EMERGENCY VEHICLE WARNING LIGHTS

STATE OF THE ART

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prepared for the

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reader for the discussions of conspicuity in Part III. Part III reviews the factors that make signals more or less conspicuous, the methods for measuring conspicuity, the physical measurements necessary for adequate characterization of a warning-light unit, and the relations of perceptual and physical measures to performance standards for lights.

Limited portions of the report -- namely Chapter 12 and some of the figures -- have been excerpted from a preliminary report, "Emergency Vehicle Warning Devices: Interim Review of the State-of-the-Art Relative to Performance Standards" (NBS Report 10478; also LESP-RPT-0501.00), which covered both warning lights and sirens. The siren work will be documented separately.

The authors are grateful to Mr. Charles A. Douglas, for helpful discussions of both physical and perceptual matters; and to Mr. I. Nimeroff, for contributing information on physical measurements.

FOREWORD

The National Bureau of Standards' Sensory Environment Section is engaged in a program of research on emergency-vehicle warning lights. The activity includes both the collection of available information and the generation of new research data, with the ultimate goal being the preparation of a voluntary standard for these warning lights. The program is administered by Mr. Avery T. Horton of the Law Enforcement Standards Laboratory of NBS, with financial support from the National Institute of Law Enforcement and Criminal Justice of the U.S. Department of Justice's Law Enforcement Assistance Administration.

The present report is meant to provide an overview of the entire field of emergency-vehicle warning lights, exclusive of our own experimental work, which will be reported separately. It is hoped that the report will prove useful to a broad class of readers. Some readers will probably use it as a reference source, browsing through selected chapters. At the other extreme, those with a requirement for detailed technical knowledge of the subject -- such as engineering consultants to large police departments -- may find it helpful to read the entire document through, from beginning to end.

Part I is concerned with the present realities of the situation, and includes a discussion of the kinds of lights now available and the bases on which the many warning-light configurations now in use are chosen. Part II contains background material on the perception of signals from emergency-vehicle warning lights, and prepares the technically oriented reader for the discussions of conspicuity in Part III. Part III reviews the factors that make signals more or less conspicuous, the methods for measuring conspicuity, the physical measurements necessary for adequate characterization of a warning-light unit, and the relations of perceptual and physical measures to performance standards for lights.

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ABSTRACT

Information is presented concerning all aspects of emergency-vehicle warning lights (EVWLs). A survey of the present situation includes: the non-uniformity of state EVWL laws; the factors entering into the choice of an EVWL configuration; a list and photographs of a variety of EVWL types; and a list of EVWL manufacturers and distributors. Background material relating to the perception of EVWL signals includes: an analysis of general warning-signal perception; a description of the visual stimulus pattern confronting a driver being approached by an emergency vehicle from various directions; and a summary of the characteristics of peripheral vision (including luminous efficiency, color perception and discrimination, and flicker and movement perception). Perceptual factors affecting the conspicuity of EVWL signals are discussed, including: effective intensity; flash rate; on-off ratio; pulse shape and flash duration; spatial sweep of beam; color; number and spatial pattern of lights; cross-sectional area; motion; temporal phase relations; and the role of the background. Physical measurements on EVWL units are described, including: angular intensity distribution and beamspread; flash rate; pulse shape and flash duration; effective intensity; color; and variables in rotating devices. A glossary, extensive enough to be helpful in reading the technical literature, is included.

KEY WORDS: Color; conspicuity; emergency vehicle; flashing light; lights; motor vehicle; photometry; signal light; standards; vehicle, emergency; vision, peripheral; warning light.

1. General Introduction

The operator of an emergency vehicle such as a police cruiser is frequently required to make his way through traffic at the greatest speed consistent with safety. In accomplishing this often critically important goal, he depends on his warning devices, both auditory and visual, to alert drivers to his approach. Drivers given adequate warning of the approach of a police car are less likely to involve the emergency vehicle in an accident, and less likely to impede its progress toward the scene of the emergency.

Until the present time, the acquisition of emergency signaling equipment has been largely a haphazard procedure, in which each police department must do the best it can in the absence of standards. Many law enforcement and other emergency-oriented personnel have personally experienced the ineffectiveness of many of the presently popular warning devices in attracting the attention of motorists. With respect to warning lights, the need for standards -- or at least generally accepted technical guidance -- exists at two levels. First, there is a clear need for some agreement on what the best color combination and general configuration is for emergency-vehicle warning lights. As things stand now, drivers are exposed to a great profusion of different warning-light systems and often are unable to interpret the signal beyond an awareness that the vehicle producing the signal is not an ordinary pleasure car.

Once the basic characteristics of a warning-light signal are agreed upon, the second need for guidance arises in connection with the performance of hardware. The police procurement officer wants to be able to judge how well a given piece of equipment will perform its desired function.

In this report, attention is paid in considerable depth both to the perceptual principles that must be understood if an effective warning-light system is to be specified, and also to the kinds of physical measurements that permit informed prediction of perceptual effectiveness. An attempt is made to clarify some of the issues that beset the field of warning-light effectiveness, and also, wherever possible, to suggest ways in which established scientific knowledge about human visual processes can be used to improve the design of overall warning-light systems.

PART I. THE PRESENT CHAOS

2. The Basis of Warning-Light Configurations

2.1. Introduction

There are many different types and colors of warning lights presently used on emergency vehicles. The greatest variety appears on police cars, but, depending on the locality, the same devices and colors may also be used on fire engines, ambulances, tow trucks, and many other emergency and semi-emergency vehicles. There is currently no single standard or recognized form of marking for emergency vehicles in this country as there is, for example, in Great Britain.

This situation has lead to a great deal of confusion among motorists and pedestrians, because of the proliferation of lights having a similar appearance, yet calling for different behaviors depending on the particular vehicle on which they are mounted, and the particular locality in which they are used. The driver of an emergency vehicle is also in an unenviable position. He is in constant danger because he does not know whether or not the driver ahead of him will be aware of his signal and react properly to it. Moreover, since the meaning of the signal (coding) varies among different states and localities, an out-of-town driver may react to a local emergency signal inappropriately, thus endangering himself, and other nearby vehicles, as well as the emergency vehicle.

2.2. Factors to be Considered

The profusion of current emergency-vehicle warning-light configurations in the various state and local jurisdictions around the U.S.A. is symptomatic of the fact that there are quite a few different factors that are considered in arriving at a standard configuration, and different groups (or individuals) assign different relative importances to these various factors. Among the factors (some of them interrelated) that the authorities of a particular jurisdiction would think about in choosing a warning-light configuration are:

A. Color
  1. Relative visibilities of different colors; differences between day and night viewing conditions; the effect of weather on relative visibilities of colors.
  2. Meanings, in a signal context, currently attached to different colors by the residents of the jurisdiction.
  3. Warning-light practice in other jurisdictions.

B. Duration of Flash
  1. Possible difficulty in locating source of very brief flash.
  2. Possible lessening of effectiveness of stretched-out flash with long rise and fall times.

C. Situations of Use
  1. Emergency-vehicle action: high-speed movement through traffic; slower than normal movement in traffic; slow movement off road; full stop in traffic; full stop off road.

2. Emergency-vehicle identification (police, fire, ambulance, other category).

3. Type of roads: number of lanes, speed limit, median strip or not, visual median barrier or not.

4. Reaction desired from drivers: pull to right and stop; proceed in lane at reduced speed; proceed and prepare to stop in lane; make way for emergency vehicle by any safe maneuver; etc.

D. Hardware

1. Commercial availability of units.

2. Initial cost of units.

3. Maintenance cost of units: frequency of replacement; labor and material costs for replacement and repair; tangible and intangible costs arising from incidents of unit failure.

4. Power consumption: availability of batteries and alternators (generators) of suitable capacity.

5. Power consumption cost: extra initial cost of heavy-duty batteries and alternators.

6. Power-supply maintenance costs: frequency of replacement; labor and material costs for replacement and repair; tangible and intangible costs arising from incidents of battery or alternator failure.

2.3. Specifying a Configuration

The term configuration is used here to refer to the principal characteristics of the warning-light devices used on a particular vehicle, or prescribed for all the vehicles of a particular type in a specified jurisdiction. Functionally, the warning-light configuration determines the nature of the light signals that will be emitted by the vehicle in various directions. Structurally, the essentials of a "configuration" are: (a) the number of lights; (b) the type(s) (rotating, oscillating, steady, flashing, alternate flashing, etc.); (c) the color(s); (d) the synchronization pattern; (e) the mounting position(s) on the vehicle; (f) the direction of peak intensity (beam axis), relative to the vehicle, for each light not uniform over 360°; and (g) the angular spread of each beam, horizontally and vertically. Debates about the configuration to adopt within a given jurisdiction are usually based on consideration of some or all of the factors outlined in the preceding paragraphs (Section 2.2.), and possibly also on other factors in special cases.

When a particular configuration (in the above sense) is chosen for formal adoption, there are two additional specifications that are usually also included in the requirements: the flash rate of the lights, and their minimum intensities, actual or "effective". ("Effective intensity" is a measure applied to flashing lights; see Section 10.6.) The prescribed flash rate or range of rates does not vary much among jurisdictions, and generally follows accepted signal practice (almost always between 60 and 120 flashes per minute). The setting of a minimum intensity is important in determining the visual effectiveness of the lights, but the value specified must be consistent with the state of lighting technology at the time of adoption of the law or ordinance. It is usually set at a level considered currently practical in an economic sense (see the Hardware factors listed under D in Section 2.2.). The fundamental minimum requirement with respect to intensity is that the emergency-vehicle warning lights be brighter than such routine flashing lights as turn signals and fixed-hazard flashers by a margin sufficient to make the emergency lights clearly distinguishable from the routine lights when they are seen at a comparable distance.

2.4. What Should the Message Be?

The most fundamental choices in selecting an appropriate warning-light configuration for a particular jurisdiction are based on the Situations-of-Use factors listed under C in Section 2.2. In practice, one of two basic approaches has usually been taken in the selection of warning-light configurations. The approaches differ with respect to the category of message to be conveyed by the signals. The first type of message is meant to communicate to the receiver of the signal that some particular behavior is expected of him. For example, in some jurisdictions, the correct response to a flashing red light on a moving vehicle is always to pull as far over to the right as possible and then to stop. In the other common approach, the characteristics of the warning signal are meant to call attention to the presence of an emergency vehicle and to identify the type of vehicle it is. It is quite common for police, fire departments, and ambulance corps -- and other groups as well -- to desire distinctive warning-light configurations for identification purposes. If an attempt is made to combine several categories of desired driver reaction with several categories of vehicle identification, the number of distinct warning-light configurations that drivers must learn to recognize can become excessive. A fundamental question is: should the driver reactions appropriate to the rapid approach of a police car, fire engine, or an ambulance, sometimes vary for the different vehicle types, or should the required reaction always be the same? If the object is simply to clear a path for the emergency vehicle, regardless of category, then an appropriate solution might be to have a single set of warning-light configurations and to confine the identifying markings of the different types of vehicles to the colors and patterns painted on the vehicles. In this way, the target driver knows at long distances what is expected of him (if he notices the lights), and can also identify the emergency-vehicle category at shorter ranges.

2.5. How Many Different Signals?

Particularly because people become flustered in emergencies, it is important to keep the number of different warning-light configurations that must be remembered to a minimum. Severely limiting the number of possible signals will tend to reduce the time required for a target driver to recognize any one of the signals and to recall the appropriate reaction. (See the discussion of "reaction time" in Section 4.1.) Information that does not affect the required reaction of the driver (such as emergency-vehicle category, in many cases) can be delayed in its presentation until after the primary message has been communicated. Restriction of identification markings to paint, rather than lights, is one means of accomplishing this goal.

In order to avoid a significant percentage of delayed or incorrect reactions, a warning-light system should incorporate a very small number of different signal patterns, probably no more than three or at most four. Examples of 1-, 2-, 3-, and 4-signal systems are as follows, with the signal patterns identified by the meanings or messages they are meant to convey:

<u>1 signal</u>. (1) "Something unusual is happening. Be alert and take appropriate action."

<u>2 signals</u>. (1) "A rapidly moving emergency vehicle is approaching. Pull over to the right and stop."

(2) "There is an obstruction or slow-moving vehicle ahead. Slow down."

<u>3 signals</u>. (1) and (2) Same as in 2-signal system.

(3) "There is a serious obstruction ahead. Prepare to come to a full stop before proceeding."

<u>4 signals</u>. (1), (2), and (3) Same as in 3-signal system.

(4) "There is an obstruction or slow-moving vehicle. <u>off</u> the road. Use caution as you pass, but maintain the flow of traffic."

Other definitions of the signals than those given above are possible, but the meanings listed reflect typical actual or proposed systems, except for the 4-signal system which is a speculative idea only. Some reflection on the above systems may suggest that a fourth signal could well be a counter-productive luxury not only in terms of cost, but also with respect to effectiveness. The 33 percent increase in configurations to be remembered, relative to a 3-signal system, might outweigh the rather marginal importance of the additional message. In the absence of contradictory empirical evidence, then, it would appear intuitively reasonable that the ideal system in any particular jurisdiction (or, most desirably, in all jurisdictions simultaneously), should include only from one to three distinct signal-light patterns, each requiring a different reaction from the target drivers.

2.6. Non-Uniformity Among State Laws

The desirability of having a single set of traffic rules throughout the United States has been clear since the automobile became a common mode of transportation. A group called the National Committee on Uniform Traffic Laws and Ordinances (in Washington, D.C.) has been working since the 1920s to develop a Uniform Vehicle Code and Model Traffic Ordinance that would be voluntarily adopted, in whole or in part, by more and more state and local jurisdictions. Their hope is that ultimately, at some Utopian moment in the future, all governmental levels within the entire country will subscribe to a single set of rules that has evolved through years of practical experience. The Committee has made progress over the years, and issues revised versions of its proposed Code and Ordinance from time to time.

Among the many issues considered by the Committee is the problem of emergency-vehicle warning lights. At a meeting of the Committee in November 1971, a report prepared by the Committee staff was presented that set forth the lack of uniformity among state laws governing warning lights on "authorized emergency vehicles". The report describes the situation as it existed in about 1968. Although there have been some changes since 1968 in the statistics cited in the report, the trend has not been clearly toward greater uniformity and the present situation is still approximately as confused as it was then. With the permission of the Committee, an excerpt from the staff report is reproduced below as indication of how much of an improvement a single nationwide system of emergency vehicle warning lights would be. (References in this quotation to "UVC" denote the Uniform Vehicle Code promulgated by the Committee.)

> "Twenty-one states have special lighting provisions for 'authorized emergency vehicles.' In addition, eleven states have laws comparable to UVC 12-227(b), (c), but have no other special lighting provisions.
>
> "Ten states provide for alternately flashing red lights, like the Code. Six of the ten require two red to the front and two red to the rear; however, three expressly allow rotating lights in lieu of or in addition to alternately flashing lights. Three of the ten require two lights to the front but have no requirements for rear lights -- one allows a rotating light in lieu thereof. The District of Columbia requires at least one alternately flashing light [sic]. In addition, one state requires alternately flashing lights but does not specify a color. Three states require or permit an oscillating, rotating or flashing red light; one state permits a red and white light in lieu thereof. One state permits a flashing or rotating red or red and white light. One state provides for a flashing red light.
>
> "Four states have unique provisions: Alaska requires a flashing red light visible to three sides; California requires a rotating, flashing or steady red light and also permits flashing amber warning lights and a flashing white light; Colorado requires a red light visible to the front and rear, but does not specify the type of light and South Dakota requires one rotating red light or two front red lights, but does not specify the type of light for the latter.
>
> "Two states authorize flashing lights for emergency vehicles, but include no description of the authorized lighting device in the statute; a second provision in one state authorizes a red light, but makes no reference to a flashing light.
>
> "Eleven states have a provision in substantial conformity with UVC 12-218(c), permitting, but not requiring, police vehicles to have lights required on authorized emergency vehicles generally. In three cases, this provision is in addition to special lighting provisions applicable to law enforcement vehicles only.

"Many states have lighting provisions specifically applicable to one or more types of authorized emergency vehicle, as that term is used by the Code, either in addition to or instead of lighting requirements for 'authorized emergency vehicles.' Twenty-one states have provisions for police vehicles, twenty-three for fire vehicles and fifteen for ambulances and rescue equipment.

"Sixteen states provide for blue lights on police vehicles: four permit oscillating, rotating or flashing blue -- in Illinois, this is for Chicago only; three permit rotating or flashing blue; two permit flashing blue; one permits alternately flashing blue and six permit blue lights, but do not specify the type of light. One state permits red and blue oscillating, rotating or flashing lights. Eight states permit red lights on police vehicles: Three permit oscillating, rotating or flashing red; one permits flashing or rotating red; one permits flashing red; one permits rotating red; one permits alternating, flashing or blinking red and one permits a red signal lamp, but does not specify the type of light. One state permits police vehicles to have an oscillating, rotating or flashing red and white light.

