Marine Visibility Research and Development Initiatives of the U.S. Coast Guard

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U.S. Coast Guard research and development activities in marine visibility support our Aids to Navigation mission area. In recent years some $1.5 million has been invested in this program. Much of the work is performed at the Coast Guard Research and Development Center located at Groton, Connecticut. There a staff of graduate physicists and professional experimental psychologists who are well versed both in theory and in the operational environment is maintained. The research can be divided into five general areas: conspicuous light sources, daymark signal effectiveness, program decision-making tools, system evaluations, and energy and transmission. Various light sources including lasers, flashtubes, and electroluminescent panels were investigated. The Coast Guard is a leader in establishing industry standards for fluorescent materials used on fixed aids-to-navigation structures (daymarks). To assist program decision makers, a conspicuity metric for light signals viewed against a complex background is being developed. The new metric is based on eye movement latencies. Companion work for a daytime color metric is being sponsored at UCLA. To help evaluate the effectiveness of the system, measures of light performance are being related to probabilities of detection and buoy motion. In other work, a highly efficient metal halide high-intensity discharge lamp is being developed. Future plans include a 1988 project to quantify changes to the 1959 atmospheric transmissivity data base.

The U.S. Coast Guard operates and administers the U.S. Aids-to-Navigation System. This system directly supports the waterborne commerce of the United States. The total amount of this commerce is 2 billion tons annually. The major commodities making up this 2 billion tons are coal, petroleum, iron and steel, grain, chemicals, and construction products. U.S. imports and exports carried over water amount to 20 percent of the world's waterborne trade. The Coast Guard's activities in marine visibility and signal improvement directly support this commerce. To improve the Aids-to-Navigation System, work is proceeding in five areas:

- Conspicuous light sources,
- Daymark signal effectiveness,
- Program decision making tools,
- System evaluation, and
- Energy and transmission.

Research and applied engineering in these areas have resulted in significant advances in marine visual signals. From a completely successful program, from between $10 and $100 million may be saved through reduction of collisions, rammings, and groundings.

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CONSPICUOUS LIGHT SOURCES

The mariner returning to port often experiences difficulty trying to identify a specific aid to navigation against literally thousands of background lights. This is the problem of conspicuity—how to make a specific aid stand out against a complex lighting background so that it can be quickly identified.

Currently, the Coast Guard uses color coding and pulse coding to improve conspicuity. Red and green lights are repetitively flashed in unique sequences. By referring to a nautical chart, the navigator can then identify a specific aid. Unfortunately, many shore-based lights are red and green, and many of these are often flashed, as traffic lights, vehicle tail lights, and commercial advertising signs. Furthermore, even steady-state lights often appear to blink on and off due to atmospheric scintillation, an effect in which light waves are refracted by turbulent air cells.

Lasers

For several years, lasers have been touted as a possible solution to the background lighting problem. It was believed that coherent light might appear unique compared to incoherent light. In the early 1980s, the Coast Guard built several prototype laser aids to navigation *(1)*. Several observers judged these lights to be significantly different in appearance when compared to incandescent lights typically used in navigational aids.

In 1985, two experiments were conducted by the Coast Guard Research and Development Center to test the hypothesis that laser light sources are significantly more conspicuous than incandescent light sources. Specifically, if lasers were more conspicuous than incandescent sources, they had to look different. This difference can be objectively measured.

For the first experiment, an apparatus that presented a helium-neon laser and an incandescent source side by side was constructed *(2)*. The incandescent source was matched in color to the red laser by placing a bandpass filter in the beam. The intensities of the two sources were matched with neutral-density filters. This procedure ensured that observers did not use intensity or color as a basis for discrimination.

