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Experimental Black-and-White Film for Underwater Photography*

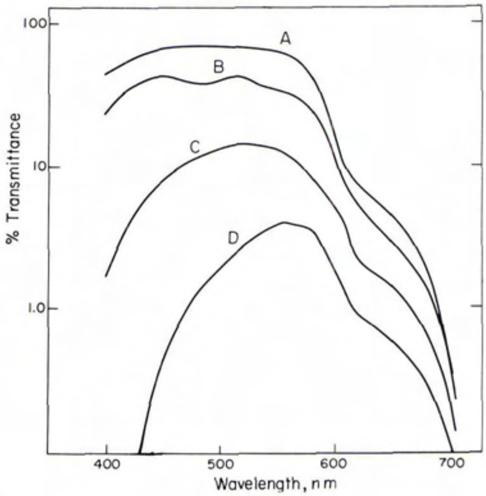

Fig. 1. Spectral transmittance for 10 meters of various water types: A, Distilled (Hulburt); *B,* Ocean (Clarke and James); *C,* Coastal (Hulburt); *D,* Bay (Hulburt).

The applications of such a film could vary from aerial mapping of underwater areas and coastal regions to recording and documenting underwater exploration or other oceanographic needs.

(Abstract on next page)

Introduction

Oceanographers have long needed a black-and-white film specifically designed for their rather specialized photographic requirements. Terms like *detectivity, image discrimination*, and *maximum information-recording capability* take on somewhat new and certainly significant meanings if the photographic system or target moves under water. In order to best meet the photographic film requirements of oceanographers, various system parameters need to be considered.

Photography at various depths under water or at long distances through the water causes a rather severe attenuation of the image contrast owing to the turbidity or light-scattering property of water. Light is also selectively attenuated as it passes through water, which reduces the penetration capability. The magnitude of these effects depends on the spectral reflectance of the target, the type of water (ocean, coastal, or bay), the turbidity, and the object distance. These various parameters have been examined and have helped shape the design of an experimental film to maximize water penetration and increase underwater detectivity.

The spectral quality of various underwater objects which are, or may become, targets can range across the entire spectrum. For this reason, this parameter could not effectively be used in a laboratory environment to predict a final system photographic response or in optimizing an experimental film. The main factors that were considered in this investigation are the various characteristics of water, namely, its scattering qualities and spectral transmission. Fortunately, considerable research already exists in this area and has been reported by the various experimenters.

A description of an experimental film, based on the characteristics of water, and a discussion of both the laboratory image-quality tests and the practical photographic tests are the subject of this paper.

Characteristics of Water

Considerable research has been conducted and reported on spectral transmittance of

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water. Hulburt in 1945[1] published curves for distilled water, coastal water, and bay water (Figure 1). As shown by Clarke and James,[2] the transmittance of ocean water is not greatly different from that of distilled water. These data are shown plotted as both percentage transmittance and density, as did Specht, Needler, and Fritz,[3] to provide the data in more useful form for photographic purposes. It is evident that maximum transmission through bay water occurs at about 550 nm or below, whereas the peak for clear ocean water, distilled water, and even coastal water occurs at a wavelength nearer to 500 nm. The shift of bay water towards longer wavelengths is primarily a result of yellow organic matter and various particulate matter. It is also worth noting that the bay water's overall transmittance has dropped; this is also probably due to more particulate matter.

Not only is the spectral transmittance of water important, but also the spectral irradiance of daylight penetrating the water to various depths. Downwelling irradiance, then, provides a method of estimating the type of light reaching underwater targets.

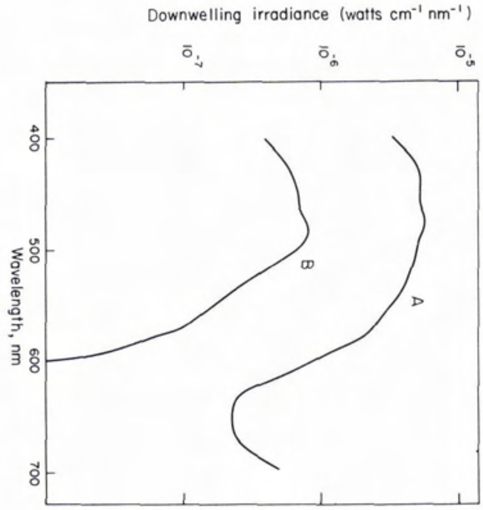

FIG. 2. Spectral irradiance measured in Ben Franklin experiment: A, submersible 10 meters deep; B, submersible 45 meters deep.