"Six states permit blue lights on certain fire department vehicles: three permit flashing blue; one permits flashing or rotating blue; one permits alternately flashing blue and one state permits a blue light on the vehicles of fire chiefs and marshals, but does not specify the type of light. Eighteen states permit red lights on fire department vehicles: four permit oscillating, flashing, or rotating red; two permit rotating or flashing red; one permits alternating, flashing or blinking red; seven permit flashing red -- one state limits this to fire police and one state to fire captains; one permits alternately flashing red and three states permit red lights, but do not specify the type. Two states permit oscillating, rotating or flashing white lights and one state permits rotating or flashing white lights. One state permits oscillating, rotating or flashing red and white lights and one state permits rotating red and white lights.

"One state permits alternately flashing blue lights on ambulances. Eleven states permit red lights on ambulances: three permit oscillating, rotating or flashing red; two permit rotating or flashing red; one permits alternating, flashing or blinking red; two permit flashing red and three permit red lights, but do not specify the type of light. Three states permit oscillating, rotating or flashing white lights. Two states permit oscillating, rotating or flashing red and white lights, but one statute applies to local ambulances only.

"New Hampshire requires emergency lights on police, fire and rescue vehicles, but authorizes the commissioner to establish the type of light.

> "Thirty-nine states have a provision comparable to UVC 12-227(b), prohibiting the use of a red light visible to the front, except on certain vehicles. Four of the 39 also prohibit blue lights; three also prohibit green lights (as did early editions of the Code) and one state prohibits the use of any colored lamp. In addition to these 39 states, one state provides expressly that only white, yellow or amber lights may be shown to the front, except on certain vehicles. Similarly, one state permits only white or amber and one state permits only white or yellow lights."

It should be noted that "authorized emergency vehicles", as defined in the Uniform Vehicle Code, include in general (unless otherwise defined by the state) only publicly owned police and fire vehicles and ambulances. The Committee staff report quoted above also contains comparable statistics -- omitted here -- on existing state rules concerning lights on other categories of vehicles. These include: (a) school buses; (b) snow-removal vehicles; (c) other highway-maintenance vehicles; (d) tow trucks; (e) mail vehicles; (f) volunteer firemen's vehicles; (g) public-utility emergency or repair vehicles; (h) public service vehicles; (i) funeral-home vehicles; (j) vehicles towing buildings; (k) pilot cars for oversized loads; (l) the oversized loads themselves; (m) mobile units of news media; (n) Civil Defense vehicles; (o) Civil Air Patrol vehicles; (p) State Medical Examiners' and coroners' vehicles; (q) doctors' cars in general; (r) state's attorneys' vehicles; (s) pest-abatement vehicles; (t) levee-maintenance vehicles; (u) sanitation vehicles; (v) church buses; (w) pet ambulances; (x) armored cars; and (y) forest wardens' vehicles.

No single state has regulations separately covering all or even most of these "semi-emergency" categories, so that within some particular states, the number of different emergency-light configurations to be memorized may be quite limited. On the other hand, there are states that permit some of their cities and counties to maintain separate emergency-light codes. A driver making a long (non-routine) trip, moving through many jurisdictions with different light codes, cannot be expected to be familiar with all the warning-light configurations he encounters. As a result, such drivers must limit themselves to noting the approach of vehicles bearing *any* rotating, flashing, or otherwise unusual patterns of lights, and they will often pull over or proceed cautiously without knowing what type of vehicle is being encountered. *In effect, then, for the considerable volume of traffic traversing jurisdictions with unfamiliar warning-light rules, a one-signal system of emergency-vehicle lighting* (as described in Section 2.5.) *is now operative.*

The only way to increase above 1 the number of signal categories reliably recognized by all inter-jurisdictional drivers is to move to a system that is nationally accepted. It would be more effective to go to a signal system in which each distinct signal was nationally agreed upon in every detail; but in the absence of such agreement, national consistency could also be achieved with respect to two or more general categories of signals. For example, if a two-category system were desired, all jurisdictions might be able to agree that yellow lights always indicate danger due to a slow-moving or standing vehicle, while the lights used to indicate danger from a rapidly moving vehicle could be of any other color desired locally. It would be easy enough for all drivers to learn a "yellow/other" system, but it is likely that drivers could react a bit more quickly to a specific system such as yellow/red, or yellow/blue, etc. (See Section 4.1 for a discussion of reaction time.)

3. Some Major Types of Warning Lights

3.1. Scope of the List

Anyone charged with the responsibility for purchasing warning lights for emergency vehicles is faced with a situation of considerable complexity. There is available a wide and confusing variety of such lights, with different optical, mechanical, and electrical characteristics. They are produced by a number of manufacturers, and sold by a considerably larger number of distributors (see Section 11). The catalogs of many of these manufacturers and distributors have been reviewed and a sizable selection of warning lights has been purchased for exploratory physical and perceptual study at NBS. These lights, which were not acquired for the purpose of routine product testing, were meant to cover a variety of available types, regardless of manufacturer, within the limitations of the budget set aside for these purchases. The set of lights acquired by NBS was not meant to be a statistically representative sample of the total warning-light market, and is certainly not a complete collection.

This section lists some of the major types of warning lights, as represented by the selection of lights currently in our possession, plus reference to the manufacturers' catalogs. The list is not known to be exhaustive; there may be other types of units that have not yet come to our attention. Moreover, there are certainly specific units available that are of one of the types on the list, but differ from the description given in some details. In particular, the possibilities for variation in combination units (Section 3.5.) are almost limitless, since some manufacturers will supply roof bars containing any desired grouping of the various units they produce. It should be kept in mind that even a list as general as this one tends to become out-dated as time passes. This is due to the increasing number of innovative changes being made in emergency-vehicle warning-light products, as well as the manufacturer's supply and demand considerations.

Emergency vehicle warning lights consist of four main types -- rotating, oscillating, flashing, and steady (spotlights and floodlights) -- and each of these categories is further divided as indicated in the classification scheme that follows.

3.2. Rotating Emergency Vehicle Warning Lights

a) Rotating base carrying one, two, three or four sealed beam incandescent lamps; dome or faces of lamps are colored. (Figs. 3.2a1, 3.2a2, 3.2a3, 3.2a4).*

b) Unit of basic type of Fig. 3.2a4 (four sealed-beam lamps) with alternate lamps clear, one tilted up (spot), the other tilted down (flood); other lamp faces colored red; dome clear. (Fig. 3.2b).

c) Rotating base carrying two or three sealed beam incandescent lamps rotating; one clear lamp also oscillates vertically through 90°; other lamp faces colored; dome clear. (Fig. 3.2c).

d) Single incandescent bulb with three or four concentrating lenses rotating around bulb; lenses or dome colored. (Figs. 3.2d1, 3.2d2).

e) Single incandescent bulb with parabolic reflector rotating around bulb; dome colored. (Figs. 3.2e1, 3.2e2, 3.2e3).

f) Rotating base carrying two incandescent bulbs, each with its own reflector; dome colored. (Fig. 3.2f).

g) Rotating base carrying one or two incandescent bulbs, each bulb with evaporated-metal reflector as part of bulb envelope; dome colored. (Figure 3.2g).

h) Other.

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*The figures are collected at the end of this section.

3.3. Oscillating Emergency Vehicle Warning Lights

a) Base with three or four sealed beam incandescent lamps turns through 95°-110°, then returns faster; faces of lamps or dome colored. (Fig. 3.3a).

b) See 3.2c. Vertical oscillation combined with horizontal rotation.

c) Sealed beam incandescent lamp moves to make "figure 8" (synchronized vertical and horizontal oscillation); lens colored. (Fig. 3.3c).

d) See 3.5d. Multi-lamp oscillation.

e) Other.

3.4. Flashing Emergency Vehicle Warning Lights

a) One, two, three, or four stationary sealed beam incandescent lamps flash by current interruption; lamp faces or dome colored. (Fig. 3.4a).

b) Sealed beam incandescent lamp flashes by current interruption; hand held; lens colored. (Fig. 3.4b).

c) Single incandescent bulb flashes by current interruption; one or two concentrating fresnel lenses (front or front and back); lenses colored. (Figs. 3.4c1, 3.4c2, 3.4c3).

d) Single incandescent bulb flashes by current interruption; parabolic reflector; dome colored. (Fig. 3.4d).

e) Single incandescent bulb flashes by current interruption; dome is double (vertical and horizontal) cylindrical fresnel lens (360° coverage); lens colored. (Fig. 3.4e).

f) Gaseous capacitor-discharge flash lamp (e.g. xenon); different types of colored domes with integral or separate 360° fresnel lenses. (Figs. 3.4f, 3.5e middle).

g) Gaseous-discharge flash lamp, dome clear or colored; separate "bullseye" fresnel lens (360°, but concentrating light in forward and rearward directions). (Fig. 3.4g).

h) Pair of gaseous-discharge lamps, flashing alternately; domes clear or colored, with integral 360° fresnel lenses. (Fig. 3.4h).

i) Ring-shaped xenon flash tube coinciding with focal circle of mirror in the form of paraboloid of revolution; dome clear or colored. (Fig. 3.4i).

j) Sealed beam bulb with gaseous-discharge flash-tube source; face of lamp colored. (Fig. 3.5e ends).

k) Other.

3.5. Combination Units

a) Roof bar with two 3.2a2 units (2 sealed beam lamps in each) at opposite ends, rotating synchronously in the same direction, beam directions offset 90°; lamps faces or dome colored. (Fig. 3.5a).

b) Roof bar with two 3.2a2 units (2 sealed beam lamps in each) at opposite ends, with opaque separation (siren unit) in the middle; units rotate in opposite directions, beams in phase; three mirrors set just inboard of each unit to reflect forward the waste light directed from each lamp toward the siren; the three mirrors in each group are offset angularly to produce a supplementary triple flash as light rotates. (Fig. 3.5b).

Newer model uses four mirrors on each side to provide supplementary double flashes both forwards and backwards.

c) Roof bar with a 3.2a2 (2-lamp) or 3.2a4 (4-lamp) unit in middle, lamp faces or dome colored; at each end a forward-directed 3.4c1 or 3.4c2 unit; lenses colored.

d) Roof bar with array of five sealed beam incandescent lamps; locations: two clear at front middle, one red (colored lamp face) at rear middle, one red at each end (side); the two clear lamps oscillate around forward direction with mirror-image relationship with respect to midline; one red side lamp oscillates around to rear, the other around to front; rear-facing red oscillates around direct rearward direction; all 5 oscillations synchronous; clear dome. (Fig. 3.5d).

e) Roof bar with a 3.4f unit in middle, dome clear or colored; at each end a forward-directed 3.4j unit, lamp faces colored. Can flash center unit only, or both end units, or all three. End units operated alone flash alternately. With all three units operating, end units flash in unison and center unit flashes in alternation with end units. (Fig. 3.5e).

f) Extensible roof platform, electrically raisable from roof level to a height of 4 to 7 feet above the roof; platform may be narrow or full width of roof; unit may contain a variety of lights, typically including one or two rotating beacons and two or more floodlights.

g) Other.

3.6. Spotlights, Floodlights, and Searchlights

a) Remotely operated (electrically or mechanically); steady-burning plain incandescent or tungsten quartz halogen lamp.

b) Hand-adjusted, on universal mount; steady-burning plain incandescent or tungsten quartz halogen lamp.

c) Hand-held; steady-burning plain incandescent, tungsten quartz halogen, or continuously operated gaseous-discharge lamp.

d) See 3.4b. Flashing spotlight.

e) Other.

