# U. S. NAVAL SUBMARINE MEDICAL CENTER

## Submarine Base, Groton, Conn.

REPORT NUMBER 551

# THE UNDERWATER VISIBILITY OF COLORS WITH ARTIFICIAL ILLUMINATION

by

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Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF12.524.004-9014D.01

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SUBMARINE MEDICAL RESEARCH LABORATORY

NAVAL SUBMARINE MEDICAL CENTER REPORT NO. 551

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# SUMMARY PAGE

## THE PROBLEM

To obtain data on the visibility of various colors in different bodies of water with artificial light sources, both mercury and incandescent, and to compare the results with previous data obtained under natural illumination conditions.

## FINDINGS

The results show the most visible colors depend upon both the type of water involved, i.e., clear or turbid, and the kind of illumination employed. However, color can be specified to maximize or minimize visibility for any combination of conditions. Also fluorescent paints are more visible than non-fluorescent of the same color for eight out of nine possible combinations of conditions.

## APPLICATION

The results are important for SCUBA* divers and operators of research submersibles who may have to work underwater, to search for items unintentionally lost at sea, or who may need to remain as invisible as possible or to camouflage items underwater.

*Self-Contained Underwater Breathing Apparatus.

## ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF12.524.004-9014D, Improvement of Vision and Orientation Underwater. The present report is No. 1 on that Work Unit. It was approved for publication on 15 October 1968 and designated as Submarine Medical Research Laboratory Report No. 551. Previous reports of work in this area have been published under superseded Work Units MF011.99-9002 and MF022.01.04-9005.

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# ABSTRACT

The visibility of various colors underwater, when viewed under artificial illumination, has been measured in three different bodies of water chosen to sample a continuum from clear to turbid. Subjects were SCUBA divers who observed the colors at night, using a mercury or an incandescent light source. The visibility results show numerous interactions among color, fluorescence, type of light source, and type of water; from them, it is possible to select the optimum combination to be used under a wide variety of conditions. Colors are specified that will (1) maximize visibility, (2) provide the best camouflage, and (3) allow distinct color differences in appearance for use in color coding. These results are summarized in terms of the colors that are most effective for use under various operational conditions encountered underwater.

# THE UNDERWATER VISIBILITY OF COLORS WITH ARTIFICIAL ILLUMINATION

## INTRODUCTION

Visibility underwater is a problem of immediate concern to SCUBA divers everywhere and it becomes of major importance to men operating in turbid water, at great depths, or at night. One obvious means of improving visibility or of camouflaging objects underwater is to paint them with specific colors. In a previous investigation,[1] the most and least visible colors underwater were determined for natural illumination conditions. In the present study, the work was extended to include the use of two sources of artificial illumination.

A major factor in determining which colors will be visible is the type of water itself. Distilled or exceptionally clear water has a maximum transmittance in the blue-green portion of the spectrum at 480 millimicrons (mμ) and absorbs to a greater extent wavelengths on both sides of this peak. Natural contaminants of water such as algae, plankton, and silt, have two effects on the transmission of light: (1) they lower the overall transmission level, and (2) they absorb short wavelengths to a much greater degree than long, thus shifting the transmittance peak to the longer end of the spectrum.[2]

The data in the previous investigation were consistent with this change in the spectral transmittance of water. In the Thames River, whose water is characterized by extreme turbidity, reds, oranges, and yellows were the easiest to see. There was a gradual shift in the most visible color toward the short end of the spectrum as the water became clearer. In the exceptionally clear water of Morrison Springs, Florida, blues and greens were outstanding. A comparison between fluorescent and non-fluorescent paints of the same color revealed the fluorescent to be superior under all conditions. The most visible non-fluorescent color for any body of water was white.