ABSTRACT: *Experience has shown that films for detecting underwater objects should possess high gamma and should be sensitized to coincide with the transmission window of water which occurs (for both fresh and sea water) in the region of 500 nm. This paper describes an experimental black-and-white material designed to meet these requirements. Sensitometric data, as well as granularity and transfer-function values, are compared with those of general-purpose films. The laboratory data show that the detectivity of the experimental film should be superior to that of the control films. Practical tests, both from an airplane and underwater, confirm the laboratory findings. Exposure and detectability differences between the experiment and the check films were noted during the practical tests. These differences are correlated with the measured parameters of sensitometry and image quality.*

A study of downwelling spectral irradiance, made by Ross, of Philco-Ford, using the Ben Franklin submersible,[4] is shown in Figure 2. In this experiment, a spectroradiometer was aimed upward through varying depths of Gulf Stream water and measured the downwelling spectral irradiance. It is clear from Figure 2 that, as the depth increases, red light is severely attenuated and blue-green becomes dominant.

From these data concerning the characteristics of water, it can be concluded that the maximum spectral transmittance of water occurs at near 500 nm or in the blue-green region of the spectrum. Therefore, light reaching any underwater scene is largely blue-green in nature corresponding to the transmission window.

DESIGN OF EXPERIMENTAL FILM

Two crucial improvements are embodied in this film: improved spectral sensitization and higher-than-normal contrast. Figure 3 shows the spectral sensitivity of some panchromatic films compared to the spectral distribution of the downwelling irradiance through 45 meters of water. It is plain that the drop in sensitivity at 500 nm comes at exactly the wrong place for maximum efficiency in water-penetration applications. The response of the film in the red spectral region is largely superfluous and may even be detrimental because any scattered red light that reaches the film will be recorded. Accordingly, a sensitizer was chosen that provided relatively uniform sensitivity across the blue-green region of the spectrum and cut off at about 530 nm. Helgeson and Ross[5] have previously suggested eliminating the red sensitivity to improve water penetration. The spectral sensitivity of the experimental film is shown in Figure 4, also plotted versus the downwelling irradiance.

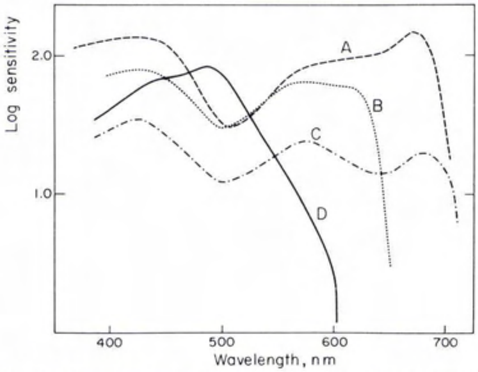

FIG. 3. Spectral sensitivities of: *A*, KODAK TRI-X AEROGRAPHIC FILM 2403 (ESTAR base); *B*, Kodak TRI-X pan film; *C*, KODAK PLUS-X AEROGRAPHIC film 2402 (ESTAR base), compared to downwelling irradiance.

Because light scattering reduces image contrast, an improved emulsion was designed which produces a higher contrast than is normally associated with films in this speed range. The sensitometric curve characteristic of this film is shown in Figure 5. The gamma of the film ranges between 4.5 and 5.0. Some exposure latitude is sacrificed, however, to gain this feature. Both the blue-green sensitivity and the high contrast of the experimental film agree with the conclusions about film characteristics reached by L. Mertens,[6] of RCA, in his book "In-Water Photography—Theory and Practice."