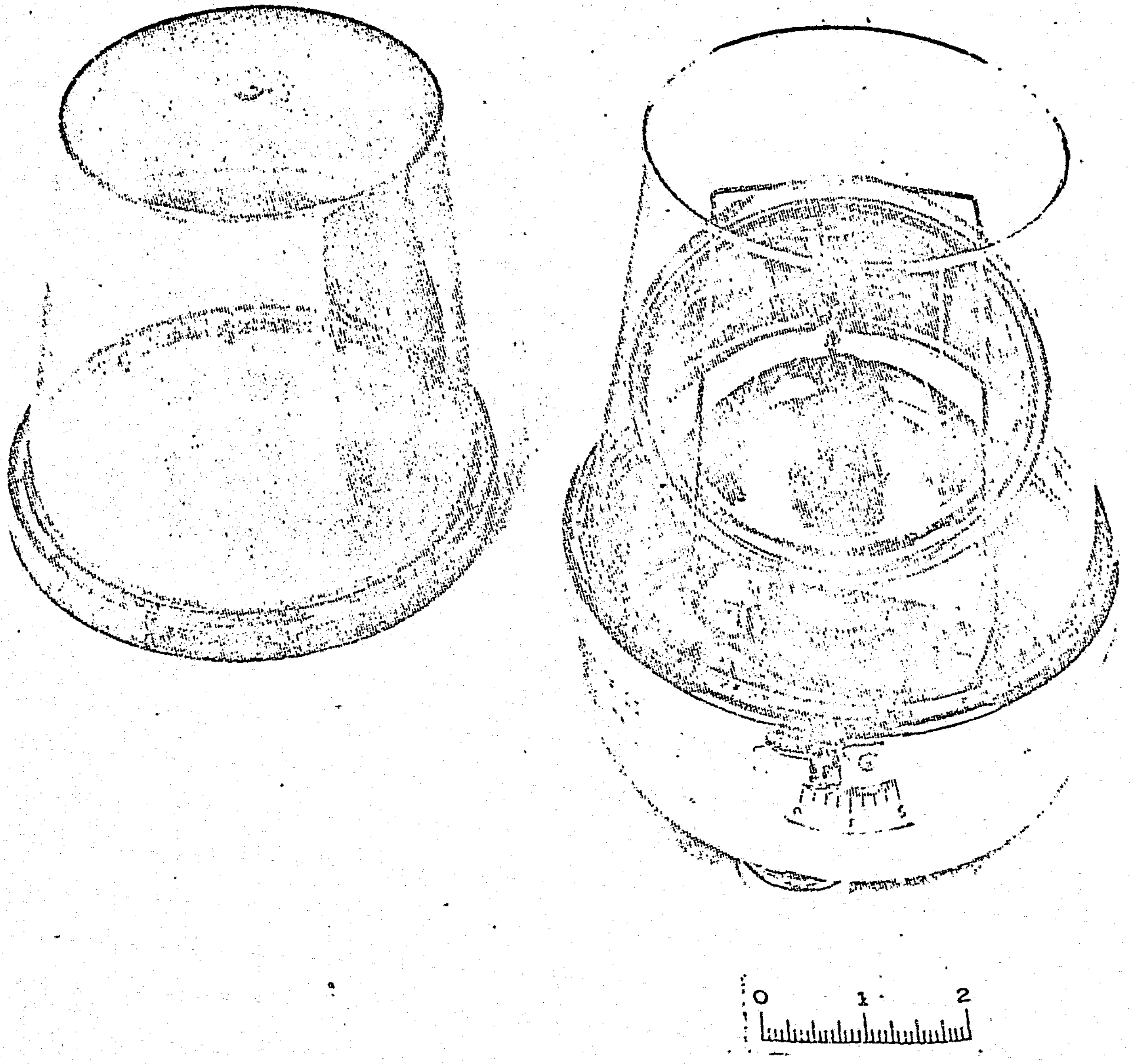


Fig. 3.2a1

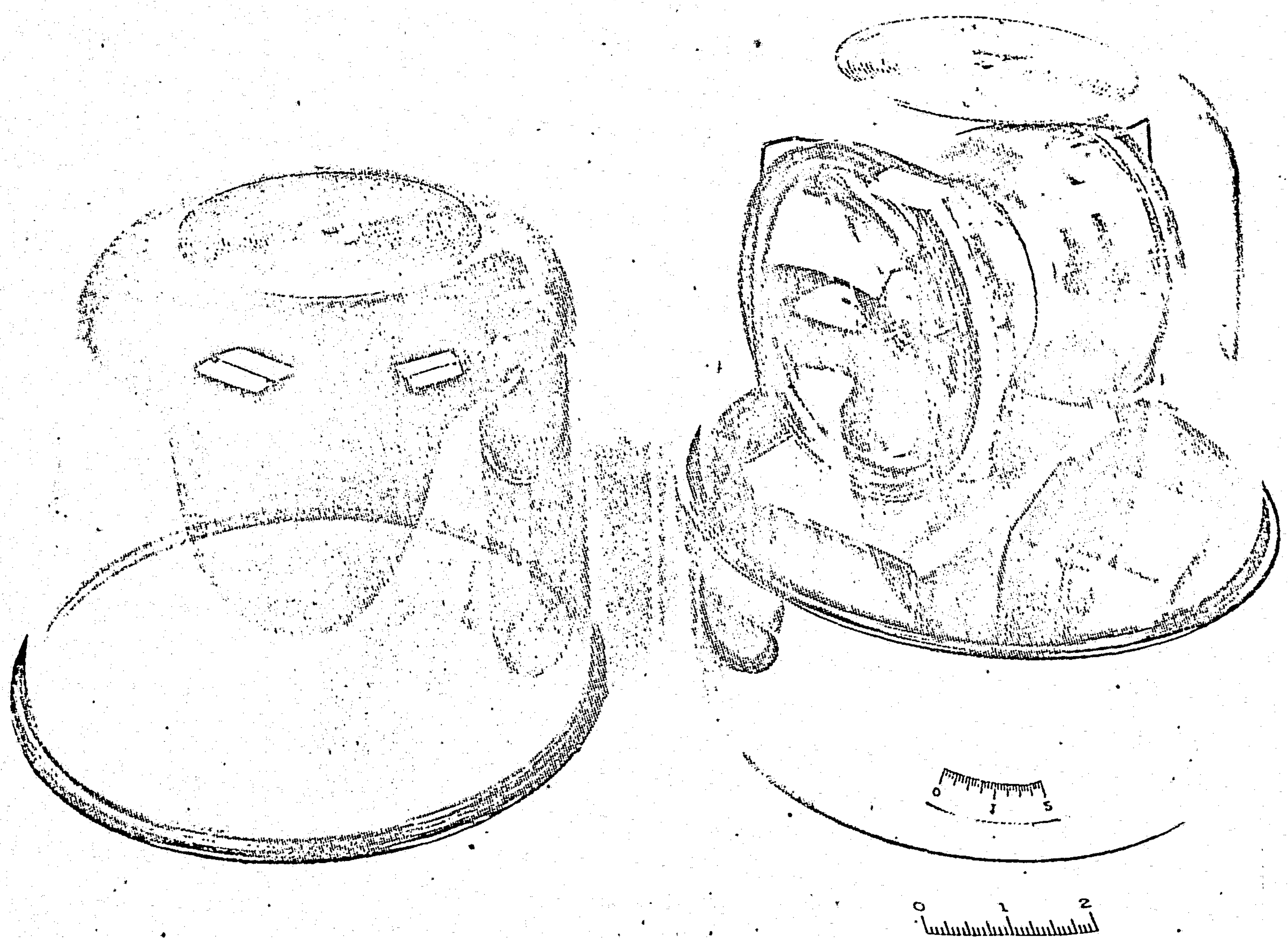


Fig. 3,2a2

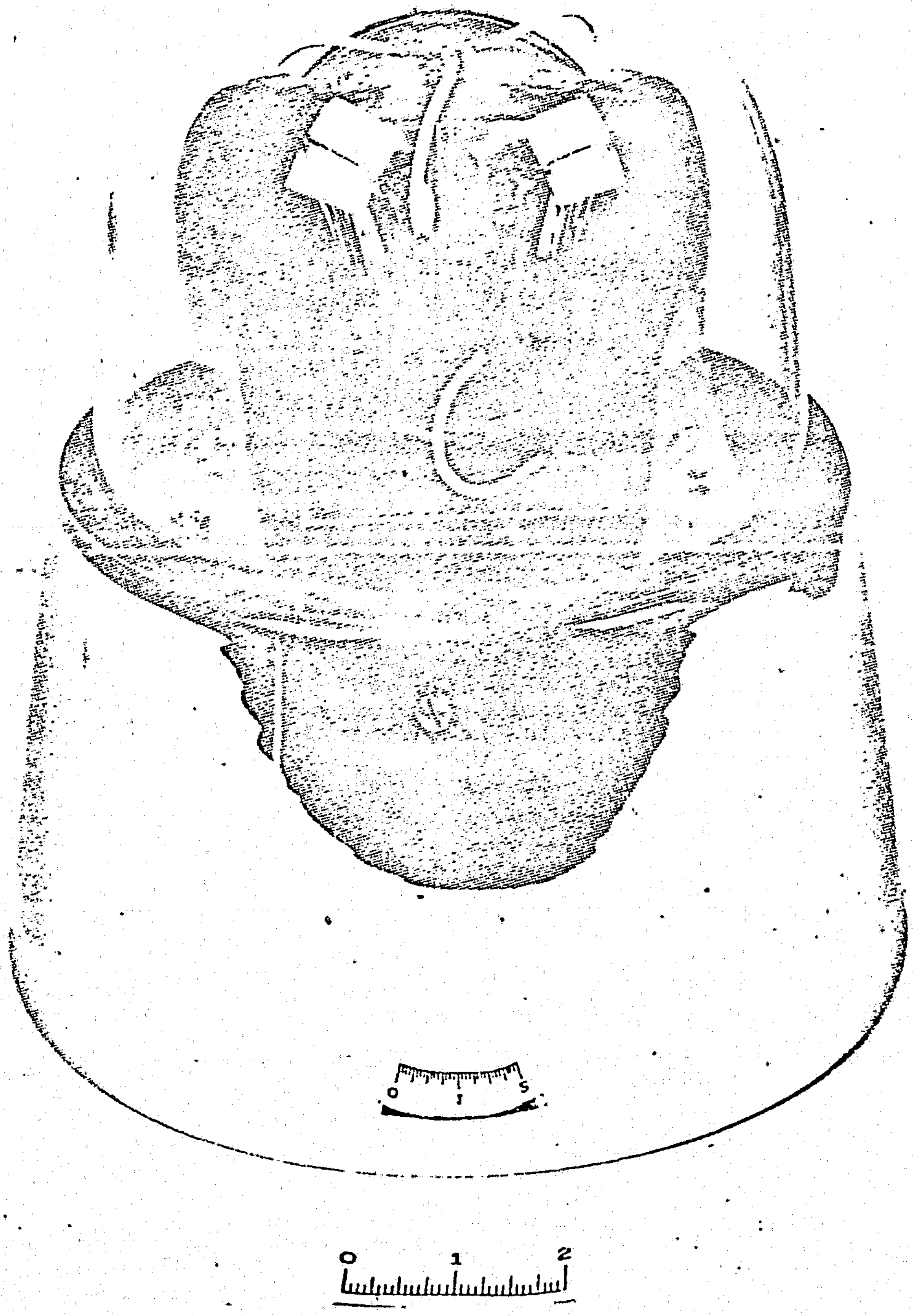
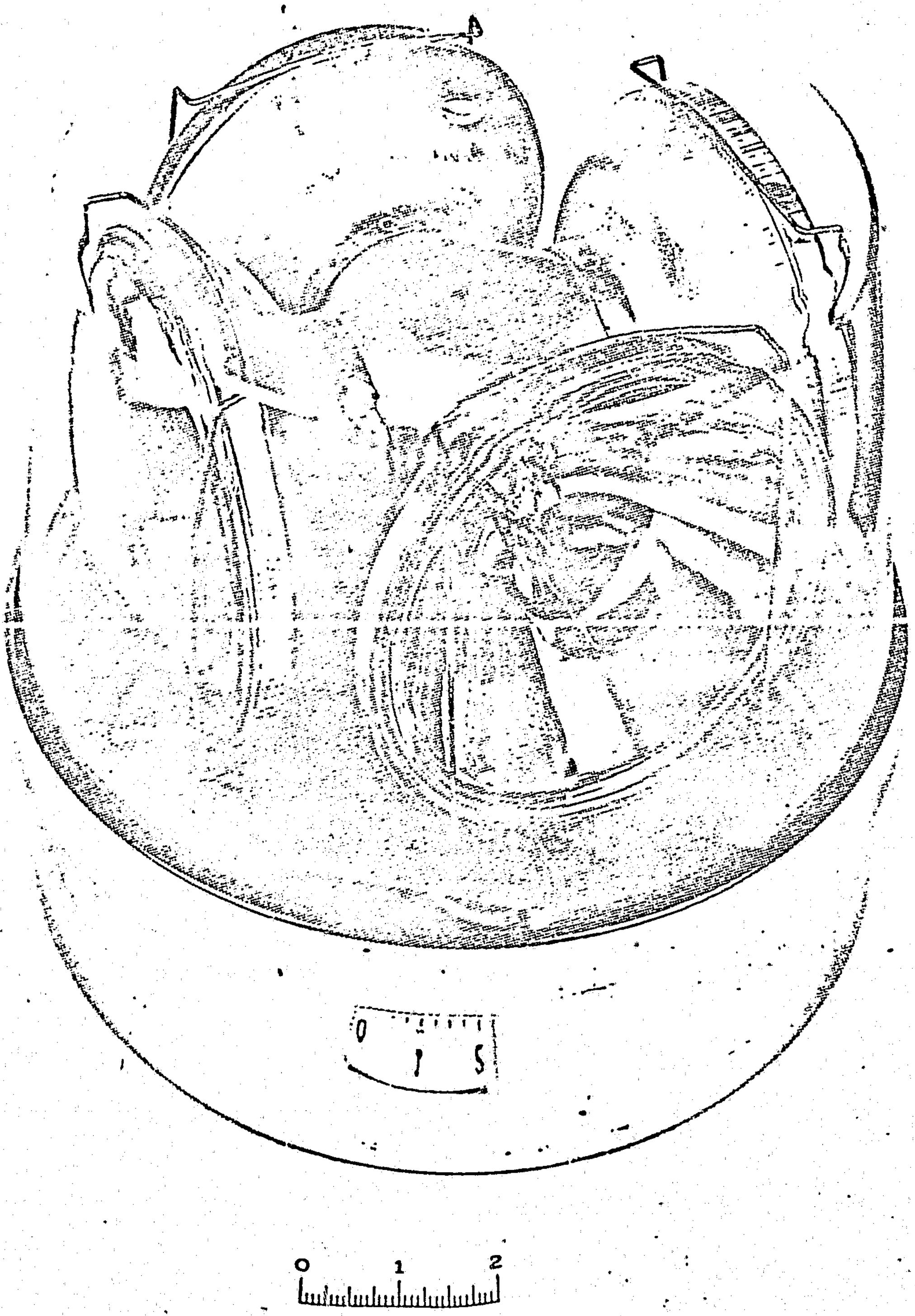


Fig. 3.2a3



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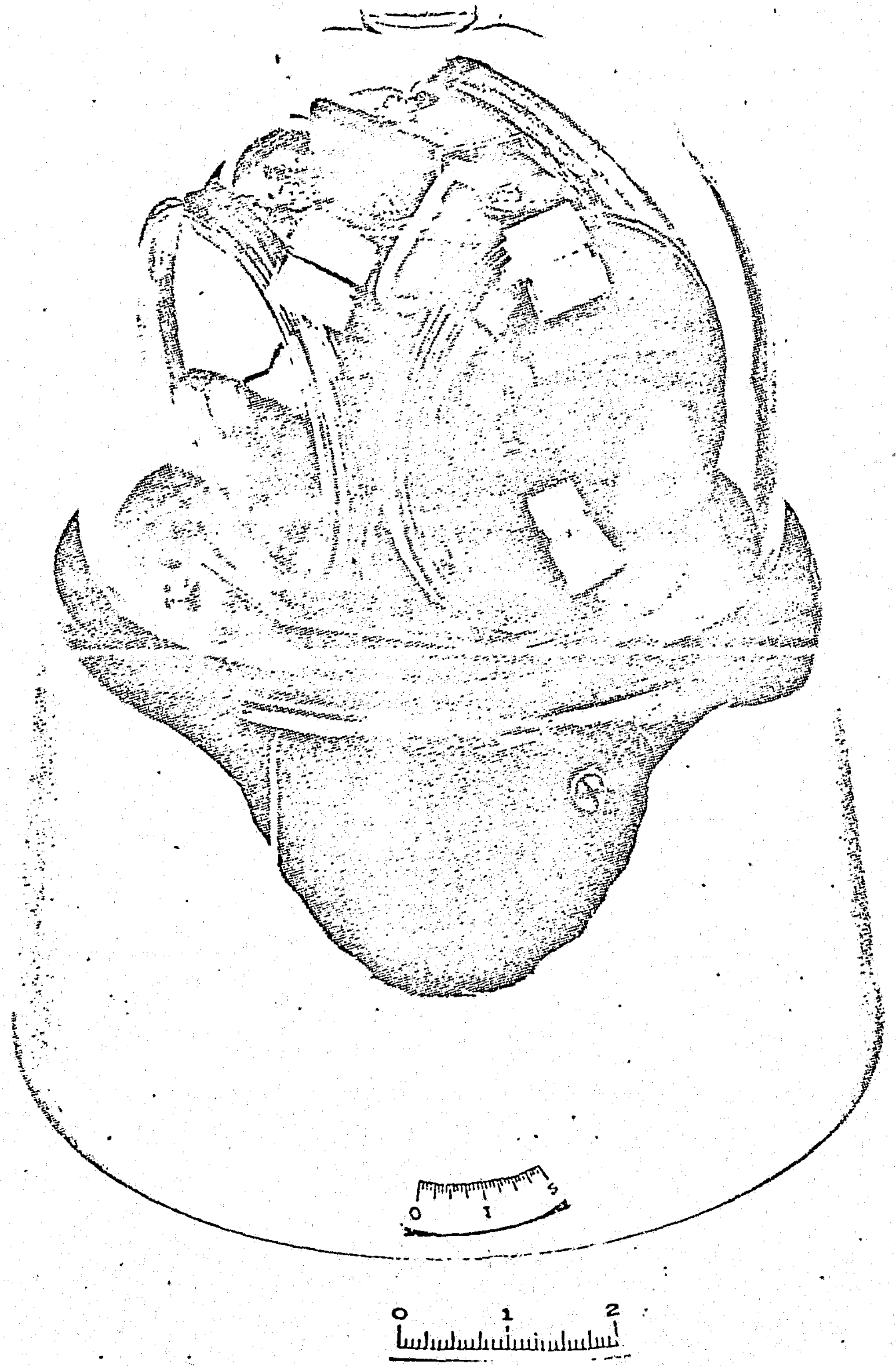