On a clear, moonless night, 37 U.S. Coast Guard Academy cadets viewed the sources from about 1 mi away. One or the other source was presented in random order at one of two intensities. The task was to determine which source was presented at any particular time. The observers were initially shown each source so they could learn its characteristics. After each presentation they were given feedback as to which source was actually presented. In 2,220 viewings, observers did not reliably distinguish between the two sources at much better than chance level; correct discrimination was 52.6 percent at the low intensity and 55.2 percent at the high intensity.

The experiment was repeated at a shorter distance so that much higher illuminance could be achieved at the observer's eye. Even at very high illuminances, observers could not reliably discriminate the laser from an incandescent source. From these experiments, it was concluded that lasers are no more conspicuous than incandescent sources.

Although lasers are not more conspicuous when viewed with the naked eye, the high degree of monochromaticity enables one to use an inexpensive bandpass filter to significantly reduce the intensities of nonlaser sources. Measurements were made of the intensities of several light sources with and without a bandpass filter. It was shown that once filtered, a 6-mW helium-neon laser would be nearly 65 times brighter than most typical background lighting sources. Put into practice, the navigator could view a harbor while looking through a bandpass filter and readily detect a laser light source from the background lighting.

In 1985, a 3-year program aimed at adapting the highly collimated light of a laser to the field of aids-to-navigation signal hardware was completed. Two devices were built and evaluated: a laser aid to navigation and a laser single point range. Over several years, tests were conducted comparing general laser performance to that of existing standard hardware. Only fixed-beam applications were appropriate, and then only where there was access to shore power *(3)*. When laser beams were rotated to cover 360 degrees (a requirement for most aid-to-navigation lights), lasers were unattractive due to the combined effects of diverging lenses and the short dwell time on the eye.

Multiple-Flick Flashtubes

A flashtube is a capacitive discharge device capable of outputting brilliant flashes of light in time periods on the order of microseconds. The highly intense flashtube burst can be detected at great distances and has been noted as a conspicuous signal in a typical aids-to-navigation system. The efficiency of flashtubes in converting input energy into visible light is greater than that of incandescent sources. These factors make the flashtube attractive as a light source. Unfortunately, there are three significant disadvantages to flashtubes:

- The intense flash tends to momentarily blind the observer.
- Mariners have difficulty fixing the exact location of the source due to the brief duration of a single flick. (A flick is a momentary single light pulse whose duration is measured in microseconds.)
- Observers have problems judging the distance to the flashing source.

The latter two problems can be overcome by presenting several flicks in rapid succession such that the observer will see what appears to be a longer duration flash and not the individual flicks.

The nominal range of a lighted aid to navigation is one measure of its signal effectiveness. This value is based on the effective intensity of the flashing light. Of the three accepted methods of calculating the effective intensities given by Allard *(4)*, Schmidt-Clausen *(5)*, and Blondel and Rey *(6)*, only Allard's method is recommended for multiple-flick flashes. (A flash is a continuous light pulse whose duration is measured in seconds. A multiple-flick flash is several flicks occurring in rapid succession such that it appears to be a flash.) The International Association of Lighthouse Authorities (IALA) recommendation *(7)* was based on the asymptotic approach of Allard's method to the steady-state response predicted by Talbot's law. Unfortunately, Allard's method involves lengthy computer calculations of the explicit solution of a differential equation, and for repeated flashes has never been experimentally confirmed.

In 1984 the Coast Guard Research and Development Center began work to find a simple, accurate method of determining the effective intensity of a multiple-flick flash *(8)*. A relationship was sought among detectability, flick frequency, and number of flicks (flash duration). A secondary goal of this work was to experimentally verify Allard's theoretical method. In the experiments, detection thresholds were measured for flashtube signals that varied in flick frequency (5 to 20 Hz) and duration of the multiple-flick flash (from 0.05 to 0.75 sec). The results produced a relatively simple equation that yields the effective intensity of a multiple-flick flash:

$$Ie = Ie1[1 + (0.203f - 0.557)(t/t + 0.2)] \quad (1)$$

where

$Ie1$ = effective intensity of a single flick (candelas) *(9)*,
t = flash duration (sec), and
f = frequency of the flick (Hz).