In the present investigation, the two underwater light sources used have very different spectral energy distributions. The incandescent source provides a continuous distribution of energy throughout the spectrum which increases dramatically in intensity as the wavelength is lengthened. The mercury source consists of discrete wavelengths or lines of energy; major lines are in the violet, yellow-green, and yellow portions of the spectrum. There are thus three parameters involved, all of which vary in spectral energy distribution: (1) the color itself including both regular and fluorescent paints; (2) the body of water—The Thames River, Long Island Sound, and the Caribbean Sea; and (3) the source of illumination, either incandescent or mercury.

## APPARATUS AND PROCEDURE

The targets were spherical floats, 8 inches in diameter, painted in various colors. The paints were selected from commercially available items and were representative of primary colors of good saturation or of the neutral colors, black, medium gray, and white. Both fluorescent and regular types of paint were included. Table I lists the paints and their specifications.

**Table I. Specifications of Paint Samples**

| Sample No | Color | Manufacturer or Fed Std No | | Luminance factor %T | CIE chromaticity coordinates x | y | z |
|---|---|---|---|---|---|---|---|
| FLUORESCENT | | | | | | | |
| 1 | Blue | Krylon | #3107 | 20.3 | .1591 | .1756 | 6653 |
| 3 | Green | " | #3106 | 60 4 | .2625 | .6005 | .1370 |
| 5 | Yellow-Green | " | #3104 | 111 2 | 4138 | .5472 | 0392 |
| 7 | Yellow-Orange | " | #3103 | 95.4 | 5558 | 4183 | 0258 |
| 9 | Orange | " | #3102 | 70.4 | 6065 | 3853 | 0082 |
| 11 | Red-Orange | " | #3101 | 49 2 | 6323 | 3364 | .0313 |
| NONFLUORESCENT | | | | | | | |
| 2 | Blue | Mil P-2852 | | 12.8 | .2199 | .2085 | 5715 |
| 4 | Green | 14110 | | 12.3 | .2755 | .5183 | 2063 |
| 6 | Yellow | 13538 | | 44.4 | 5052 | 4548 | .0401 |
| 8 | Orange | 12197 | | 16.6 | .6024 | .3535 | .0441 |
| 10 | Red | 11105 | | 9.0 | 6024 | .3047 | .092 |
| 12 | White | 37875 | | 81 5 | .3080 | .3188 | .373 |
| 13 | Gray | 26134 | | 13 6 | .3197 | 3325 | .347 |
| 14 | Black | 37038 | | 3 7 | .3058 | 3209 | 383 |

Paint samples were constructed for measurement; the spectral transmission curves for the regular paints were made on a GE spectrophotometer. Fluorescent paints were activated by Illuminant C and matched visually to the output of a MacAdam colorimeter. CIE (Commission Internationale de l'Eclairage) chromaticity values were calculated from the data and are plotted in Figure 1. Due to the conversion of short wavelength energy to longer wavelengths to which the eye is more sensitive, the fluorescent paints are naturally both brighter and more saturated.

The underwater light sources were both 1000-w lamps requiring an external source of power. The incandescent source was a tungsten bulb manufactured by Westinghouse and the mercury lamp and transformer, by Hydro Products.

The targets were lowered into the water on a pulley system. A triangular configuration was formed underwater with the colored target, the light source, and the subject occupying positions at the points. Distances along the sides of the triangle were adjusted for the specific underwater conditions encountered. The depths of the subject, target, and light source were the same, two meters from the surface. All data were collected at night to eliminate natural illumination from consideration.