LABORATORY EXPERIMENTS

Throughout the laboratory experiments and the practical tests, the following development conditions were used: (a) KODAK TRI-X Pan Film, developed for 8 minutes in KODAK Developer D-76 at 68°F, and a processing rate of 5 ft. per min. in a KODAK VERSAMAT Film Processor at 85°F using KODAK VERSAMAT Liquid Developer, Type C; (b) KODAK PLUS-X AEROGRAPHIC Film 2402 (ESTAR Base), developed for 8 min. in KODAK Developer D-19 at 68°F; (c) KODAK TRI-X AEROGRAPHIC Film 2403 (ESTAR Base), developed for 8 min. in KODAK Developer D-19 at 68°F; (d) experimental film developed for 5 min. in KODAK Developer D-19 at 68°F.

A basic sensitometric comparison using daylight exposures (Figure 6) showed the experimental film to be nearly nine times slower than the KODAK TRI-X Pan Film control. Such a speed loss with daylight-quality light is expected, based on the spectral sensitivity curves. The experimental film is inherently slower and does not record any of the red information. In very shallow water, where there is less attenuation of red light, the standard panchromatic films will have a higher effective film speed. As the depth of water or the horizontal film–target distance increases, the red light becomes more rapidly attenuated and the effective speed of the panchromatic films drops. Under these same conditions, the experimental film's effective speed will change less. A KODAK WRATTEN Filter, No. 44A, was using to simulate the transmission of deep water (100 meters of pure water according to Mertens[7]). Figure 7 shows that the sensitometric effect of such an exposure was to form a tighter speed grouping of the films compared to a daylight expos-

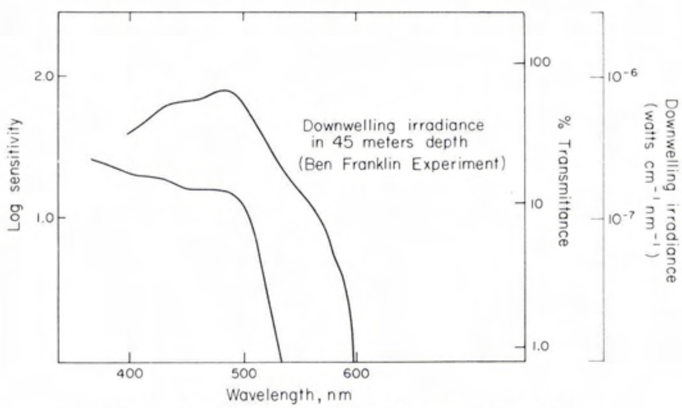

FIG. 4. Spectral sensitivity of experimental film compared to downwelling irradiance.

ure. Under these conditions, the experimental film is only five times slower than the TRI-X Film.

As mentioned before, high-contrast film has the disadvantages of a shortened exposure latitude. This can be seen by examining the sensitometric curves of Figures 6 and 7. Under the conditions of this experiment, the disadvantage of smaller exposure latitude may be offset by more nearly constant effective speed at different water depths and underwater distances.

Standard image-quality measurements (Table 1) have shown the experimental film to have equal or lower granularity and higher resolving power than the control films. The modulation-transfer-function data show the experimental film to be equal to or better than the aerial control films but somewhat worse than TRI-X Pan Film.

A method of measuring the detectivity or threshold discrimination of these films was desired. Marchant[8] and Altman[9] have indicated that in detecting faint stars against a light sky background (a problem not dissimi-

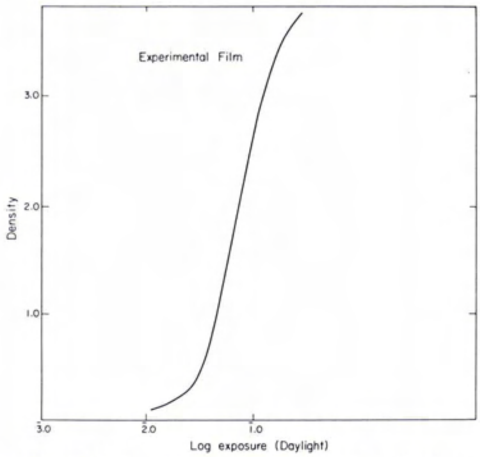

FIG. 5. *D-Log E* curve of experimental film.