Fig. 3.2b

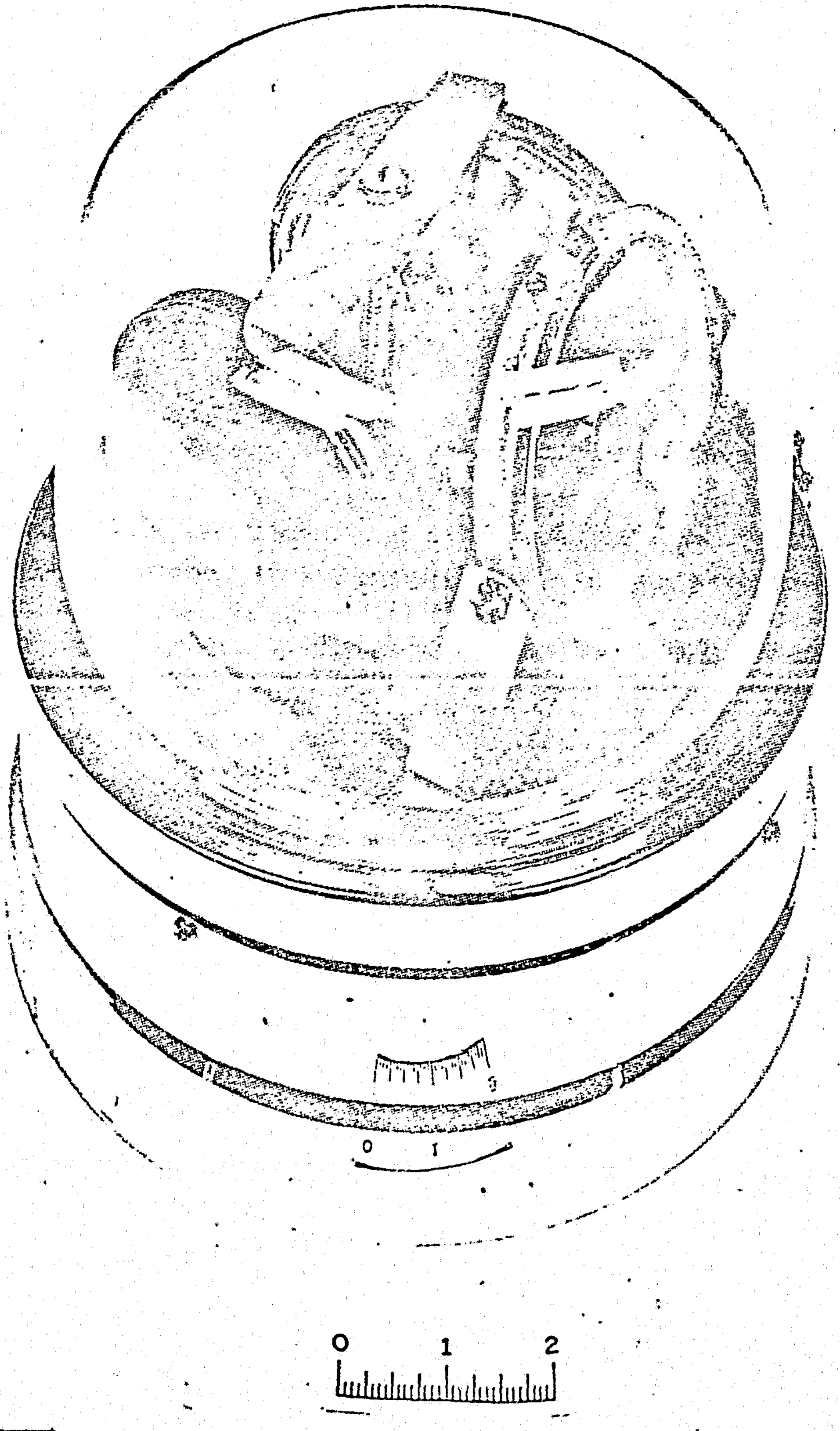
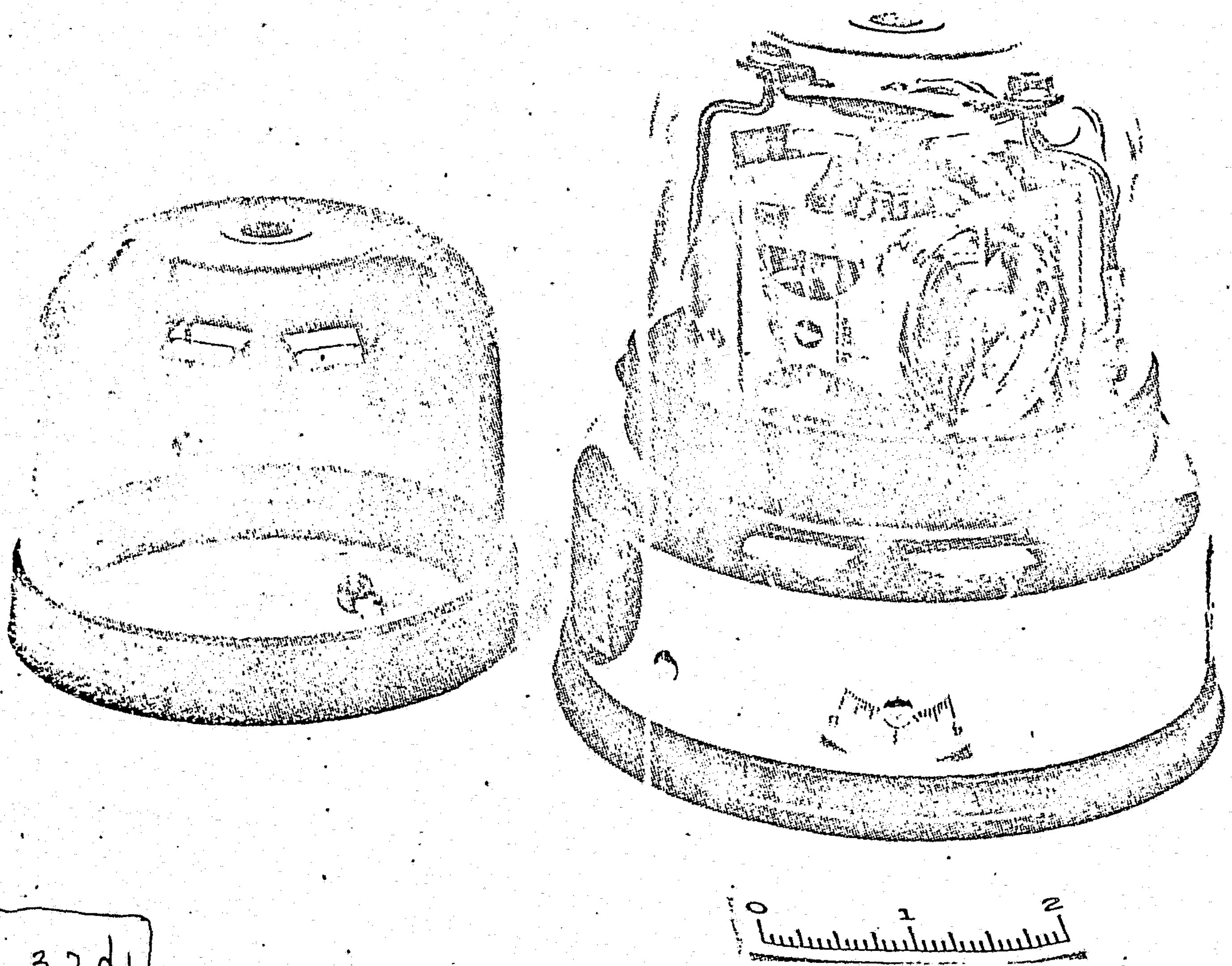


Fig. 3.2c



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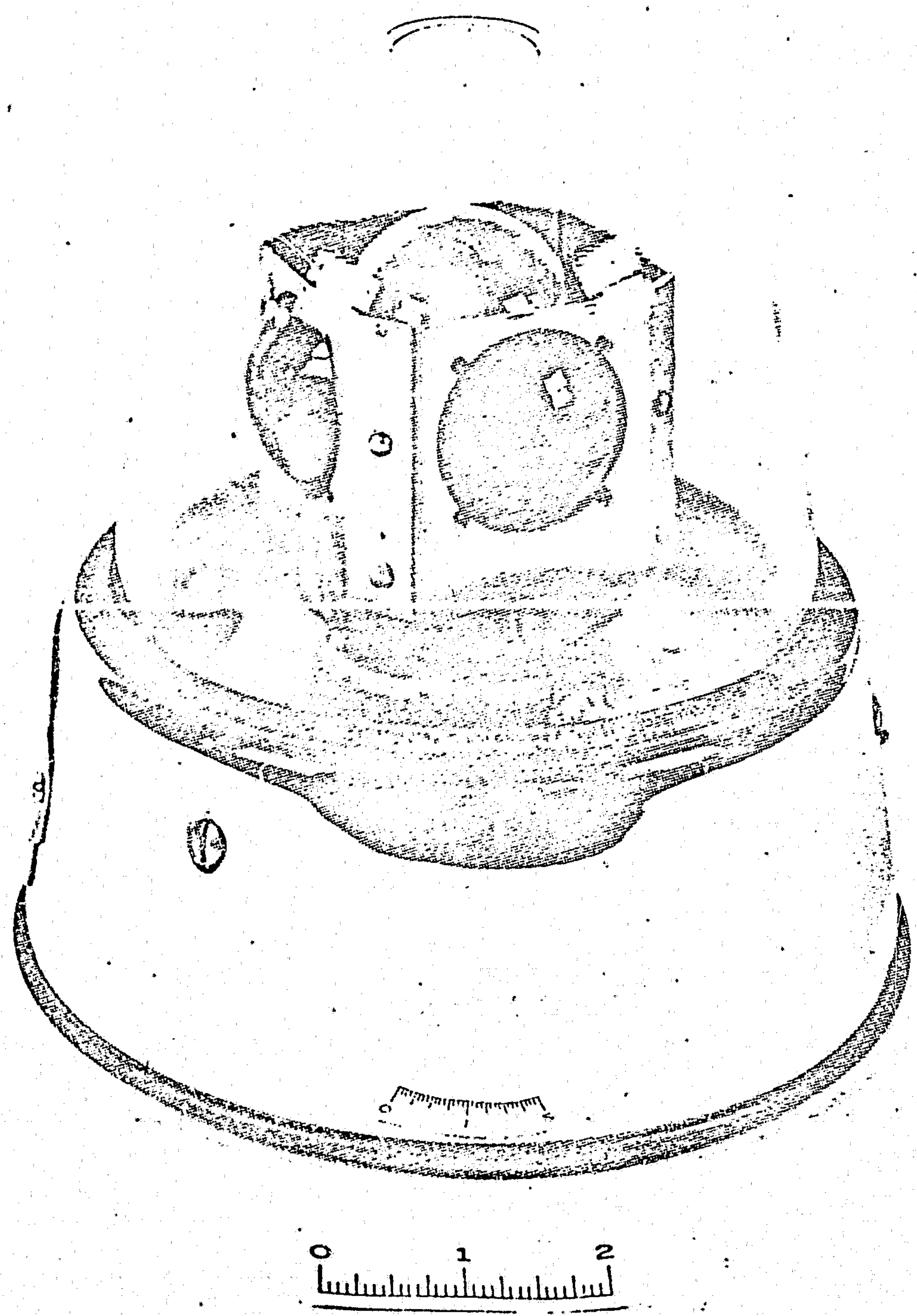
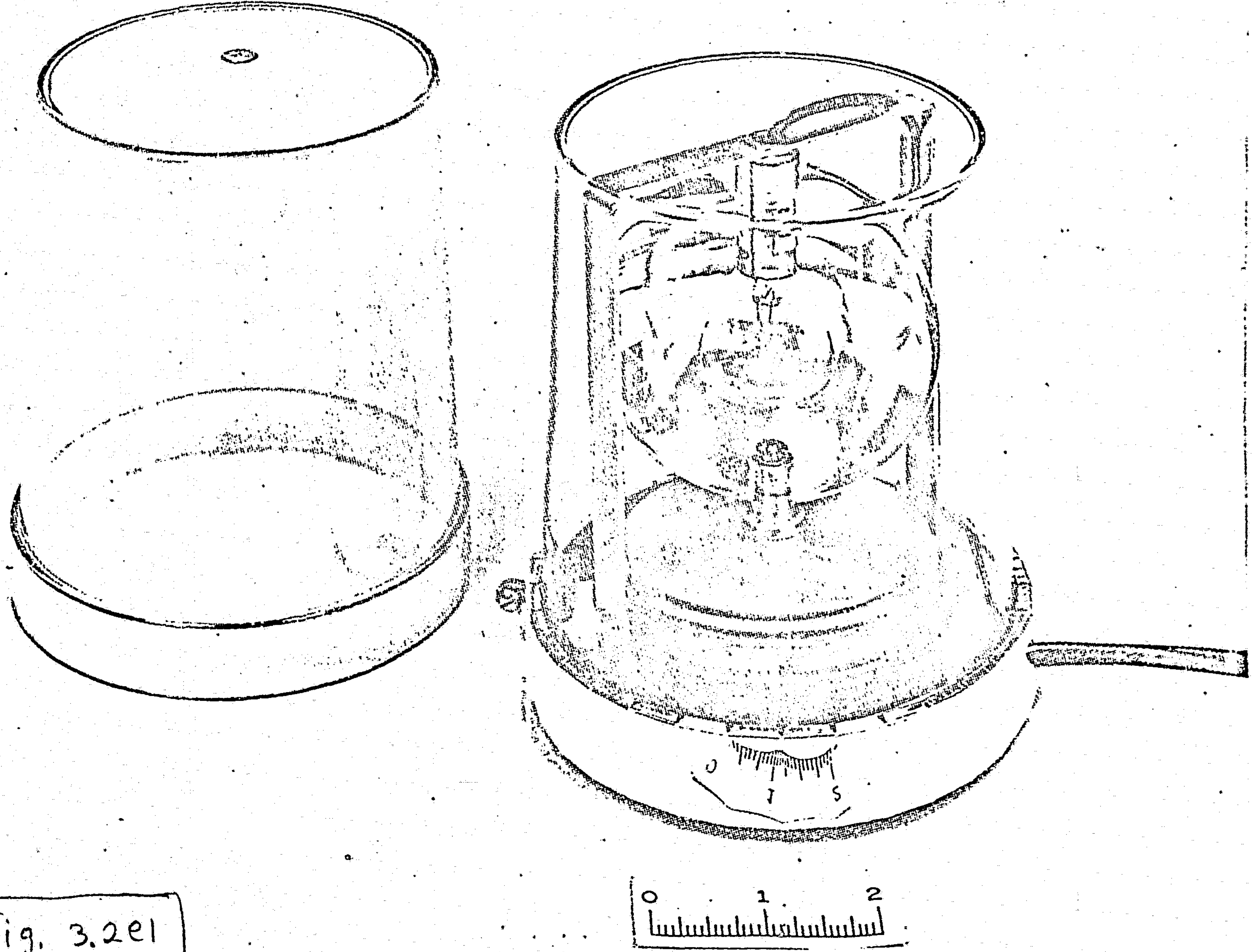


Fig. 3.2d2



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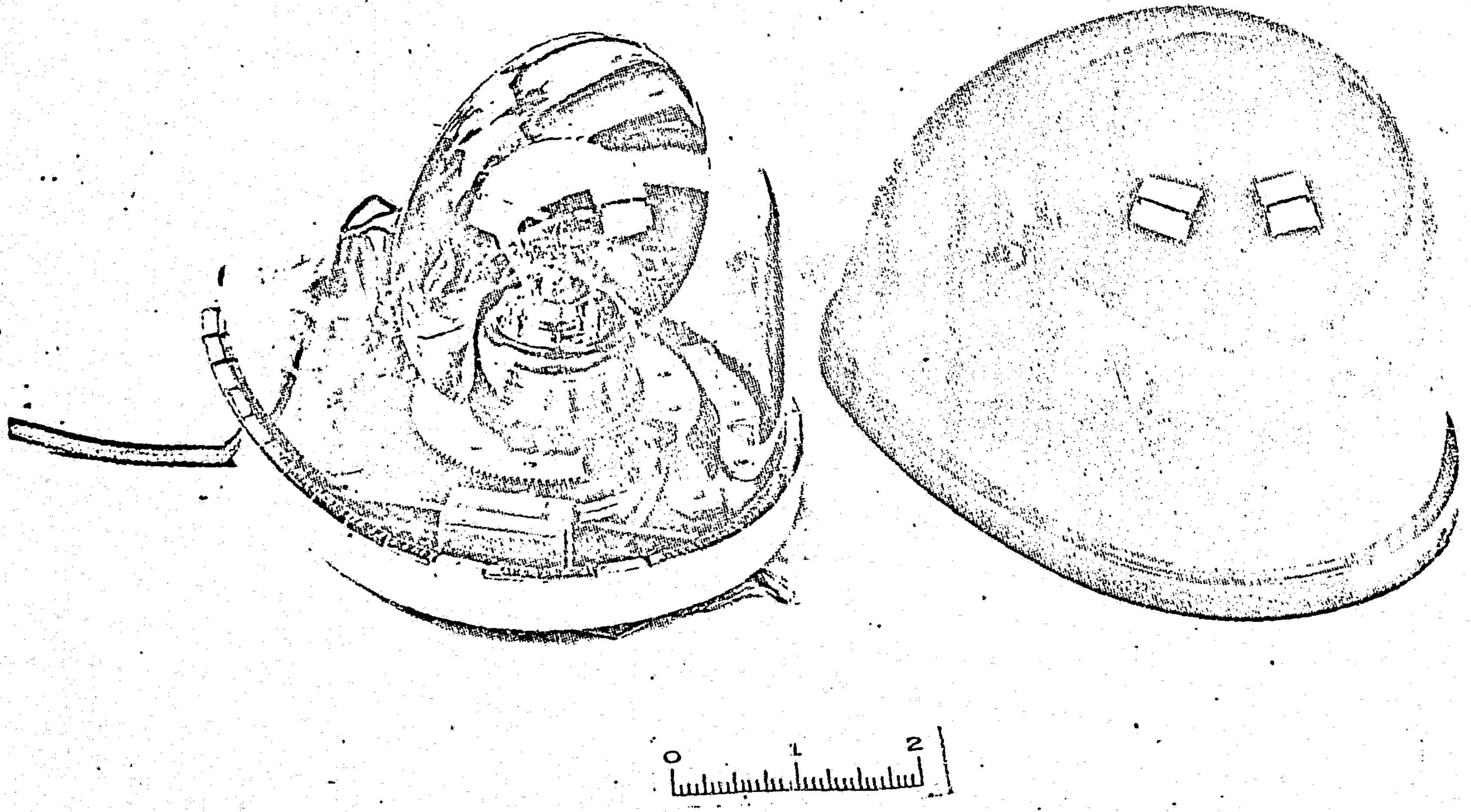