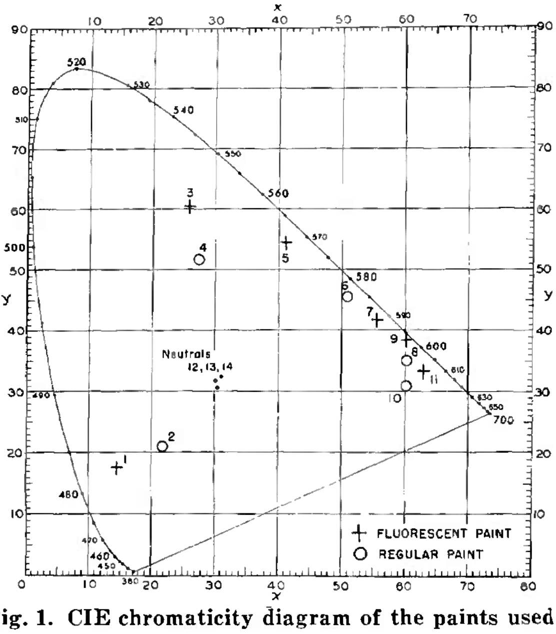

**Fig. 1. CIE chromaticity diagram of the paints used.**

The relative visibility of the colored targets was measured by color naming and the targets were presented one at a time. Subjects were asked to report what they saw, blue, green, yellow, orange, red, white, gray, black or nothing. The distance between the subject and the target was adjusted between the position at which he could see all of the targets clearly, and one at which none could be seen. This distance is referred to as the threshold or limit of visibility. Previous experience had shown that operationally this distance could be found by lowering the white target and having a diver move away from it until he could just barely see it.

Data were collected on five to ten divers and are reported in terms of the percentage of times each color was reported. This required two to three nights of work in each body of water. While the condition of the water varied somewhat from night to night, every effort was made to keep conditions constant through each run of the 14 colored targets. Targets were always presented in a random order and the order in which the light sources were used was counter-balanced.

## TYPES OF WATER INVESTIGATED

Data were collected in three bodies of water chosen to sample a continuum from clear to turbid. At one extreme was the Thames River near the Naval Submarine Base, Groton, Conn.; the water here is characterized by extreme turbidity, overall visibility of about two meters or less and a spectral transmission curve showing a peak in the long wavelengths. At the other extreme was the Caribbean Sea, beside a little-used pier at the U. S. Naval Base at Roosevelt Roads, Puerto Rico. Here the water was clear, blue-green wavelengths are transmitted maximally, and visibility was about ten meters.

Water samples were collected at each site and measured in a Beckman spectrophotometer. Alpha readings were also made in the Thames River and the Caribbean Sea using a Marine Advisers' alpha meter. Pertinent data on the various bodies of water are given in Table II.

The spectral transmittance of one meter of each body of water is shown in Fig. 2. The differences in spectral distributions depicted here for one meter become extreme when calculated for greater distances of water, since the relation between transmittance and distance is a power function. As Tyler[3] has emphatically demonstrated, one of the most efficient monochromators known to man is a long distance of water. Thus, if used in great enough quantity, only blue-green wavelengths will be transmitted by the Caribbean, yellow-green by the water of Long Island Sound, and red wavelengths by the Thames.

**Table II. Specifications of Various Bodies of Water**

| Body of water | Description | Transmittance of sunlight by 1 meter of water | $\alpha$ | Distances (meters) | |
|---|---|---|---|---|---|
| | | | | Lamps to targets | Targets to divers |
| Thames River near Submarine Base | murky polluted | 02- 05 | 3 5 | 4 | 2 |
| Long Island Sound in Fort Pond Bay | moderately turbid | 50 | | 4 | 4 5 |
| Caribbean Sea at Roosevelt Roads | clear | 67 | 3 | 6 | 10 |

Calculations of the effect of specific amounts of water, appropriate to the actual viewing conditions, were performed for the two light sources. An example is shown in Fig. 3 for the two extremes of water. This figure shows the chromaticity values for each light after passing through either ten meters of Caribbean water or two meters of the Thames River water. The light from the mercury lamp is changed very little by the Caribbean but appears decidedly yellow-green in the Thames. The tungsten light appears quite orange after passing through two meters of the Thames and desaturated yellow-green in the Caribbean.