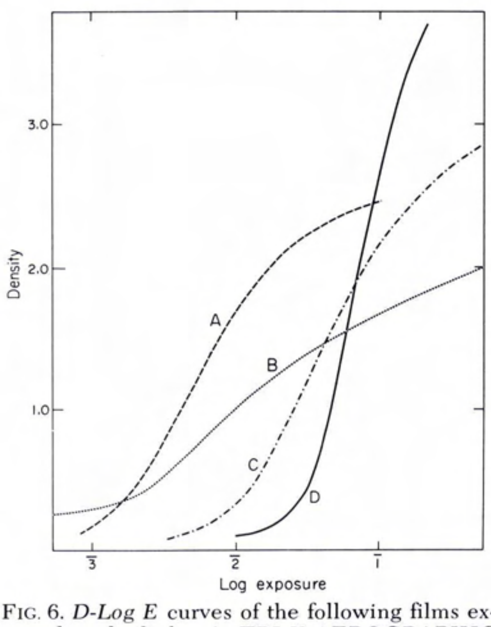

FIG. 6. *D-Log E* curves of the following films exposed to daylight: *A*, TRI-X AEROGRAPHIC FILM 2403 (ESTAR base); *B*, KODAK TRI-X Pan film; *C*, PLUS-X AEROGRAPHIC film 2402 (ESTAR base); *D*, experimental film.

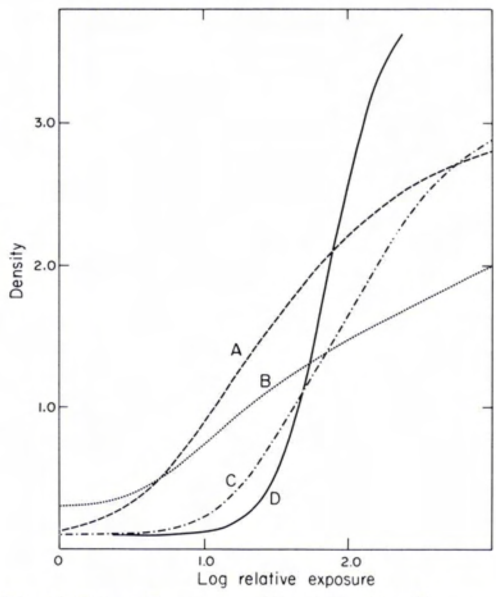

FIG. 7. *D-Log E* curves of the following films exposed to tungsten and a WRATTEN filter, No. 44A: *A*, KODAK TRI-X AEROGRAPHIC film 2403 (ESTAR base), *B*, KODAK TRI-X Pan film; *C*, KODAK PLUS-X AEROGRAPHIC film 2402 (ESTAR base); *D*, experimental film.

TABLE 1. GRANULARITY AND RESOLUTION

Film	RMS Granularity	Resolving Power (1000:1 TOC)	Modulation 10 c/mm	Transfer 50 c/mm	Function 100 c/mm
Experimental	16	178	80%	49%	24%
PLUS-X AEROGRAPHIC	23	112	80%	42%	19%
TRI-X AEROGRAPHIC	40	80	73%	26%	12%
TRI-X Pan	16	141	104%	53%	33%

lar to recording low-contrast objects in a luminous body of water), the ratio of the gradient of the film to its granularity, where both are measured at the same density, is a useful measurement. Shepp and Kemmerer have derived a similar relationship for use in evaluating low-gamma processing. Granularity was measured for several densities on each film with a microdensitomater using 48-μ circular aperture. The value of the gradient (that is, $\Delta D/\Delta$ *log E)* can be obtained from the density traces and the sensitometry. This value, if divided by σD, the measured granularity, and plotted against its appropriate density value (Figures 8-11), gives a measure of detectivity. As would be expected, the high contrast of the experimental film and its relatively low granularity combine to give a very high detectivity compared to the control films. TRI-X Pan Film has a medium detectivity, primarily because of its low granularity. The lowest detectivity of the four films is shown by the TRI-X AEROGRAPHIC Film, principally because of its high granularity. This detectivity measurement also proves to be a useful exposure predictor, as will be shown in the following section.