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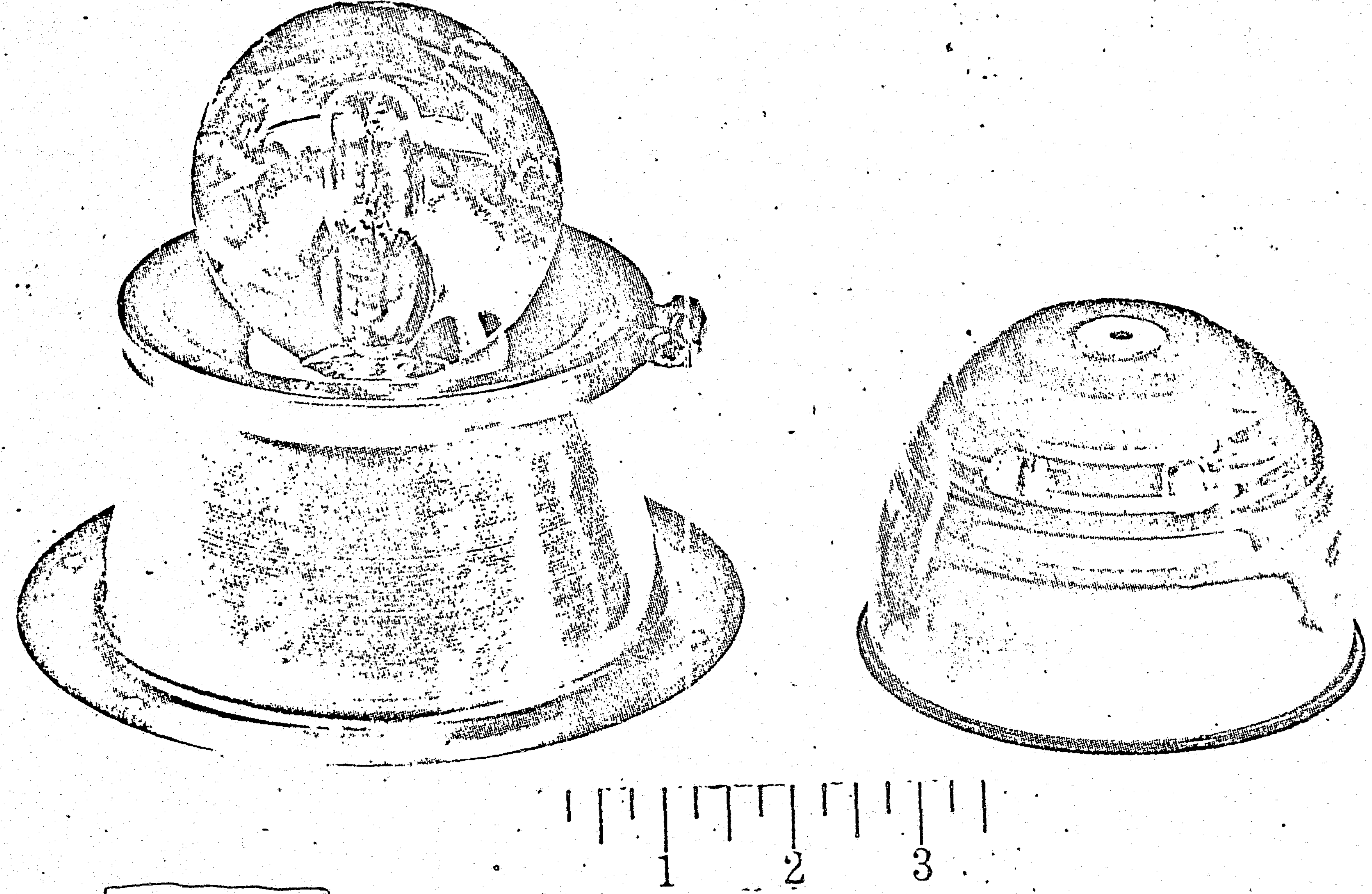

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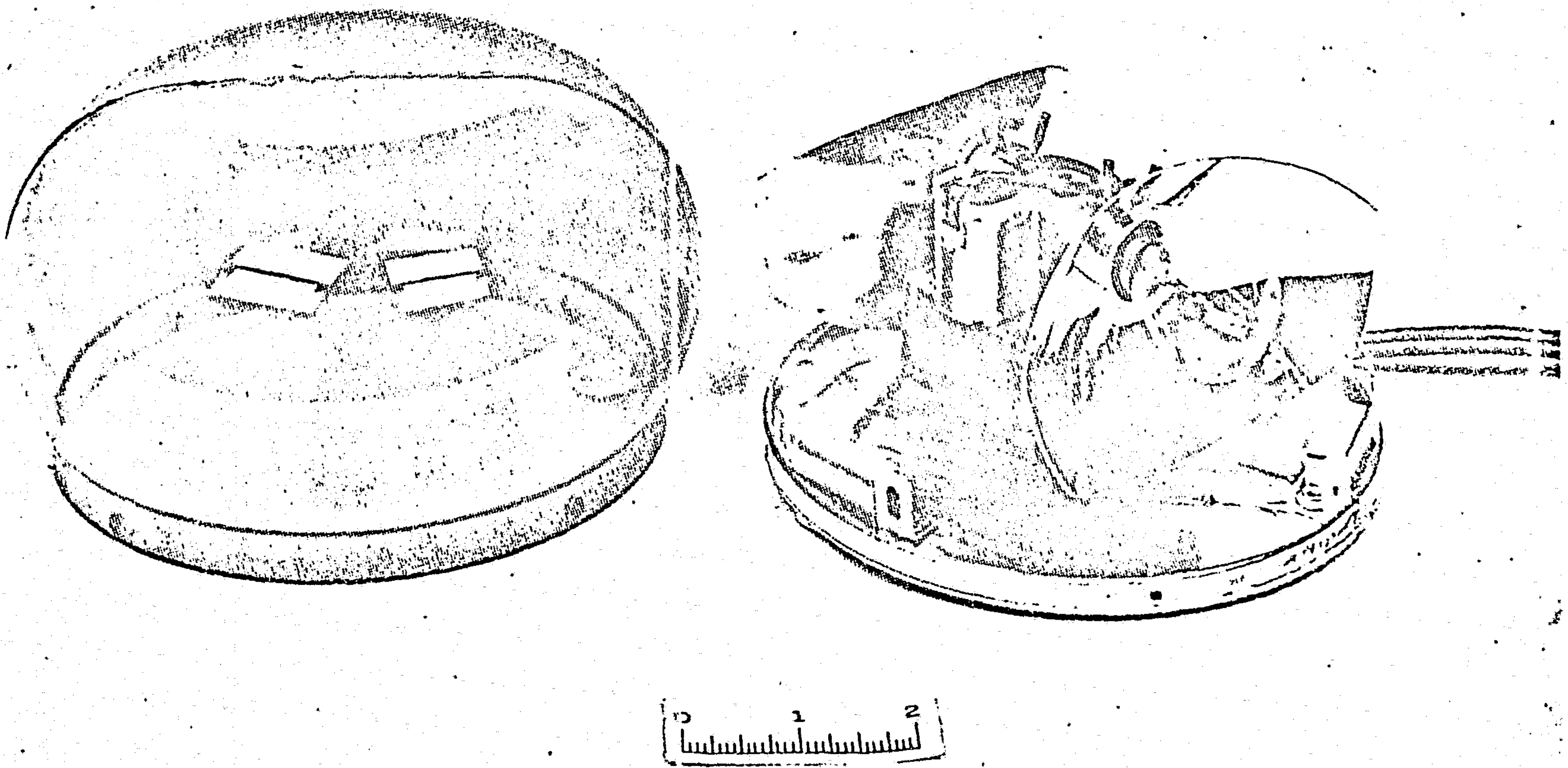