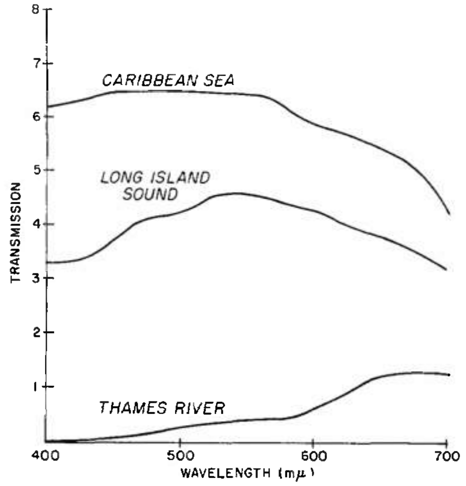

Fig. 2. **Spectral transmittance of 1 meter of each of the bodies of water.**

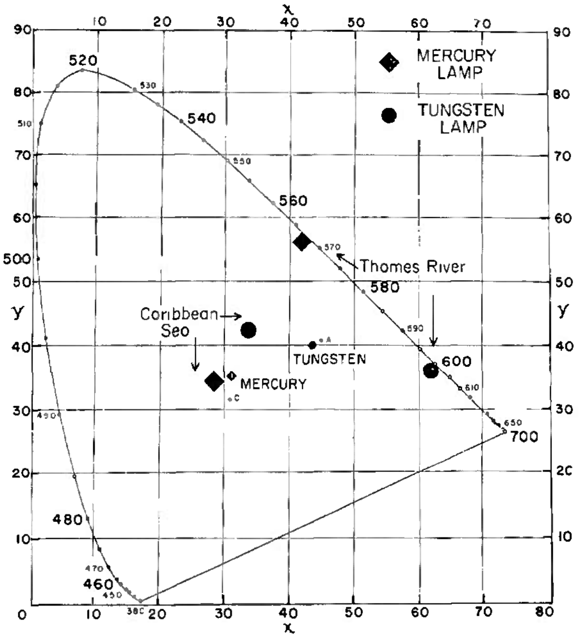

Fig. 3. **CIE chromaticity diagram showing the color appearance of the light from both sources after filtering by 2 meters of the Thames River and by 10 meters of the Caribbean Sea.**

## RESULTS

Figure 4 gives the results obtained with the incandescent source in the three bodies of water. The percent correct of the color names reported is shown as a function of the colors presented, the latter being arbitrarily spaced on the abscissa. In Long Island Sound and the Caribbean Sea, there is a sizeable difference in the effectiveness of the fluorescent paint over regular paint of the same color. This advantage is almost completely lost in the Thames River.

Among the fluorescent paints, yellows and oranges are visible no matter which body of

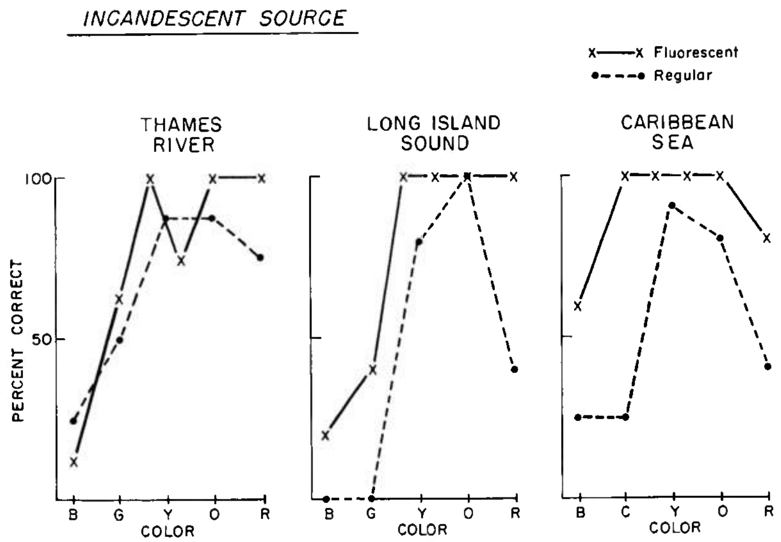

Fig. 4. The percent of each of the colors correctly identified by divers with the incandescent light source. (Fluorescent colors X———X; regular paint ● — — — ●)