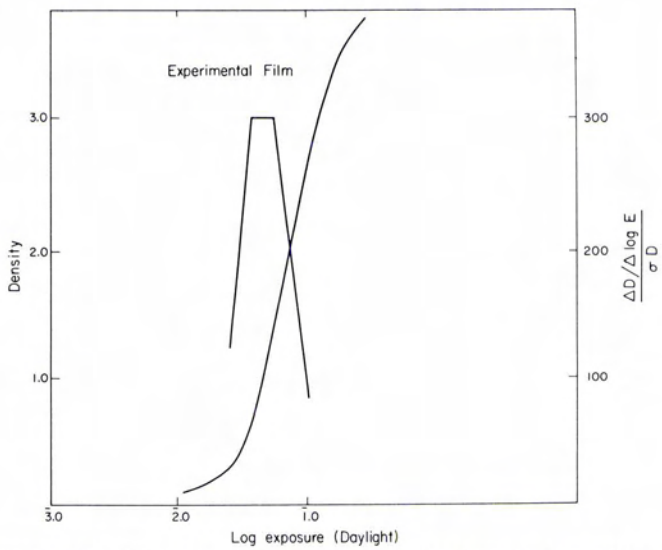

FIG. 8. *D-Log E* curve *vs.* detectivity curve for the experimental film.

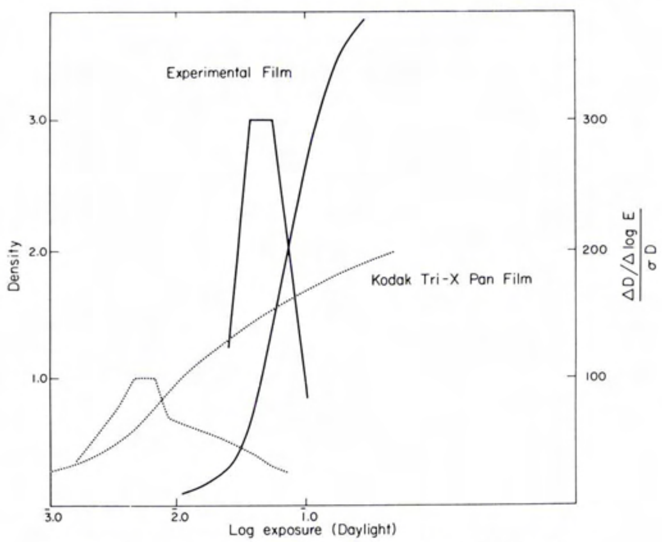

FIG. 9. *D-Log E* curve *vs.* detectivity curve for the experimental film and KODAK TRI-X Pan Film.

Practical Experiments

Practical aerial tests, designed to illustrate water penetration, were made using four matched HASSELBLAD cameras equipped with 80-mm ZEISS PLANAR lenses. An electrically operated control system provided simultaneous exposures in all cameras. The simultaneous exposures in all cameras. The tests were made at an altitude of 5,000 feet over an area northwest of Martha's Vineyard off the coast of Massachusetts. This area had depths varying from a few feet to about 30 feet. An exposure series was made over each of several targets. In all instances, a KODAK WRATTEN Filter, No. 3, a haze filter, was used over the lens. The combination of the filter's transmittance with the film's spectral response provides a narrow bandpass corresponding to the downwelling irradiance through water (see Figure 12). Both the film/filter bandpass response and the downwelling irradiance fall within the

