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SOME FACTORS AFFECTING VISIBILITY OF AIRCRAFT NAVIGATION LIGHTS

1. PURPOSE

The purpose of this document is to discuss various factors affecting the visibility of aircraft navigation lights, so that they might be better understood by all persons concerned with this subject.

2. DISCUSSION

The visibility of a light signal may be defined in terms of the illumination it produces at the observer's eye under a given set of conditions. This will depend on many factors. In general, the visibility of a light signal will be greater when it produces more illumination at the observer's eye than when it produces less illumination at the observer's eye. This is merely a way of saying that a brighter light is more visible than a less bright light. However, as will be shown in the following discussions, there are a number of other factors which do greatly affect the visibility of the light. Many of these factors are inter-related, and it becomes very difficult to separate them as individual factors and discuss them without consideration of their effects on each other. The following lists some of these factors, but not necessarily in order of their importance.

1. Visual Threshold of the Observer.
2. Intensity of Light Source in Direction Toward the Observer - Distance from Observer.
3. Atmospheric Transmissivity.
4. Flashing vs. Steady-burning.
5. Size of the Light Source.
6. Color of the Light.
7. Background Luminance.
8. Presence of Other Lights in the Background.
9. Back-scatter from Observer's own Lights.
10. Optical Quality, Size, and Location of Windows Through Which Lights Are Viewed.
11. Portion of the Observer's Retina on Which Image of Light Impinges.
12. Observer's Adaptive State.
13. Individual Visual Capabilities.
14. Alertness and Search Habits.
15. Distractions.
16. Empty Field Myopia.

2.1 It should be noted that many of these factors are concerned with the light itself. Other factors are concerned with the conditions under which the light is viewed, while others have to do with the observer. In attempting to evaluate aircraft exterior lights or lighting systems, it will be seen that variables are so numerous and varied that it is difficult to segregate them and predict performance in particular circumstances. The following paragraphs will briefly discuss the items listed above.

2.1.1 Visual Threshold of the Observer: The threshold illumination, Eo, has been extensively investigated with varying results. Threshold illumination for white point-source signals observed against a dark background with fair probability of seeing under favorable conditions is of the order of 0.01 mile candle (equivalent to a light of 0.01 candela intensity toward the observer one mile away). For situations where the position of the light source is not known, actual sighting will require a considerably higher intensity. For marine navigation, a value of threshold illumination of 0.5 mile candle has been agreed upon and accepted by experts in this field (including the U. S. Coast Guard) as a practical value for threshold illumination. However, in the aviation field it is the consensus that a higher value for threshold should be used, because of higher speeds, other brightness is background, different elevations of aircraft, etc. A threshold of 2 mile candles is used in computing the visual range of runway lighting and this value will be in use henceforth in this Aerospace Information Report. This is equivalent to a source emitting 2 candelas toward the observer one mile away, with no attenuation by the atmosphere.

2.1.2 Intensity of Light Source in Direction Toward the Observer - Distance From Observer: It is obvious that only the intensity of a light in a direction from the light toward the observer at any particular instance is of value. Most aircraft navigation lights vary considerably in intensity in different directions. Intensity is normally expressed in candelas (formerly candles or candlepower).

2.1.2.1 The term "high intensity" has come into rather common use in describing aircraft exterior lights. This term has no particular meaning outside of the sales field. It is a general qualitative term and has no place in a technical description of a light or lighting system.

2.1.2.2 In the absence of atmospheric attenuation, the illumination, E, produced at an observer's eye, located at a distance, D, from a light source of intensity, I, is given by the "inverse square law."

$$E = \frac{I}{D^2}$$

By way of example, the apparent intensity of a source is the same as a second source which is four times as intense but twice as far away. Thus, the distance from the light source to the observer is important, since the illumination at the eye is inversely proportional to the square of the distance.

2.1.3 Atmospheric Transmissivity: Paragraph 2.1.1 and 2.1.2 above discuss inverse square law and threshold illumination under conditions of 100% transmission of light through the atmosphere. However, practically, there is attenuation (absorption and scattering) of light in the atmosphere, which further limits the distance from which lights can be seen. As haze becomes more dense, the distance for threshold visibility for any given light source becomes less. Allard's Law is used to compute the intensity of the light source needed to be visible at a given distance with a given atmospheric transmissivity. It is:

$$I = \frac{E_o D^2}{T^D}$$

Where I = Intensity of Light Source in Candelas

E_o = Threshold Illumination at the observer's eye in mile candles

D = Distance in miles

T = Transmissivity, or transmission of the atmosphere per mile

2.1.3.1 Figure I shows the computed threshold distances (based on a threshold of 2 mile candles) for intensities of 10, 100, 1,000, and 10,000 candelas versus atmospheric transmission per mile or transmissivity. Note that with an atmospheric transmissivity of 1 (100%) the range for a 100 candela source is about 7 miles. If the transmissivity is reduced to 0.5, more than 10,000 candelas are required for the same range. If the transmissivity is reduced to 0.01, the visual range for a 10 candela source is about .6 miles, whereas the range for a 10,000 candela source is increased to only 1.7 miles. Thus, it becomes evident that it is impractical to install lights on aircraft which would have sufficient intensities to provide long-range visibility under anything but good weather conditions. Information is available showing transmittance through the atmosphere of different colors of light. While there are some measured differences, the differences are not of such magnitude as to be significant in aircraft lighting.