Fig. 3.2f

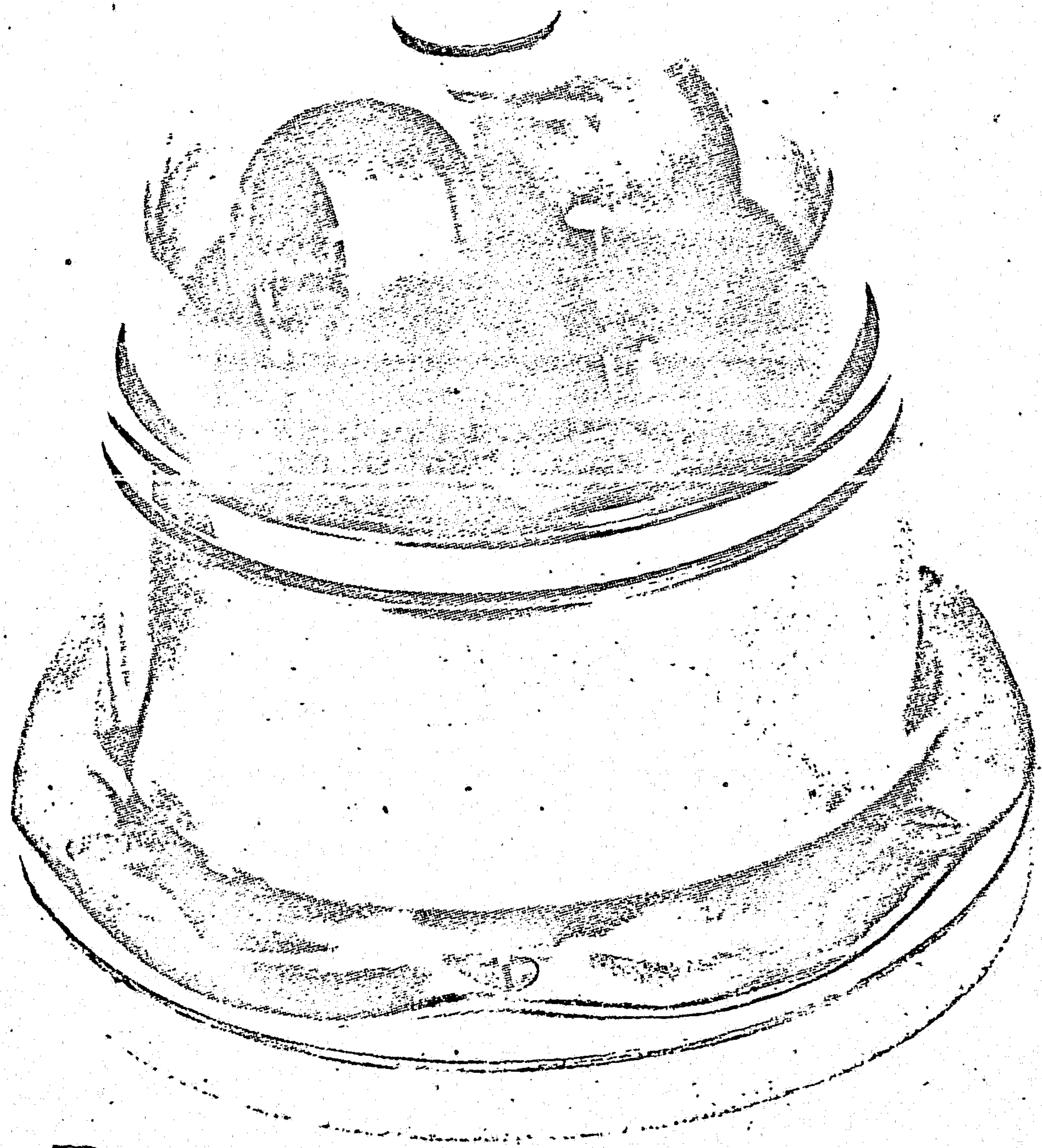


Fig. 3.29

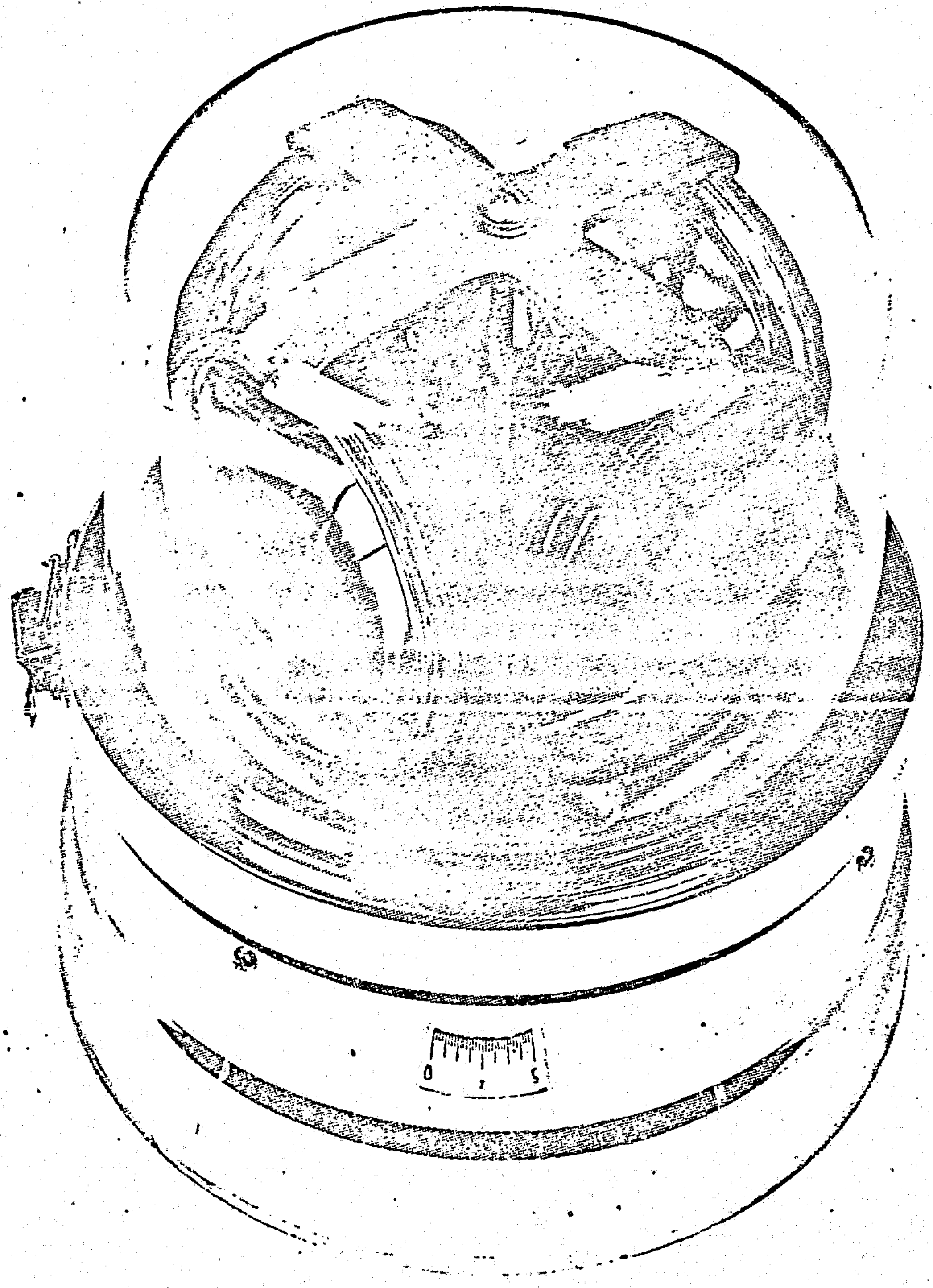


Fig. 3.3a

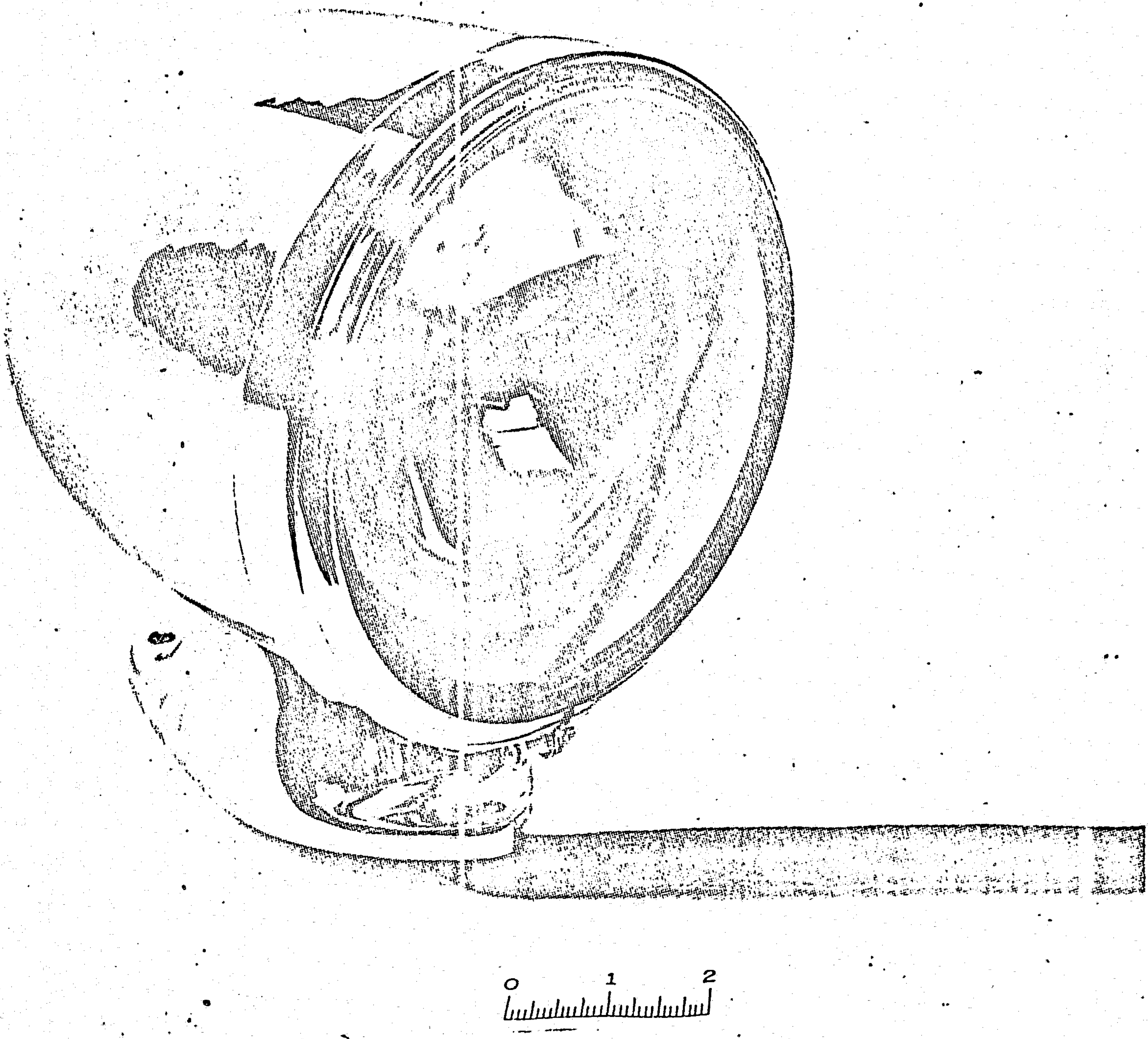
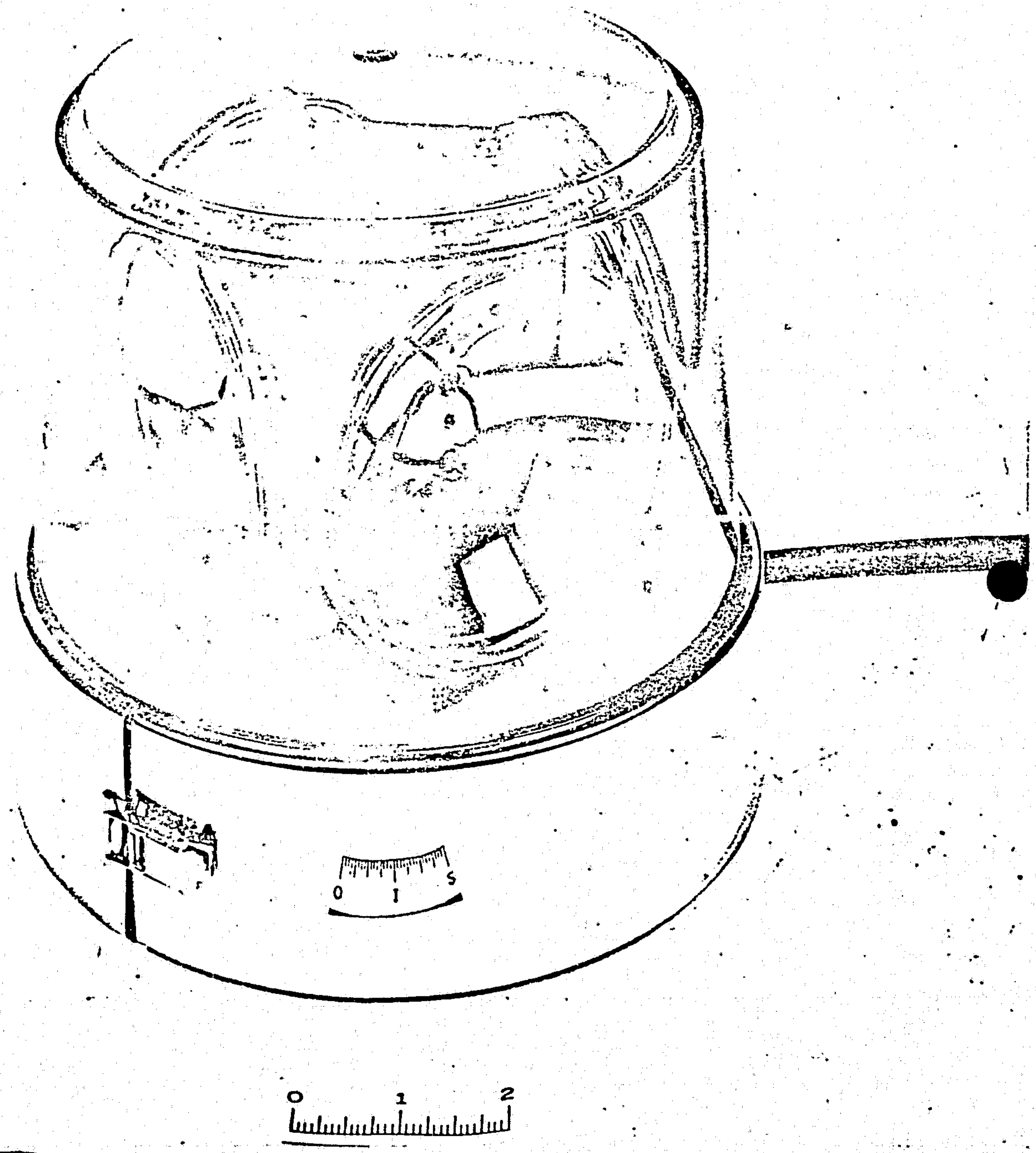


Fig. 3.3c



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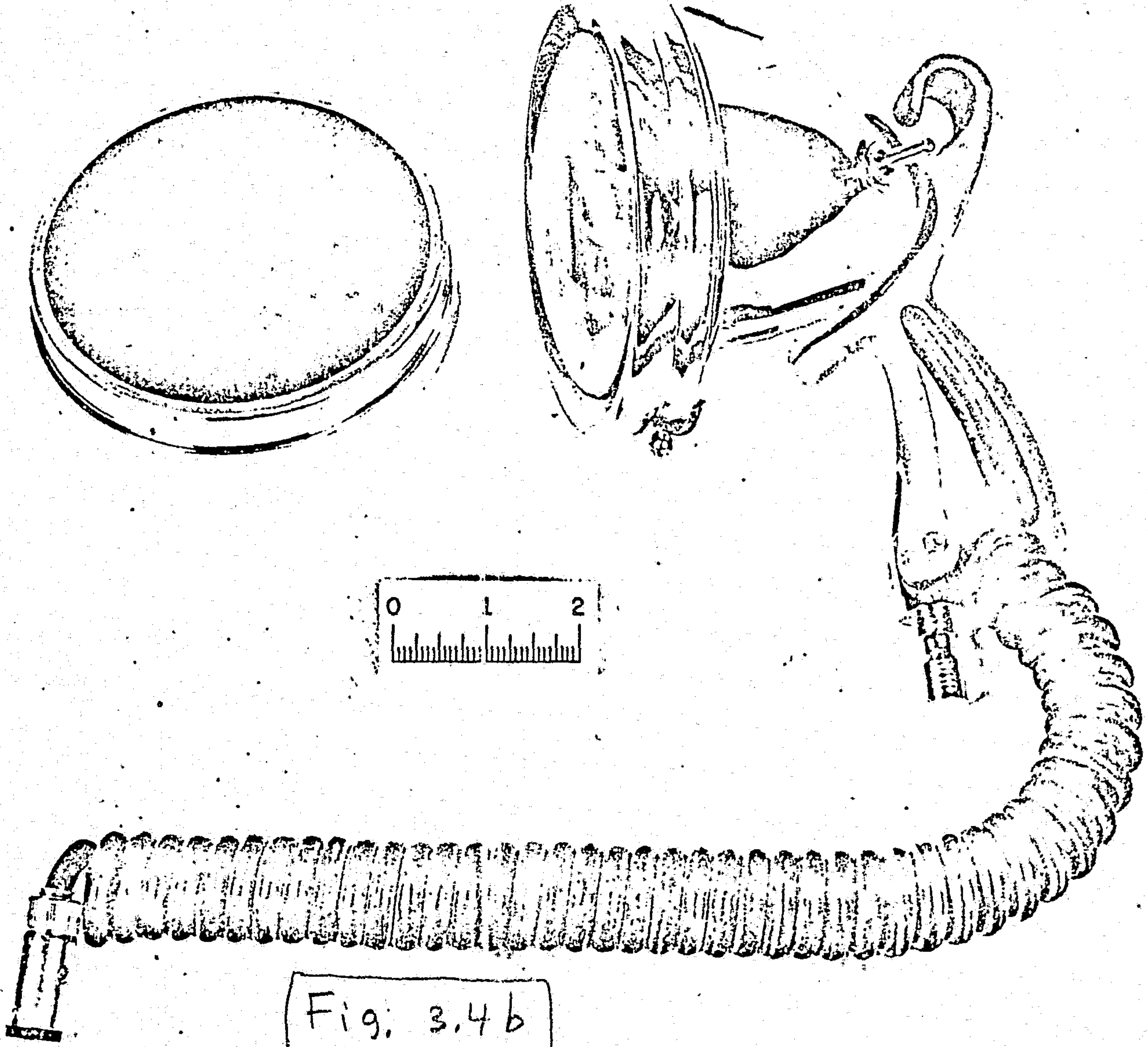
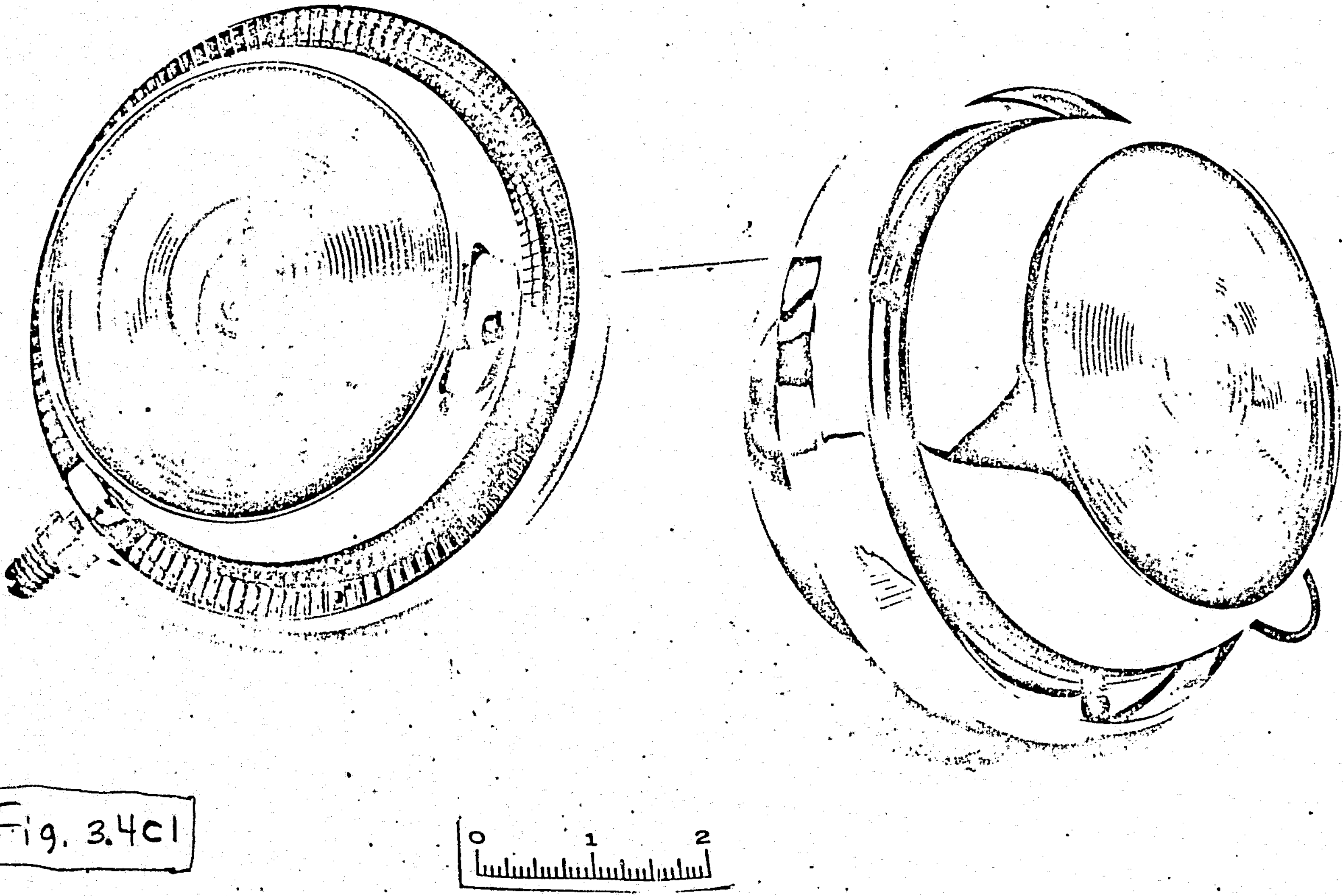


Fig. 3,4b



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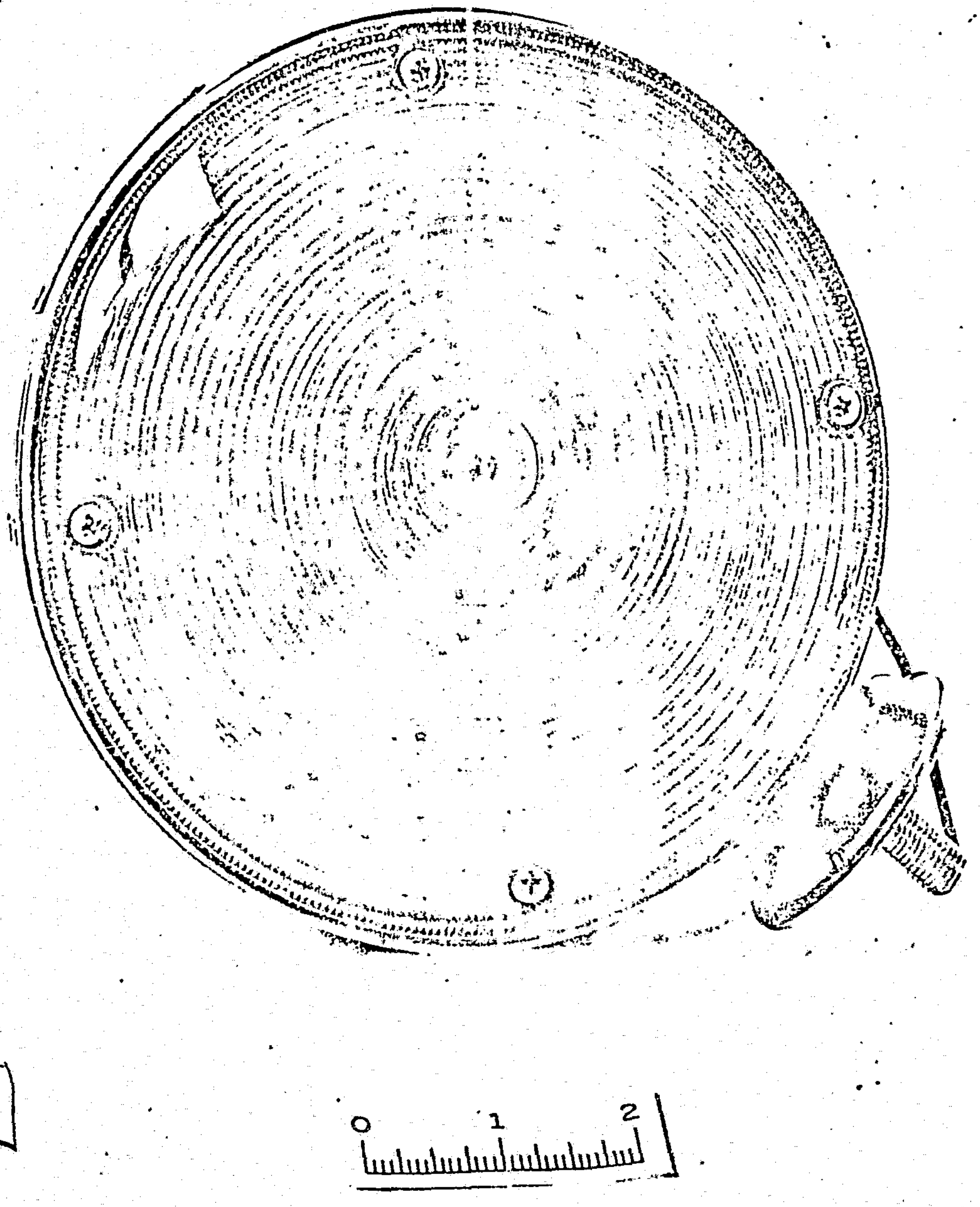
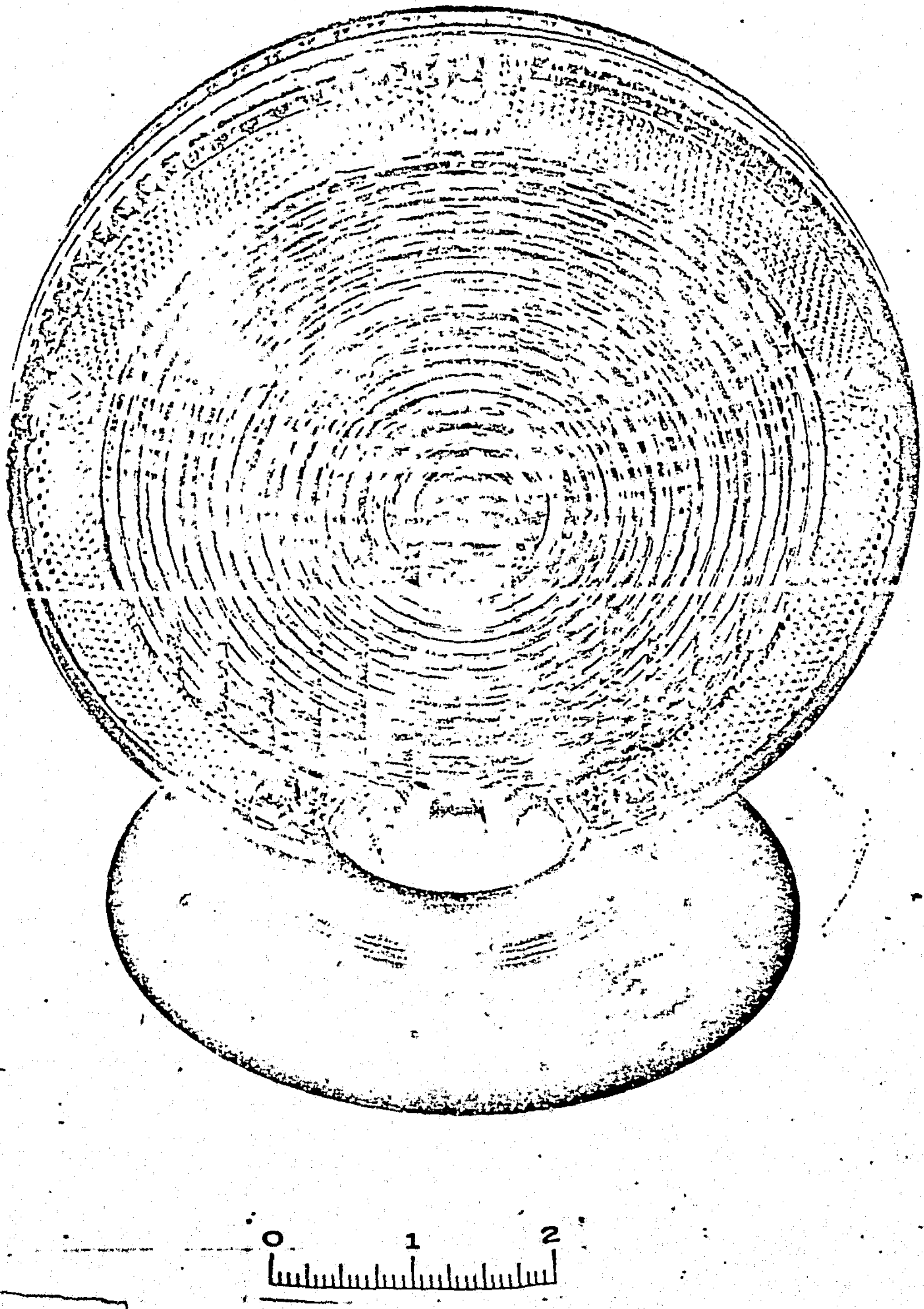