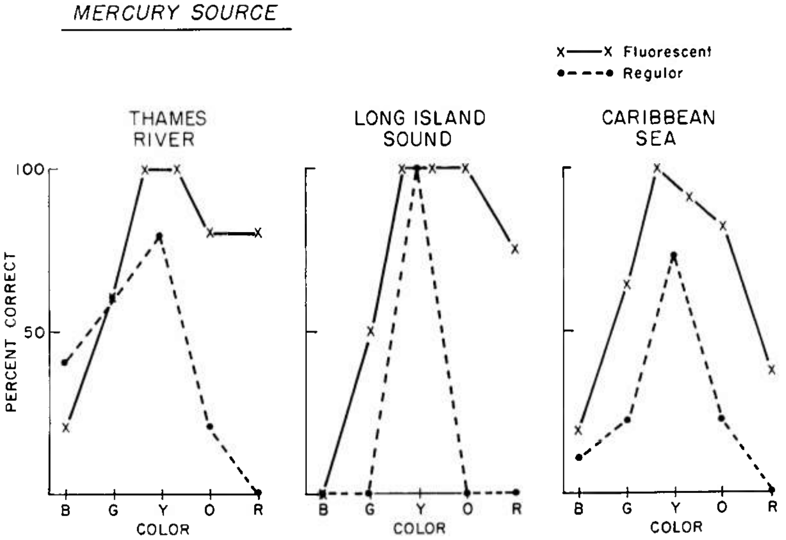

Fig. 5. The percent of each of the colors correctly identified by divers with the mercury light source. (Fluorescent colors X———X; regular paint ● — — — ●)

water is utilized; fluorescent blue and green are much more effective in the Caribbean than in other waters and fluorescent red less so. Among the regular paints, yellow and orange are best throughout with long wavelengths becoming less visible as the water gets clearer.

The results obtained with the mercury source are given in Fig. 5. When this light source is utilized, the fluorescent paints are vastly superior to the regular paints in every type of water. The visibility of fluorescent yellows and reds deteriorates in clearer water and fluorescent yellow-green is the most visible for any body of water. The major findings with the regular paint are similar for all waters: yellow is highly effective and orange and red are rarely seen.

The data on the neutral colors are given in Table III. White is very visible in both light sources and all types of water while gray and black are perceived only infrequently.

**Table III. Percent Seen of the Neutral Colors in Various Waters**

| Color | Thames River | Long Island Sound | Caribbean Sea |
|---|---|---|---|
| INCANDESCENT SOURCE | | | |
| White | 100 | 100 | 100 |
| Gray | - | - | 20 |
| Black | 12.5 | - | - |
| MERCURY SOURCE | | | |
| White | 80 | 75 | 100 |
| Gray | - | - | 11 |
| Black | - | - | - |

Data are also available in these measures on the color confusions made by the divers. Tables IV and V list the color names employed, in order of their frequency of occurrence. Only those names reported two or more times are included. Most confusions occur for white, yellow, and fluorescent yellow-green. Minor confusions are found between blue and green and between orange and red.

**Table IV. The Color Names Employed by Divers Using the Tungsten Lamp**

| Target Color in Air | Body of Water<br>Thames River | <br>Long Island Sound | <br>Caribbean Sea |
|---|---|---|---|
| FLUORESCENT | | | |
| Blue | - | - | blue |
| Green | green | - | blue-green |
| Yellow-green | yellow<br>white | yellow<br>white | white |
| Yellow-orange | orange | orange | orange |
| Orange | orange | orange | orange<br>red |
| Orange-red | orange<br>red | orange | orange |
| NONFLUORESCENT | | | |
| Blue | - | - | blue |
| Green | green | - | blue |
| Yellow | white<br>yellow | yellow<br>white | yellow<br>white |
| Orange | orange | orange | orange<br>red |
| Red | orange<br>red | red | red |
| White | white<br>orange | white<br>yellow | white<br>blue-green |
| Gray | - | - | - |
| Black | - | - | - |