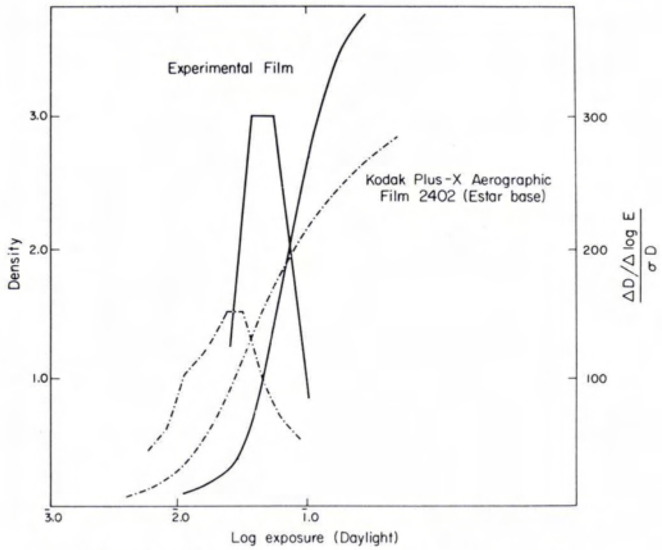

FIG. 11. *D-Log E* curve *vs.* detectivity curve for experimental film and KODAK TRI-X AEROGRAPHIC Film 2403 (ESTAR base).

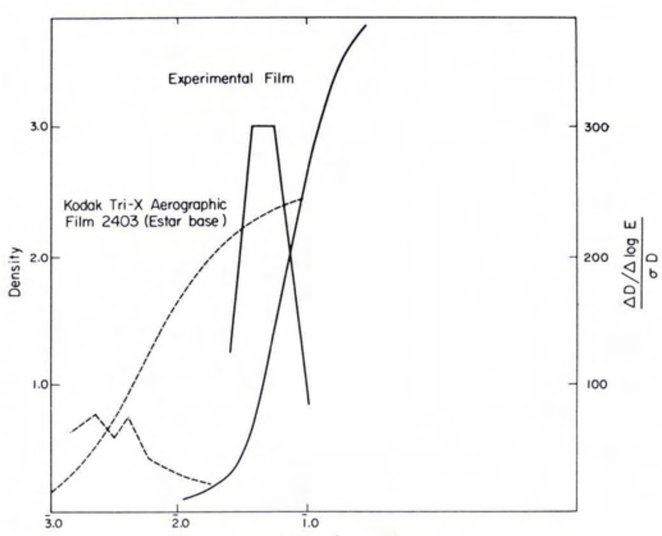

FIG. 10. *D-Log E* curve *vs.* detectivity curve for experimental film and KODAK PLUS-X AEROGRAPHIC Film 2402 (ESTAR base).

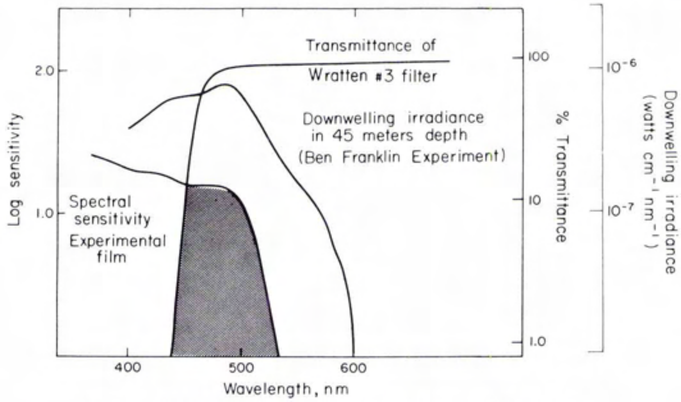

FIG. 12. Experimental film spectral sensitivity plus camera filter (WRATTEN No. 3) *vs.* downwelling irradaince through 45 meters of ocean water.