The Allard method also overestimated the effective intensity of multiple-flick flashes by as much as 22 percent. Figure 1 shows a direct comparison between the predictions of the Allard integral and direct experimental observations. The predictions of the Allard integral are shown as circles, whereas the best-fit curve to the data is the solid curve. Figure 2 shows how the relative effective intensity is related to flash duration and flick frequency. The relative effective intensity increases as both the duration and flick frequency increase.

Electroluminescent Panels

Electroluminiscent lighting (EL) is a relative new technology in the marine environment. EL panel life expectancy, energy efficiency, and signal chromaticity have been evaluated. All of these quantities were within the acceptable range for marine signals. Currently two prototype panels are being evaluated on the Poplar Street Bridge in St. Louis. From this evaluation, field life test data and sample user opinion on extended sources can be obtained. User comments are expected to be positive because most of the background lights in St. Louis are point sources. The uniqueness of the signal should enhance its conspicuity.

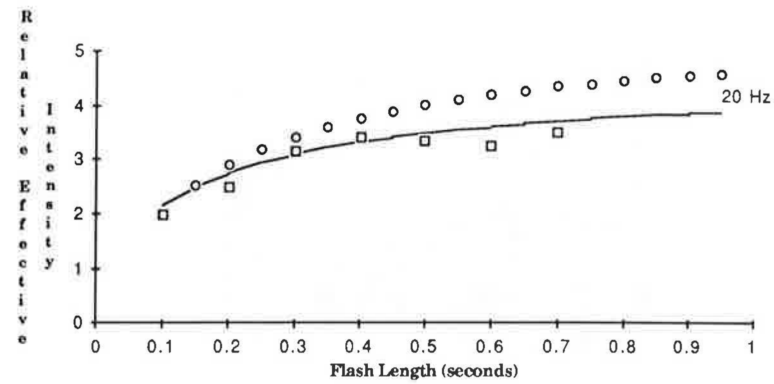

FIGURE 1 Relative effective intensity function.

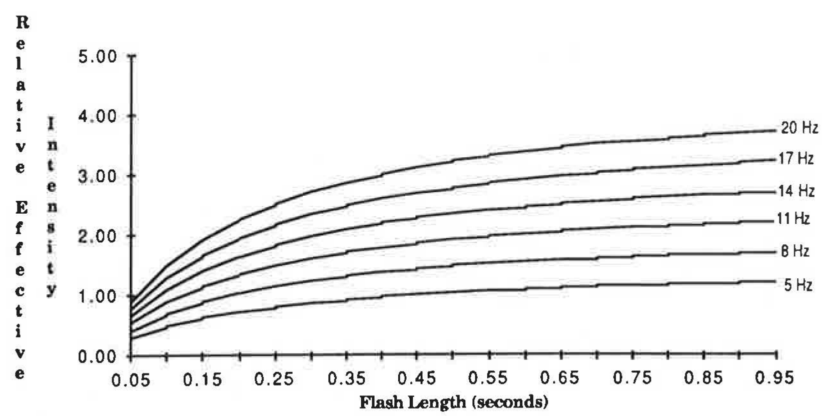

FIGURE 2 Composite relative effective intensity function.

DAYMARK SIGNAL EFFECTIVENESS

The Coast Guard is actively involved with questions of daymark signal effectiveness (for marine highway signs). The Coast Guard Research and Development Center was one of the first to use the increased luminance of fluorescent materials and night signals from retroreflective materials in signaling devices. Through participation in societies such as the Commission Internationale de l'Éclairage (CIE), American Society for Testing and Materials (ASTM), and American National Standards Institute (ANSI), the Coast Guard supported the original industry specification of these materials. The work in classifying commercial fluorescent material degradation curves resulted in compilation of the USCG Ocean Engineering Specification for Fluorescent Elastomeric Films *(10)*. This specification was used by ANSI and ASTM as input to technical committees involved with these products.