**Table V. The Color Names Employed by Divers Using the Mercury Lamp**

| Target Color in Air | Body of Water<br>Thames River | <br>Long Island Sound | <br>Caribbean Sea |
|---|---|---|---|
| FLUORESCENT | | | |
| Blue | - | - | blue |
| Green | blue-green | green | green |
| Yellow-green | white | yellow | green<br>yellow<br>white |
| Yellow-orange | yellow-orange | orange | orange<br>yellow |
| Orange | orange | orange | orange<br>red |
| Red-orange | orange | red | red-orange |
| NONFLUORESCENT | | | |
| Blue | - | - | - |
| Green | green | - | green |
| Yellow | yellow<br>white | yellow<br>white | yellow<br>white |
| Orange | - | - | - |
| Red | - | - | - |
| White | white | white<br>yellow | white<br>green |
| Gray | - | - | - |
| Black | - | - | - |

## DISCUSSION

The data illustrate the complexities that occur with three spectrally-varying parameters. To be highly visible, the same wavelengths of energy must be present in the distribution of the light source, they must be reflected rather than absorbed by the target, and they must be transmitted by the body of water. To this is added the fact that for fluorescent paint to be activated, short wavelength, visible energy (blues and greens) must be present in the source and must be transmitted through the water to the fluorescent target.

The shift in the most visible colors from the long wavelengths toward the short wavelengths as the water becomes clearer, is generally a product of the change in spectral transmission characteristics of the water. The effect is sometimes not so marked with artificial lights as with natural illumination due to overriding characteristics of the sources. Thus, the distribution from the mercury lamp, since it is almost completely lacking in long wavelengths, never produces highly visible red colors, not even in the Thames River. Furthermore, it would take attenuation by clear water of considerable depth or distance to overcome the strong lines at 546 and 578 mμ in favor of the extremely weak one at 491 mμ to produce good visibility blues. While theoretically possible, the distances required usually mean there is no light left by which to see.

Similar statements can be made about the lack of short wavelengths and excess of long wavelengths in the tungsten source. Thus, yellow, orange, and red are effective with the tungsten source in all bodies of water while yellow and yellow-green are best wherever the mercury source is used. Within these somewhat restricted color ranges, however, there are decided shifts in the most visible colors depending upon the body of water utilized.

Inadequate activation of the fluorescent paints may be due to little short wavelength energy in the source or to the absorption of this energy by the water. When these two factors are combined, as with the use of an incandescent source in the Thames River, the result is that the activating wavelengths are completely lost and the fluorescent paint appears no different from regular paint. All other possible combinations of energy distribution and body of water did however produce superior visibility with the fluorescent paints. The particular effectiveness of the combination of the mercury source and fluorescent paint has two explanations: (1) there is sufficient short wavelength energy in the mercury source to activate the fluorescent oranges, and (2) there is very little long wavelength energy to be reflected from the regular oranges; the difference in visibility of orange is therefore dramatic. The advantage is somewhat reduced in clearer water but only near the limits of visibility where the long wavelengths, which have been converted from short wavelengths, are lost in the long viewing distances employed.

Some of the color confusions in naming made by the divers are specific to the combined light-source and water spectral energy distribution encountered while others would be expected in air also. As an example of the latter, the fluorescent yellow-green has a dominant wavelength in the neutral region for foveal tritanopia; at long viewing distances in air, therefore, it appears white and indistinguishable from the white target. On the other hand, both white and fluorescent yellow-green were commonly confused with the color of the illuminated water. White was called green in the Caribbean, yellow in Long Island Sound, and even orange in the Thames when the tungsten source was employed. This type of confusion was also prevalent in the study using natural illumination. Thus, while white is consistently the most visible of regular paints, it is also the easiest to confuse and should never be employed for color coding.

Specification of the colors that are least visible or the best camouflage requires consideration of the background conditions, since visibility is always a function of the contrast between target and background. In all these investigations, the target was seen against a water background which appeared dark or unlighted. Positive contrast targets, that is, those that were brighter than the background, were always the easiest to see.