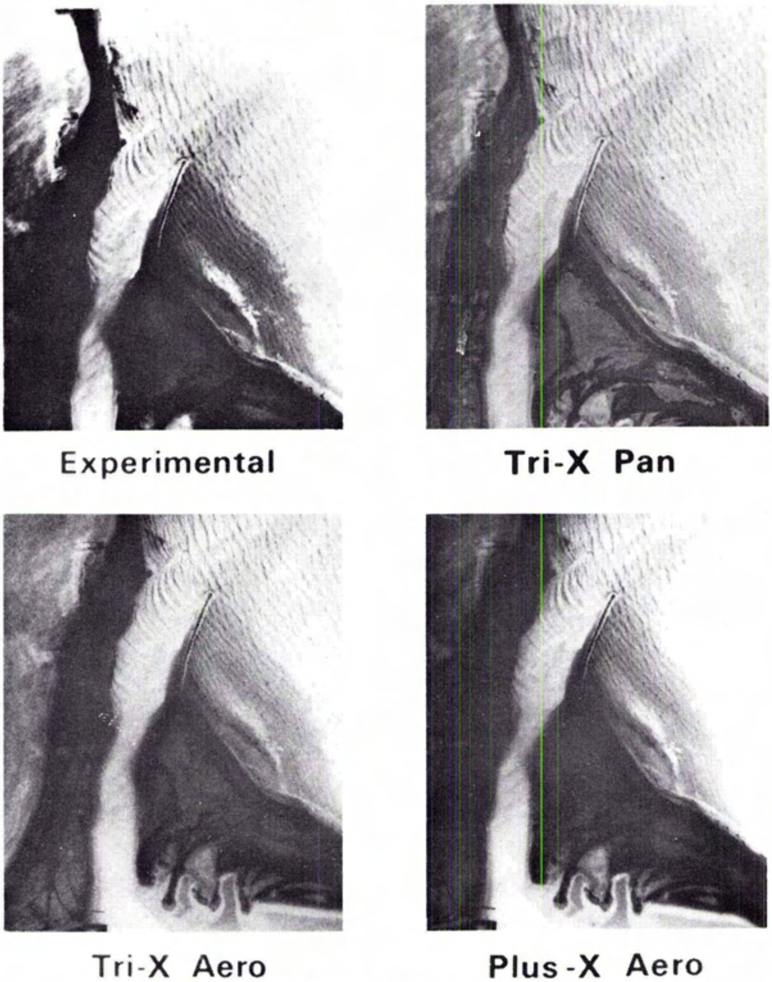

FIG. 13. Photographs of an area near Martha's Vineyard, Massachusetts, made with: *A*, experimental film; *B*, KODAK TRI-X Pan Film; *C*, KODAK PLUS-X AEROGRAPHIC Film 2402 (ESTAR BASE(: *D*, KODAK TRI-X AEROGRAPHIC Film 2403 (ESTAR base).