There are significant differences in commercially available films. When exposed to the environment, some films tend to lose their fluorescence while others tend mainly to lose their color dyes. In the first case, total surface luminance is reduced, whereas color (chromaticity coordinates) remains essentially unchanged. In the latter case, color changes as the dye fades while luminance remains relatively constant. In some materials, the luminance actually increases as the sample fades.

Recently, detection and color recognition and identification ranges were assessed for various materials as a function of environmental exposure *(11)*. The assessment was done by measuring the luminance detection threshold of a material on a white background. The threshold values were converted to relative detection distances through the inverse square law. In much this same fashion, recognition and identification distances were estimated. Observers were required to judge which of two samples was being presented. One was always white and the other was one of the test materials. The luminances at more than the previously determined detection thresholds and at which the test material could be discriminated from the achromatic sample were again converted to relative distances. The increase of the color recognition threshold above the detection threshold relates to how much shorter the recognition range is than the detection range.

All laboratory results were validated in an outdoor setting. Observers viewed 1.5-cm-diameter circles of test material from a distance of 600 ft. As the observers approached the targets, the distances at which they could positively detect a target and positively identify the color were recorded. They then moved closer to the targets and the same distances were recorded as they moved away from the test material.

Excellent agreement was obtained between the two sets of data. Variations as much as 15 percent in detection and recognition and identification ranges were measured over the 24-month exposure time. The experimental procedure was shown to map field performance. Figure 3 shows actual detection and identification data taken in the field for new material and that

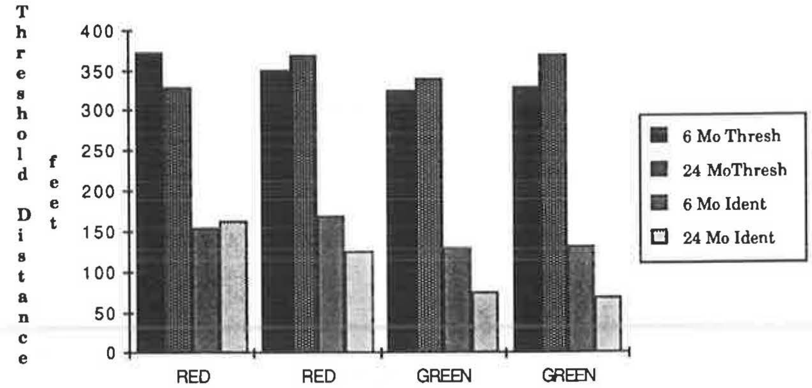

FIGURE 3 Field identification and detection distances.

weathered for 24 months. Figure 4 shows proportional distances calculated for laboratory data.

In addition to the primary findings, the data showed the importance of chromatic contrast in the detection of targets. Blackwell *(12)* and Blaise *(13)* each reported similar results. Each of these showed the importance of chromatic contrast. Blackwell defined a multiplicative conspicuity factor (CF) that, when multiplied by the luminance contrast of the target and background, provided an adequate measure of the visibility of a chromatic sample. Blackwell found red-orange fluorescent samples to have the greatest CF. These works show the importance of establishing a metric to account for the effects both of luminous and chromatic contrasts. Starting in 1987, the Coast Guard sponsored research to develop just such a metric. This work was to become a program decision-making tool.

PROGRAM DECISION-MAKING TOOLS

The Coast Guard is responsible for the design and maintenance of the federal aids-to-navigation system. Each research area is directed toward the development of design tools (performance metrics) for this system. Those lights that have greater attention-getting power or conspicuity are sought. Currently, the only measure of the effectiveness (conspicuity) of a light is its intensity. In the case of a flashing light, the equivalent fixed intensity is used. These quantities are used both to rank-order lights and to predict performance. Variables such as chromatic contrast, area distributions, and monochromaticity may significantly affect the conspicuity of light signals.