2.1.4 Flashing vs. Steady Burning: A flashing light has more conspicuity or "attention getting power" than a steady burning light. However, at conditions of threshold, a flashing light requires greater instantaneous candlepower than a steady burning light for equal visibility. The basic experimental work on this was done by Blondel and Rey more than 50 years ago. Researches in more recent times have essentially confirmed their work. The Blondel-Rey formula for a square wave flash is:

$$\frac{E}{E_o} = \frac{(t + a)}{t}$$

Where Eo is the threshold eye illumination from a steady light

E is the eye illumination during the flash.
t is the duration of the flash in seconds.
a is a constant equal to .21 seconds.

2.1.4.1 It is now common practice to express the "Effective Intensity" of a flashing light in terms of the intensity of a steady burning light which provides an equal signalling effect at the eye. The accepted formula for this (based on Blondel-Rey) is:

$$I_e = \frac{\int_{t_1}^{t_2} I \, dt}{.2 + (t_2 - t_1)}$$

Where I_e = the effective intensity.

I = the instantaneous intensity in candelas at any time, t, during the flash.

t_1 and t_2 = time near the beginning and end of the flash, selected to maximize I_e

2.1.4.2 Although this applies only for threshold viewing under specific conditions such as with a dark background, it is the best method developed to date for the evaluation and comparison of flashing lights which have different characteristics such as peak intensity, distribution of intensity vs. time, total flash duration, etc.

2.1.4.3 The frequency of the flash is another variable that can have considerable effect on the visibility of the light. An observer who is scanning will be less likely to detect a light with long dark periods between flashes than one of the same intensity, but with a faster flashing frequency.

2.1.5 Size of the Light Source: For the most part, in considering aircraft exterior lights, the size of individual lights when viewed from any distance can be considered as point sources; that is, the source size is negligible compared with the distance to the observer. However, there are some aircraft exterior lighting applications where light sources with apparent extent larger than a point has been found to be of value. For instance, in formation flying, lights that have a definite size can provide better range information to the observer than small sources.

2.1.6 Color of the Light: It is well established that the average human eye does not have equal response to all parts of the visible spectrum. The sensitivity ranges from low at the blue end of the spectrum and the deep red end of the spectrum, to a peak at the middle in the green region. The candela is defined in terms of its effect on a standardized human eye taking into account the sensitivity of the eye. Therefore, equal intensities of lights of various colors under the same standardized conditions should provide equal effect on the eye. It is a matter of practical interest that, for the most part, it is not practicable to generate colored light directly. Light sources which are in common use generate light as white light, with incandescent filament lamps emitting "yellow-white" light, and condenser–

discharge lamps emitting "blue-white" light. Green, yellow or red light is obtained by filtering out unwanted colors. This means that to obtain red light for exterior aircraft lighting from a condenser-discharge type source, 83 to 90% of the light must be absorbed. For an incandescent lamp, 70 to 80% of the energy is lost. For "redder" reds, even a higher percentage of light is absorbed.

2.1.6.1 Color of exterior lighting fixtures is a means of providing information to the observer. An example of this is the well-known three-sector system of red, green and white exterior lights.

2.1.7 Background Luminance: A light source is seen by virtue of its contrast in brightness and/or color with the background against which it is viewed. A light of relatively low intensity may be seen in clear weather for considerable distances against an almost completely black sky background. The background brightness from typical dark night conditions to bright daylight conditions can vary on the order of one billion to one. The background luminance or brightness can also have a considerable effect on the observer's adaptive state. The intensity of the light would have to vary more or less proportionally to the square root of the background brightness to provide equivalent visibility over this wide range. It is possible that under some conditions, back-scatter from lights close to the observer shining into haze can contribute to an increase in the applicable background luminance. The sky brightness in the vicinity of a city or even a small town is considerably higher than the natural background brightness with the same meteorological conditions.

2.1.8 Presence of Other Lights in the Background: Aircraft exterior lights are viewed under a large number of different conditions. The background may be a black, overcast sky at night, a starlight sky, scattered lights on the countryside, or closely clustered city lights. Intensities of background lights can vary from faint stars to floodlights on the ground producing thousands of candelas. Colors can range through the complete spectrum. Therefore, it becomes important that color, intensity, and flashing cycles be used with aircraft lights to make their appearance under different conditions as different as possible from various lights which may be viewed in the background.