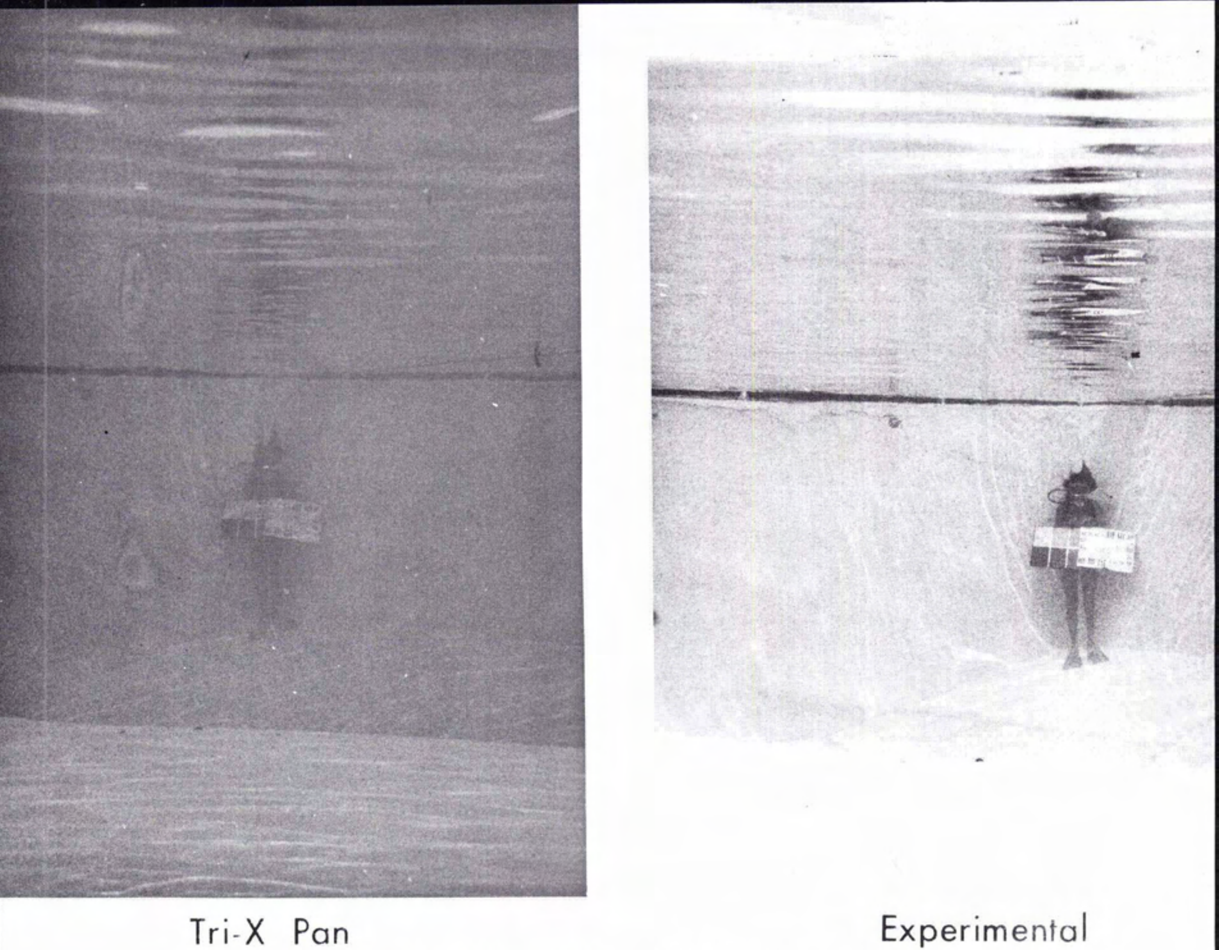

FIG. 14. Photograph made with experimental film compared to TRI-X Pan Film at 65 feet horizontal distance in a swimming pool.

slightly broader transmission window of water. In an examination of pictures exposed on the four films (Figure 13) the improved image contrast and enhanced underwater detail of the experimental film is evident. The pictures obtained were ranked in order of discrimination of underwater detail by visual examination at up to 30× magnification. This ranking coincided with the ranking obtained using the $(\Delta D/\Delta\ log\ E/\sigma D)$ measurement.

In examining the exposure series, we selected the optimum practical exposure for underwater detail in each instance. This means the section of land shown in each frame is overexposed. The minimum density of the water areas (deep water in this case since it is a negative process) was found to correspond to the density obtained at or very near the peak of the $(\Delta D/\Delta\ log\ E/\sigma D)$ plot. The more-shallow areas or objects, which reflect more light, appear darker and, therefore, lie further up the sensitometric curve. The $(\Delta D/\Delta\ log\ E/\sigma D)$ measurement, then, also provides a criterion for selecting exposure levels.

Underwater exposures were made with matched sets of NIKONOS cameras in a swimming pool at various distances from a resolution chart. Figure 14 shows a picture on TRI-X Pan Film compared to the experimental film at a distance of 65 feet. These tests show clearly the increased detectivity of the experimental film. Practical underwater tests off Andros Island, in the Caribbean, by Mertens have also verified the superior qualities of the experimental film over other Kodak films included in the test.

CONCLUSIONS

The superior water penetration and underwater detectivity of an experimental black-and-white film have been demonstrated with both laboratory experiments, including image-quality tests, and practical experiments. A method of graphically depicting the detectivity of the film experiment was described and related to practical exposure situations.

The applications of such a film could vary from aerial mapping of underwater areas and coastal regions to recording and documenting underwater exploration or other oceanographic needs. Whatever the applications might be, more extensive evaluations would be required, preferably in the actual environment and in the intended system. It should be mentioned that this paper in no way commits the Eastman Kodak Company to manufacture or sale of the black-and-white experimental film described.

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