Conspicuity Metric

The individual elements of the conspicuous light program deal with evaluating a number of independent variables such as size, source distribution, and flash characteristic. A metric using eye movement latencies will assess the composite effects. Prior studies by the Coast Guard *(14)* have shown that gross ship movements within a channel vary little with the addition of confusing background lighting. However, additional studies *(15)* show that the effort expended by mariners is sensitive to increases in loading variables. These variables include area geometry, environmental conditions, vessel characteristics, aids to navigation, and task requirements. It is believed that effort expended will be sensitive to changes in light signals that can be measured by this new metric. The performance of lights ranked with this metric will be correlated to cognitive workload studies.

Color Metric

To enhance the effectiveness of daytime signals, maximum contrast is desired between the daymark and the background. This contrast determines the ranges at which the daymark is detected and identified. The well-defined scale of luminance contrast is used as the metric to evaluate performance.

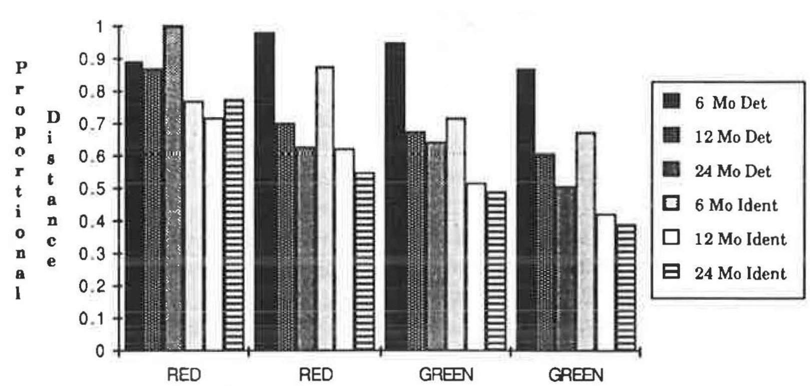

FIGURE 4 Calculated laboratory distances.

In many situations, target and background luminous contrast is very nearly zero. In such cases, recognition and identification result from chromatic contrast. The importance of chromatic contrast has not been evaluated with a composite metric that accounts both for luminous and chromatic contrast. A general metric that will predict distances at which targets will be detected is now being developed under contract at UCLA. This metric will be functionally dependent on target size, luminance, and chromaticity, as well as background luminance and chromaticity. This will form the new composite metric for use in aids-to-navigation design.

SYSTEMS EVALUATION

In addition to conducting research, the Coast Guard monitors current technology in marine signaling. From time to time, new systems are evaluated for use within the federal Aids-to-Navigation System.

Leading Marks

The precise alignment (location) of a vessel is necessary when it is navigating in restricted waters. Information of this type is provided by two station horizontal-parallax ranges. Approximations to this performance have been provided by directional and sectored lights. Recently, an evaluation of the INOGON leading mark *(16)* was completed. INOGON is a visual guidance system based on optical interference. Interference between two closely spaced gratings creates a moiré pattern of arrows when viewed from off-axis. The pattern presented is proportional to the off-axis distance of the viewer. This presentation is useful in maintaining a line of position when navigating in restricted waters.

The laboratory evaluation included detection range measurements and measurements of alignment accuracy. A field evaluation of the device was conducted at Constable Hook, New York. Thirty-one responses from mariners were analyzed. The mariners were asked to respond to a series of questions related to how well they could locate the device in daylight, twilight, and nighttime. In addition, they responded to questions about the position and directional sensitivities of the device as well as the quality of the rate-of-motion information provided. The field evaluation confirmed the 2,000-yd detection range of the device. Those mariners responding favorably toward the device saw its greatest virtue as the off-axis information. Possible Coast Guard applications as well as device limitations have been recommended to the Office of Navigation.