Fig. 3.4C2



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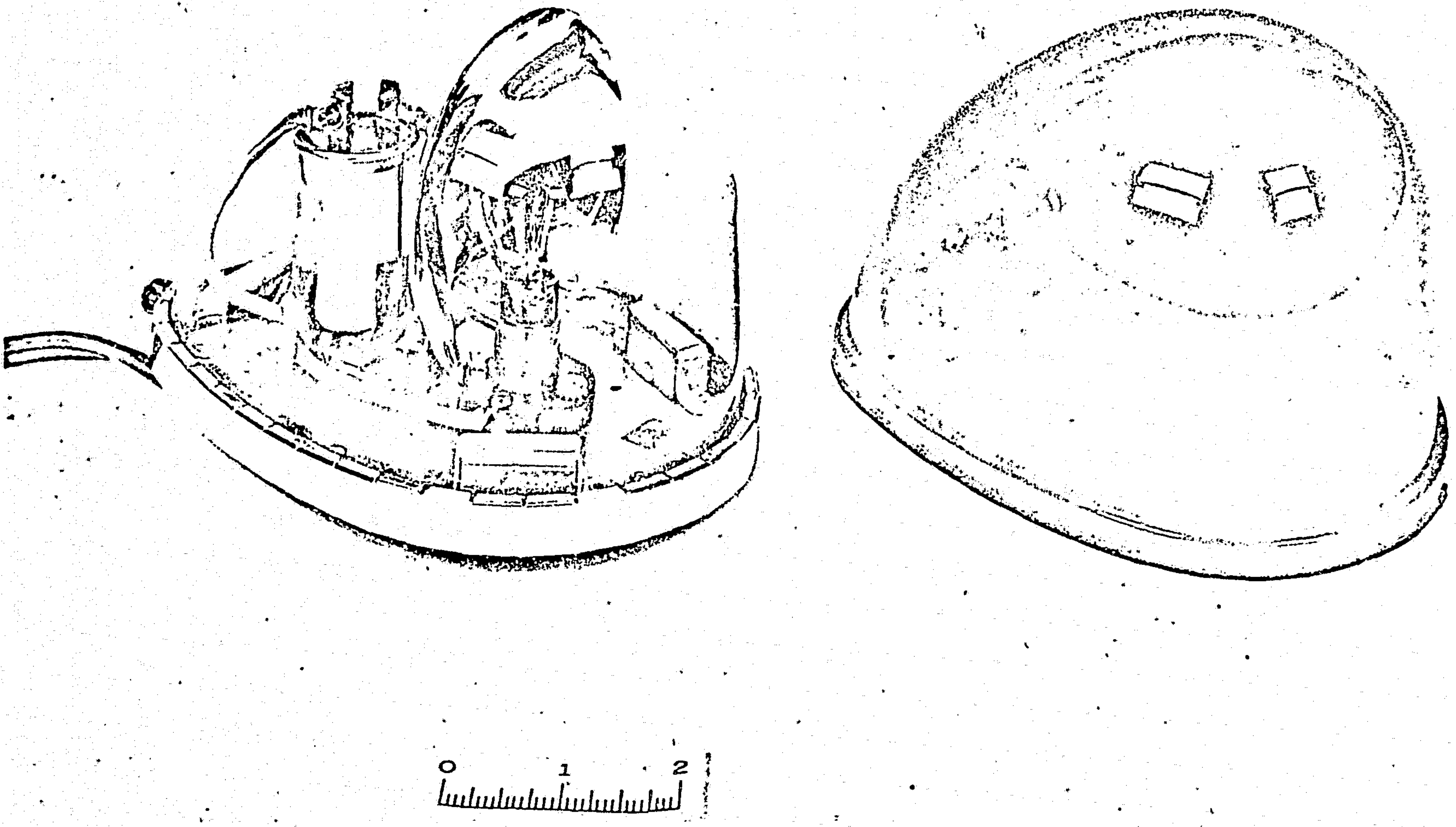