2.1.9 Back-Scatter: This factor must be given considerable importance in any consideration of aircraft exterior lighting. We can define back-scatter generally as light reflected or refracted into the cockpit by the atmosphere from lights installed on the exterior of the aircraft. The effect of back-scatter from steady-burning lights on the pilot may be to create a veiling background luminance or perhaps provide sufficient luminance to affect his dark adaptation. When lights are flashed, the back-scatter may be much more serious, in that in extreme conditions it can cause a vertigo which can result in loss of control of the aircraft. White lights were first considered for anti-collision lights. The major reason that the red color was adopted for anti-collision lights was due to the back-scatter effects of the flashing light, since for equal intensities of light, red light will produce much less back-scatter than white light. For the same reason, early installation of anti-collision lights were made on the top of the vertical fin of the aircraft, since back-scatter is reduced by locating the backscatter source as far from pilot as possible. Back-scatter may be a much greater problem on small aircraft than on large, as exterior lights of necessity must be located closer to the cockpit.

2.1.10 Optical Quality, Size and Location of Windows: In considering the visibility of exterior lights on aircraft, any medium interposed between the light and the observer's eye must be considered, as it will have an effect. In the design of new aircraft, a good bit of consideration has been given to the size and location of cockpit openings. However, there are many aircraft in operation in which the visibility from the cockpit is greatly restricted. Small aircraft with formed plastic windshields are more likely to have poor optical quality than airline aircraft. Also, the maintenance of these windshields is such that they are more likely to become scratched or crazed, further reducing the visibility through them. Dirty and bug-smeared windshields which are also common should be kept clean.

2.1.11 Portion of the Observer's Retina on which Image of Light Impinges: A pilot flying at night is assumed to have some degree of dark adaptation. This may range from minimum dark adaptation of a pilot departing from a brightly lighted commercial airport, to nearly complete dark adaptation of a pilot flying in complete darkness between cloud layers or over water for a half hour or more with cockpit lights set at a very low level. In this factor there is a close inter-relation between color of the lights, the observer's adaptive status as determined in part by the color and light level in the cockpit, the portion of the retina on which the image impinges, and the pilot's ability to make an early sighting.

2.1.12 Observer's Adaptive State: As indicated above, an aircraft pilot under some conditions may be very well dark-adapted, and under other conditions will not have attained a substantial degree of dark-adaptation. Theoretically, for equal intensities, a white, blue or green light could be seen more easily with peripheral vision by the dark-adapted eye than a red light. However, although it might affect the distance of first sighting, there is some question as to the importance of this factor in the over-all consideration of aircraft exterior lighting. In order for a light to provide meaningful information to the observer, it must be seen with foveal vision, (e.g. he must be looking "at" the light) as its position in space must be accurately identified in order for the pilot to take any necessary action.

2.1.13 Individual Visual Capabilities: Individuals do have widely different visual capabilities. This is one area, however, where these variations are controlled to some extent in that persons without reasonably good vision and with any degree of color blindness are denied a pilot's certificate. In addition to the considerable variations between individuals, there is also considerable variation in an individual's visual capabilities from time to time, depending on personal habits of the individual, fatigue, etc.

2.1.14 Alertness and Search Habits: It is obvious that lights or a lighting system, no matter how good, when installed on an aircraft will not be seen by the pilot of another aircraft unless he is looking alertly for the lights. Some work has been done by the FAA at NAFEC which would indicate that this is an area in which the level of safety might be increased by pilot training to improve his alertness and search habits.

2.1.15 Distractions: There are many and varied distractions which may affect the pilot's ability to distinguish exterior lights on other aircraft. These may range from normal pilot duties which prevent his constant attention outside the aircraft, to reflections of instrument lights or even ground lights in the windshield and side windows, which can be mistaken for lights of other aircraft. Back-scatter factors can produce effects ranging from minor distractions to serious disorientation.

2.1.16 Empty Field Myopia: There are a number of conditions encountered when flying at night, as well as daytime, where there is no detail of any kind to be seen outside the aircraft. Under these conditions, when the pilot looks outside the aircraft, his eyes will tend to be focused for a distance very close to the aircraft, of the order of 20 feet. Obviously, under these conditions, a light must be brighter or otherwise more distinctive to attract his attention.

3. EVALUATION OF DIFFERENT LIGHTS OR LIGHTING SYSTEMS

There is a definite need for a method to provide an objective evaluation of various proposed aircraft exterior lighting systems. However, to date, due to the many variables involved, no simple, precise system has been developed. However, guide lines have been set forth.

3.1 The first step in evaluation should be a detailed analysis of the proposed system in terms of:

(a) The information it can convey.
(b) The light-coding technique used to convey it.
(c) The ability of the pilot to assimulate and use this information.
(d) The engineering and economic considerations.

The results of this analysis will be used to determine whether or not further evaluation should be made of the proposal. For instance, if it attempts to present information known to be without value, or if it employs a light-coding technique known to be subject to excessive interpretation error, no further time should be spent on it.

3.1.1 If the proposal survives the analytical screening, then it should be subjected to experimental investigation. This may include, as needed:

(a) Photometric and engineering tests.
(b) Visibility tests.
(c) Psychological tests.
(d) Simulator tests.