Small Boat Navigation Lights

In 1987, a study examining how spillover between sectors of navigation lights on small boats affects mariners' ability to judge the direction of motion of oncoming vessels *(17)* was concluded. Navigation lights required on vessels operating at night are specified in the 1972 COLREGS and Annex 1 of the Inland Navigation Rules Act of 1980. These documents specify the required placement, intensity, chromaticity coordinates, and sectors of coverage. The horizontal sectors for red and green side lights are defined as from right ahead to 22.5 degrees abaft the beam. The white stern light is shown from right aft to 67.5 degrees on each side of the vessel. The intensity of these lights is required to decrease to a practical cutoff within 3 degrees in the forward direction for sidelights and 5 degrees aft for side lights and stern lights. This cutoff is defined in the Inland Navigation Rules as 12.5 percent and is undefined in the 1972 COLREGS. The American Boat and Yacht Council has recommended 67 percent.

A small boat simulator was constructed. The practical cutoff was alternated between the values of 0, 12.5, and 67 percent. The direction of the oncoming vessel was set at courses of 5, 10, 100, 110, and 120 degrees. A total of 56 trials were presented to each of the 15 observers. With greater spillover (increasing practical cutoff), the mariners' ability to judge direction of motion increased. Thus, by providing the mariner with more information, his ability to discriminate the courses of approaching vessels is increased.

Probability of Detection and Buoy Motion Studies

The horizontal and vertical divergences of buoy lenses are fixed. If the buoy rolls significantly, a mariner may see a diminished flash or even miss a light flash altogether. Thus buoy motion can affect the probability of detecting or properly identifying a signal. The Coast Guard Research and Development Center is developing a method to remotely record buoy motion. The system will sample a time-varying phase signal that is proportional to the buoy's motion. This information will be used to construct a probability density function for each buoy class as a function of environmental conditions.

ENERGY AND TRANSMISSION

Energy-Efficient Metal Halide Signal Light Source

The Coast Guard presently uses an incandescent lamp inside a drum lens as the signal light on some 4,100 lighted buoys and 12,000 lighted shore aids to navigation. The lens is manufactured from either glass or acrylic. The colors red and green are obtained by filtering the white light through the colored lens. This system has changed little since it was installed in 1960. The inherent inefficiencies of incandescent lamps (2.3 percent) and the filtering loss (67 percent) make the signal light production only 0.76 percent efficient. This means that of the $2,500,000 the Coast Guard spent in 1985 for primary batteries, $2,480,000 was consumed in system losses. Conversion to a more efficient source would allow more lighted aids to be solarized. With this process, the material and energy costs could save the Coast Guard more than $2,000,000 per year.

The luminous efficacy of present incandescent light sources varies from 10 to 20 lumens/W. Table 1 shows the efficacies of other light sources. Of these potential light sources, all but metal halides can be excluded from consideration: sodium produces unacceptable wave length radiation; mercury is a strong ultraviolet producer; fluorescent lamps have weak luminance, which significantly increases their physical size; and short arc lamps are very strong ultraviolet producers that have short lifetimes.

Thus the search narrows to developing a 12-V (dc), direct-emitting, flashed, red and green metal halide lamp. Discussions

TABLE 1 COMPARISON OF SOURCES

System	Lamp	Efficacy (lumens/W)
Present system	Incandescent	16
Systems that cannot meet signal requirements	H.P. sodium	80–90
	L.P. sodium	100–120
	Mercury	20–30
	Fluorescent	30–50
	Short arc	30
New-program	Metal halide	55–70

with various lamp manufacturers indicate that a 7 percent efficient metal halide source is within current technology. Over the next 3 years, this technology, including prototype sources, performance and life testing, and production specifications, will be investigated. This effort, if successful, will greatly reduce the present life cycle costs of the Coast Guard's aids-to-navigation system.