Any factor that caused the target to lose brightness or appear dark decreased its visibility; three such factors are effective in this regard. First, the use of inherently dark paints, such as gray or black, is an obvious method. Second is the use of colors whose major spectral component is not transmitted effectively by the water, such as blue and green in turbid water and orange and red in clear water. The results of the previous investigation[1] showed, in fact, that a major color confusion was between either of these combinations and black. Finally, visibility can be reduced by the use of a color whose major spectral components do not exist in the light source to be used, such as orange and red with a mercury light.

It is, of course, possible to arrange viewing conditions so that negative contrast targets (dark target against a light background) are more visible than positive. Underwater this might occur by having the subject look up toward the surface in daylight or by presenting the target between the subject and a light source. Under these conditions, any factor causing the target to lose brightness will cause a gain in visibility. Under extreme conditions of back lighting, the inherent color of the target does not matter at all, since any object when silhouetted will appear black.

## SUMMARY OF THE VISIBILITY OF COLORS UNDERWATER

The data from this study have been compiled with that of the previous study (Sub MedResLab Report No. 503, Oct '67) to specify what colors to use for various operational conditions underwater:

I. **Best Visibility Against a Water Background.**

  A. For murky, turbid water of low visibility (rivers, harbors, etc.).

    1. With natural illumination:
      a. fluorescent yellow, orange, and red.
      b. regular yellow, orange, and white.
    2. With incandescent illumination:
      a. yellow, orange, red, white (No advantage in fluorescent paint).
    3. With Mercury light source:
      a. fluorescent yellow-green and yellow-orange.
      b. regular yellow, white.

  B. For moderately turbid water (sounds, bays, coastal water).

    1. With natural illumination or incandescent light source:
      a. any fluorescent in the yellow, orange, or reds.
      b. regular paint of yellow, orange, white.
    2. With Mercury light source:
      a. fluorescent yellow-green or yellow-orange.
      b. regular yellow, white.

  C. For clear water (Southern water, deep water off shore, etc.).

    1. With any type of illumination, fluorescent paints are superior.
      a. with long viewing distances, fluorescent green and yellow-green.
      b. with short viewing distances, fluorescent orange is also excellent.
    2. With natural illumination:
      a. fluorescent paint.
      b. regular paint of yellow, green, or white.
    3. With incandescent light source:
      a. fluorescent paint.
      b. regular paint of yellow, orange, or white.
    4. With a Mercury light source:
      a. fluorescent paint.
      b. regular paint of yellow or white.

II. **Poorest Visibility Against a Water Background.**

The most difficult colors to see at the limits of visibility with a water background are dark colors as gray and black. This applies to incandescent, mercury, and natural illumination.

In addition, any factor causing the major spectral components of a color to be lost, such as absorption by the water or lack of appropriate wavelengths in the light source, will result in poor visibility. Among regular paints, examples are:

a. blue and green in turbid water
b. orange and red in clear water
c. blue and green with incandescent sources
d. orange and red with mercury sources.

## III. Efficient Color Coding.

For color coding, use only three or four colors. Green, orange, and black are easily discriminable in natural and incandescent illumination. With a mercury source, change to green, yellow, and black. To add a fourth color in natural illumination, use blue in clear water, substitute yellow and red for orange in turbid water. With artificial sources it is difficult to add a fourth color that will not be confused with one of the other three. Nothing appears acceptable for the mercury source. For the incandescent source substitute yellow and red for orange in all bodies of water.

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13. ABSTRACT

The visibility of various colors underwater with artificial illumination has been measured in three different bodies of water chosen to sample a continuum from clear to turbid. Subjects were SCUBA divers who observed the colors at night, using a mercury or and incandescent light source. The visibility results show numerous interactions among color, fluorescence, type of light source, and type of water; from them, it is possible to select the optimum combination to be used under a wide variety of conditions. Colors are specified that will (1) maximize visibility, (2) provide the best camouflage, and (3) allow distinct color differences in appearance for use in color coding. These results are summarized in terms of the colors that are most effective for use under various operational conditions encountered underwater.

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