overlooked. Above the level of the equilibrium directional distribution of light the movement of the sun through the sky and changes in sky overcast would be reflected by characteristic changes in the polarization pattern. At the present time we know that the polarization patterns are there. We also know that polarized light sensitivity and corresponding behavior patterns also occur widely in one phylum at least. To what extent the natural behavior of such animals may be modulated or initiated by these factors is still largely unknown.

To answer this question, more must be known about the physiology of polarized light sensitivity and arthropod vision in general (*26*). Further data on polarized light behavior patterns must be gathered, and their relationship to the distribution and migrations of planktonic animals determined. When such biological knowledge is correlated in detail with the physical optical facts, we may then look forward to an understanding of the importance of polarization patterns in submarine illumination. Meanwhile, the prospect of such correlation and evaluation should act as a stimulus to workers in the many pertinent fields of science.

This report may be briefly summarized as follows. Polarization patterns of submarine illumination in the upper layers of the sea near Bermuda have been observed by means of a sensitive detector and analyzer, which produces an oriented interference figure when traversed by linearly polarized light. Underwater polarization was found to consist of two primary components, one directly transmitted through the surface from the blue sky, the other originating in the water itself and being nearly everywhere oriented at right angles to the direction of penetrating light. As a result of their ultimate dependence on the sun's position, both of these components were found to undergo marked changes during the course of the day. The polarization arising within the water would seem to be largely accountable on the basis of Rayleigh scattering of light in the water. If this is so, the deep water pattern of polarization would most likely be similar to that near the surface on a heavily overcast day. Since a number of aquatic animals are known to be visually sensitive to polarized light, the possible relationship of the patterns described to the orientation and migration of zooplankton offers a promising area for future research.

References and Notes

* Contribution No. 213.

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News and Notes

Advances in Calorimetry

Approximately 130 scientists representing more than 80 government, academic, and industrial laboratories in the United States, Canada, and Europe attended the 9th annual Calorimetry Conference, held at the General Electric Research Laboratory, Schenectady, N.Y., 17–18 Sept. The meeting included four sessions with a total of 36 papers delivered by leading calorimetrists from various branches of science. The final session consisted of informal discussions on new products and techniques in calorimetry in which the entire memberhip participated.

The conference program was arranged by the writer under the chairmanship of E. J. Prosen (National Bureau of Standards). Vincent J. Schaefer, director of research for the Munitalp Foundation, spoke on "Jet stream, thunderstorms and project sky-fire" before the conference dinner. David Turnbull (G.E. Research Laboratory), delivered the welcoming address and reviewed the several regions of calorimetric research in which G.E. is actively interested. Guy Waddington (Bureau of Mines, Bartlesville) delivered the first of a series of lectures that will hereafter be given annually and will be known as the Hugh M. Huffman memorial lectures in honor of the late Dr. Huffman, organizer and first chairman of the conference. Dr. Huffman's work, his contributions, and their significance to the field of thermochemistry were summarized. Some of this work has formed the "basis of master tables" of thermodynamic properties. Other features of the lecture referred to technical advances in thermochemistry, such as the "rotating bomb," and to the problems and accomplishments in the thermochemistry of compounds containing sulfur, halogens, and fluorocarbons.

The latest developments and modifications in high-precision bomb calorimetry were reported in a series of three papers that were a part of the first session. A. K. Meetham (National Physical Laboratory, England) described N. P. L. No. 1 bomb calorimeter. Some of the special features reported were (i) a simple method of ignition, (ii) complete sealing of the calorimeter, and (iii) a numerical method of correction for heat transfer. The second rotating bomb calo-