Atmospheric Transmissivity

The U.S. Coast Guard has the responsibility of ensuring that all visual aids to navigation (e.g., lighthouses, beacons, buoys) provide adequate visual coverage wherever they are located. This implies that lights be visible under certain meteorological conditions at specified ranges. To determine the required candlepower and hence the visual range of a given lighted aid to navigation, the average atmospheric transmissivity must be obtained.

Atmospheric transmissivity is the fraction of incident light flux remaining in a beam of light after it has gone through a unit length of atmosphere. For example, a transmissivity of 0.75 per nautical mile means that only 75 percent of the light energy remains after it has traveled through 1 nautical mile of air.

In 1923, the Coast Guard produced its first set of nighttime atmospheric transmissivity curves for various portions of the United States, including Alaska and the Hawaiian Islands. These curves were redrawn in 1961 *(18)* because the geographic changes in industry and local changes in climate rendered the 1923 curves obsolete, and the 1923 curves left big gaps in coverage of the U.S. coastline. The following list gives the locations of available atmospheric transmissivity curves.

Coast of Maine (except Penobscot Bay)
Penobscot Bay
Massachusetts Bay
Nantucket and Vineyard Sounds
Long Island and Block Island Sounds
Lower New York Bay
Delaware Bay and Entrance
Chesapeake Bay Entrance
Chesapeake Bay
Gulf of Mexico
San Francisco Bay and Entrance
Coasts of Oregon and Washington
Columbia River Entrance
Straits of Juan de Fuca and Georgia
Puget Sound, Washington
Admiralty Inlet, Washington
Hawaiian Islands
Southeastern Alaska
Lake Ontario
Lake Erie
Lake Huron and Straits of Mackinac
Lake Superior
Lake Michigan
Green Bay and Entrance, Wisconsin
Atlantic Coast—New Jersey to Cape Charles
Atlantic Coast—Cape Henry to Charleston
Atlantic Coast—Charleston to Key West
West Coast of Florida
Southern California Coast (11th Coast Guard District)
California Coast (12th Coast Guard District)
Detroit River, Lake St. Clair, and St. Clair River

An example of an atmospheric transmissivity curve is shown in Figure 5. The curve can be interpreted as follows: the curve

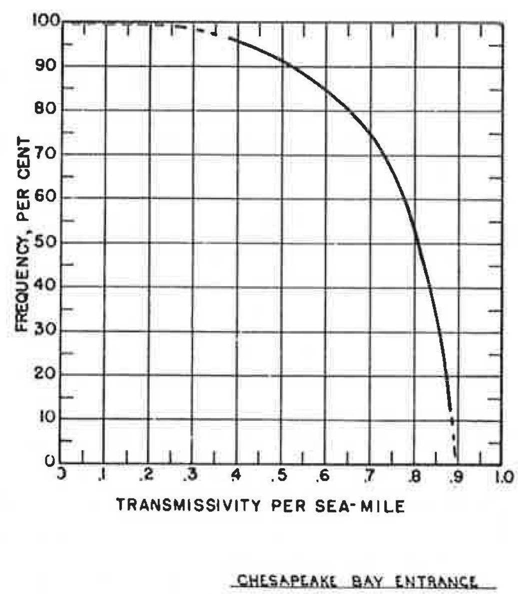

FIGURE 5 Distribution curve of atmospheric transmissivity.

goes through percentage = 0.90 (the Coast Guard design criterion for a major aid to navigation) at the point where the transmissivity is 0.52. This means that for 90 percent of the year, the transmissivity for Chesapeake Bay is equal to or greater than 0.52 per nautical mile. This $T = 0.52$ value becomes the design criterion for determining the required candlepower of the light.

The transmissivity curves must be reexamined because of the general decrease of atmospheric clarity due to industrial pollutants. In 1987, all available transmissivity data were to be reviewed. Statistically selected observations will be used to update the data base rather than reconstruct it in its entirety.

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