Fig. 3.4d

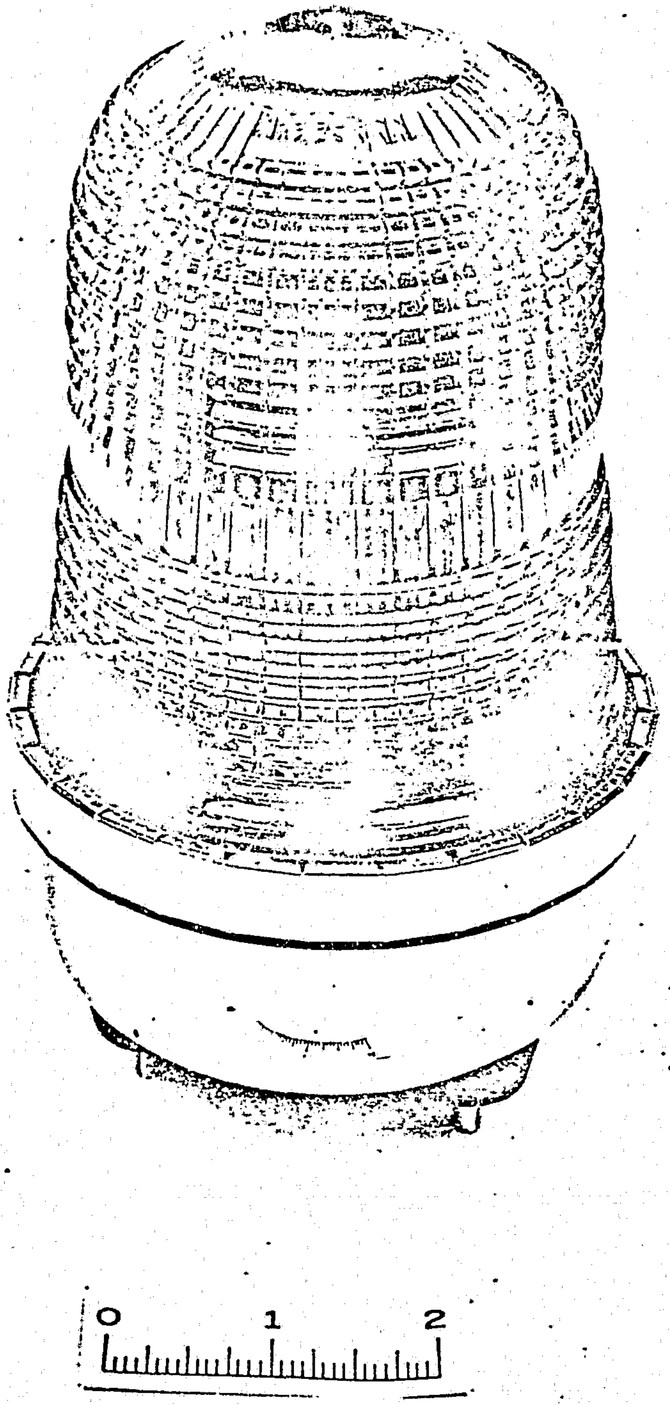

Fig. 3.4e

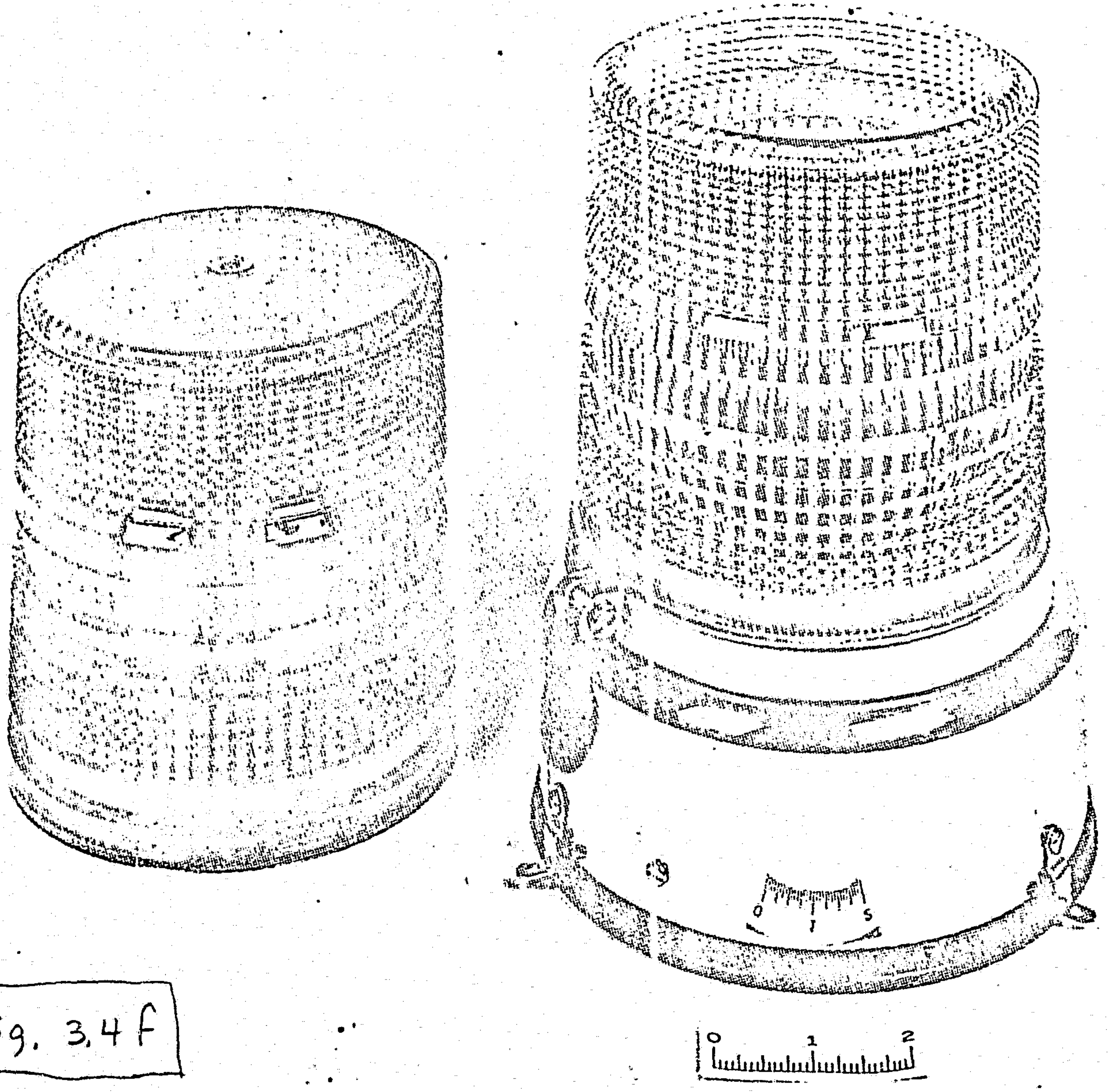

Fig. 3.4 f

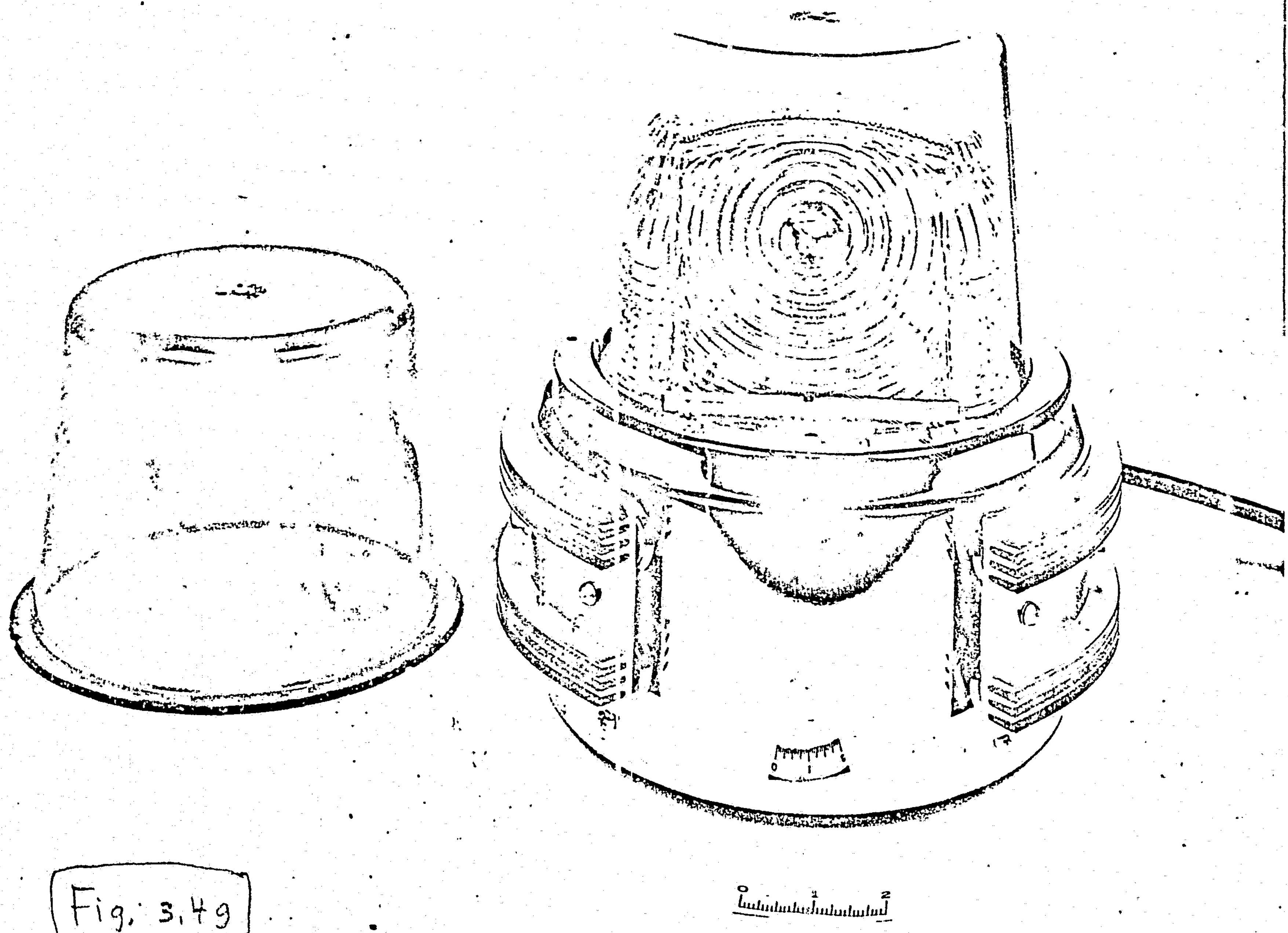

Fig. 3.49

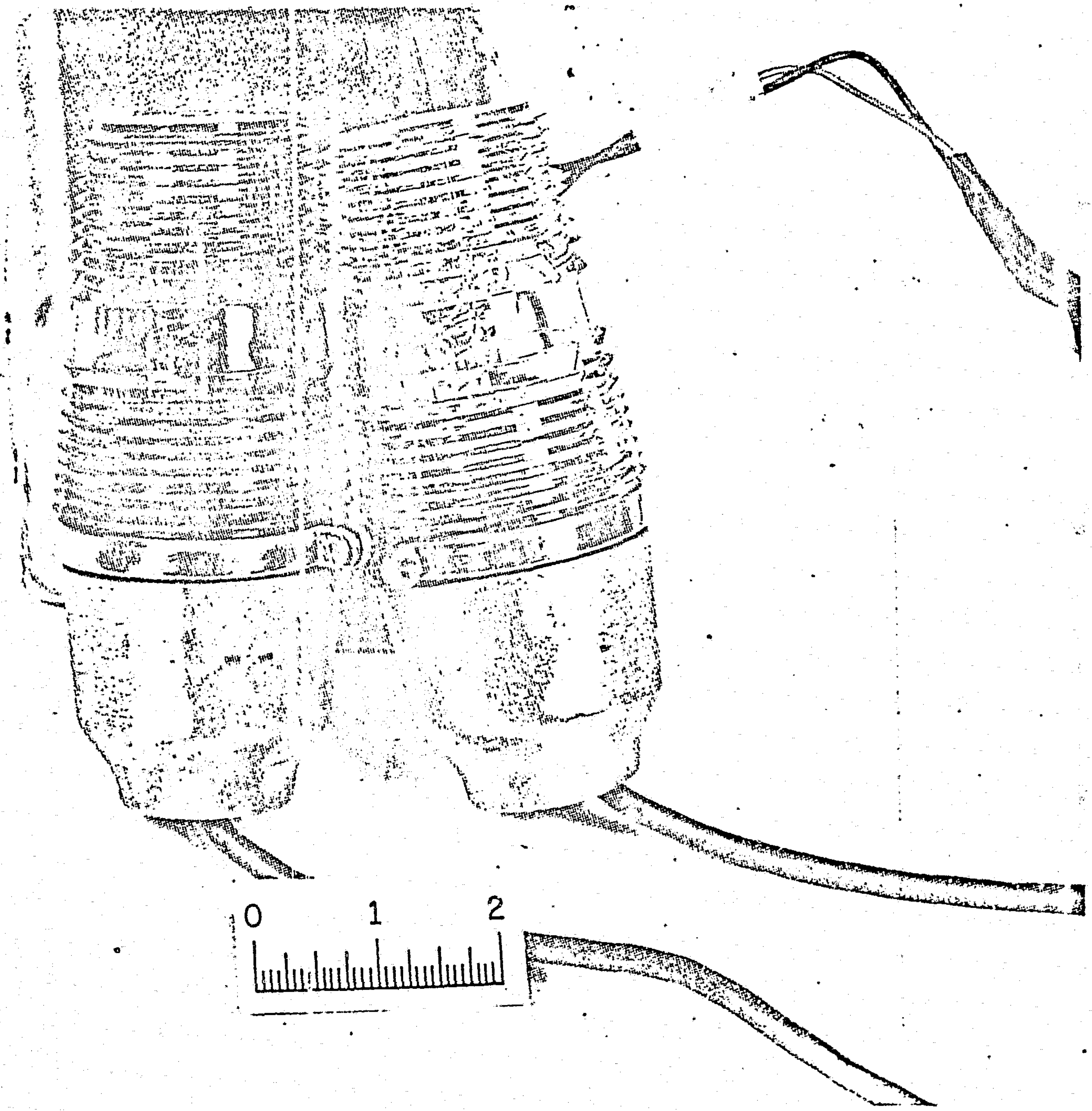

Fig. 3.4h

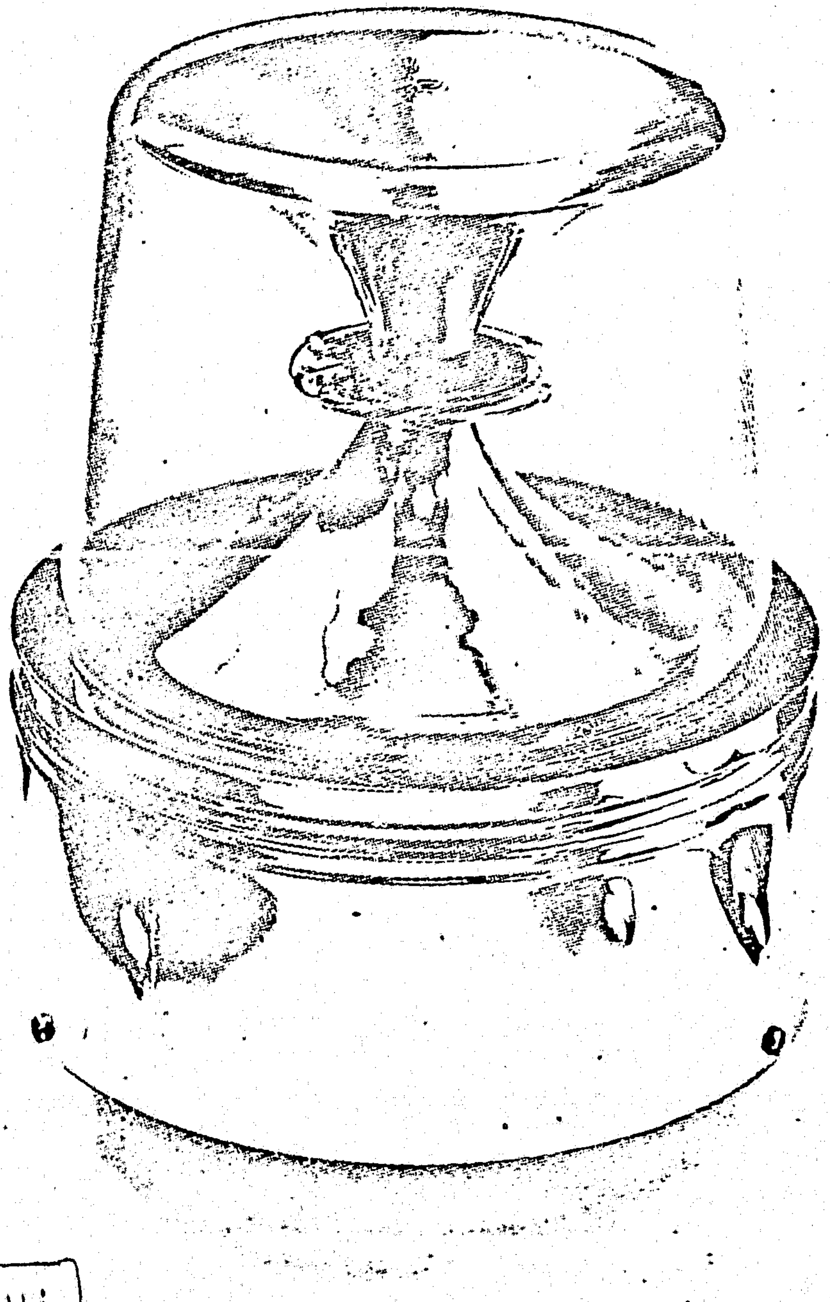

Fig. 3.4i

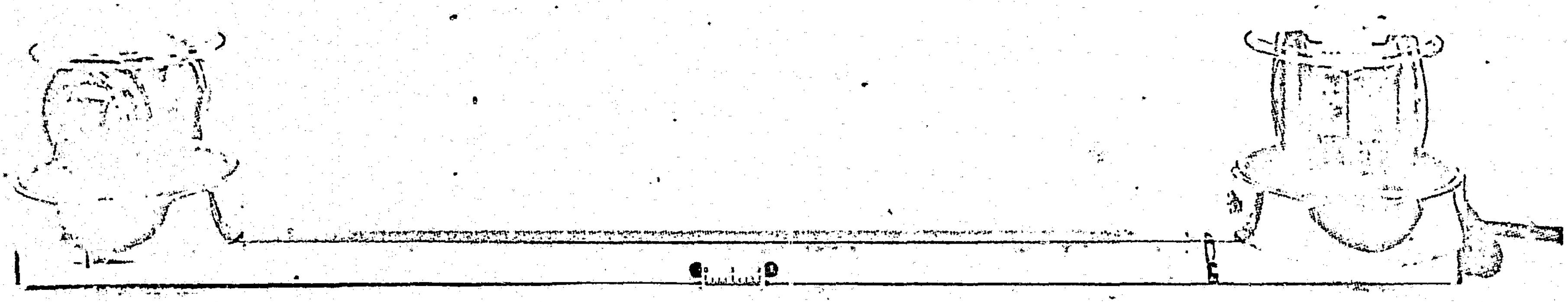

Fig. 3.5a

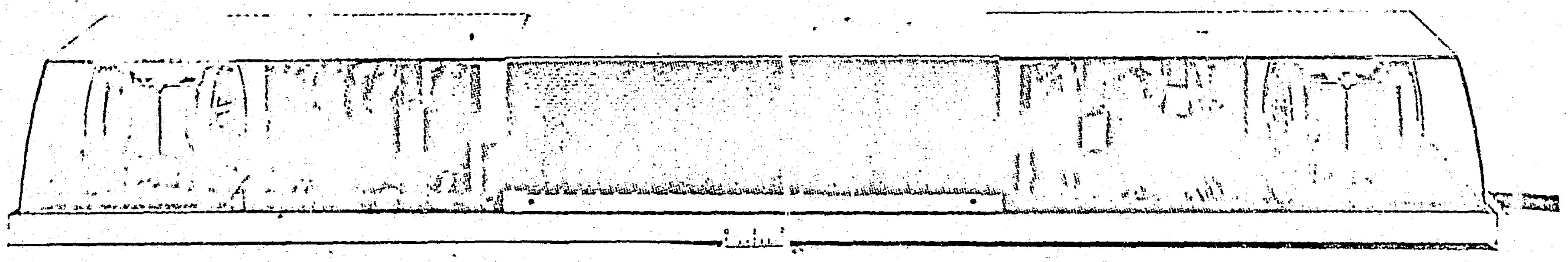

Fig. 3.5b

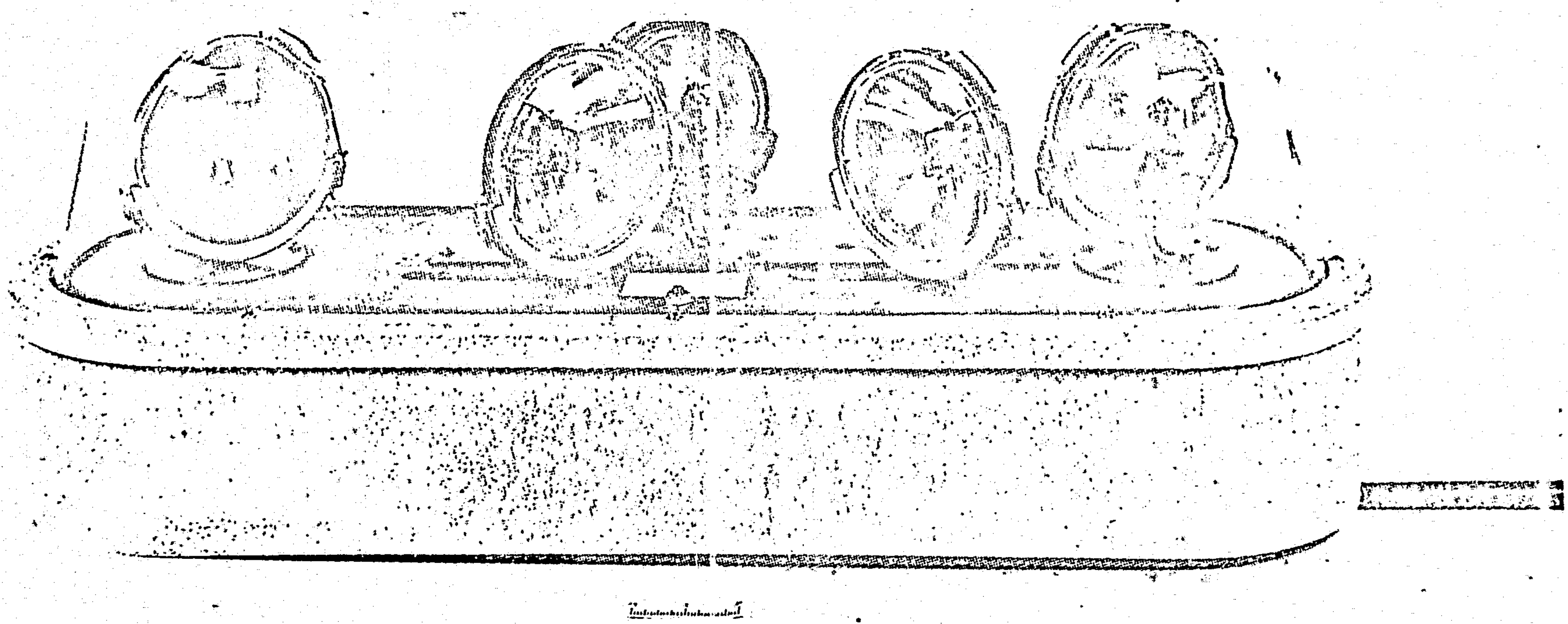

Fig. 3.5d

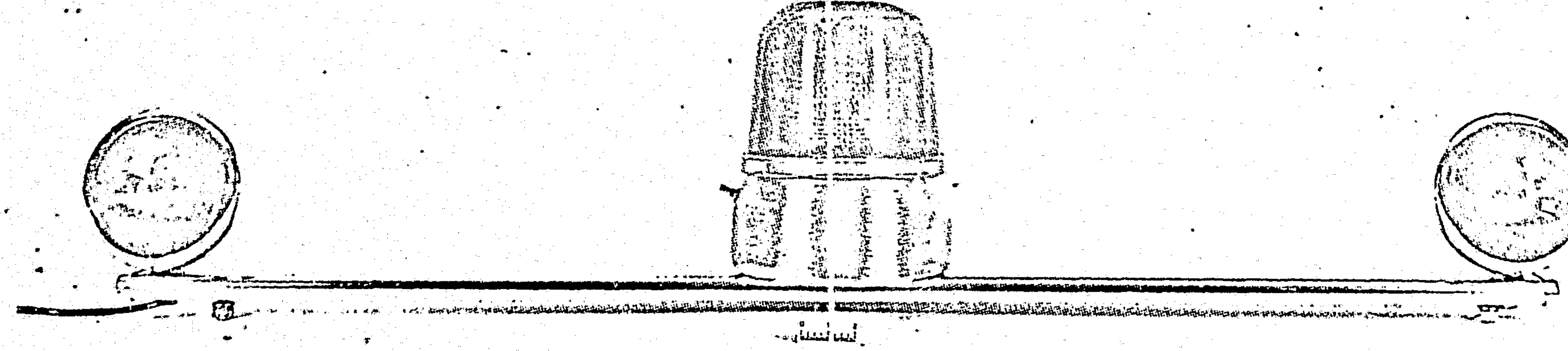

Fig. 3.5e

PART II. BACKGROUND MATERIAL

4. Theory of Warning Signals

4.1. Scope of This Treatment

The flashing lights, sirens, and horns of an ordinary emergency vehicle are meant to serve as general alerting signals. Their purpose is to make drivers (and pedestrians) aware that an emergency vehicle is approaching, but not to communicate instructions concerning what action is to be taken to facilitate the safe passage of the emergency vehicle. In many jurisdictions, the correct action is prescribed by law or regulation. Frequently, the required behavior is fixed in nature (for example, pulling over to the right and stopping), and is not a function of the direction of approach of the emergency vehicle or the category of the vehicle (police car, fire engine, or ambulance). All licensed drivers in such jurisdictions are presumed to know what the prescribed action is and are legally responsible for acting appropriately as soon as the emergency signal is noticed. In this report, the essential concern is the effectiveness of light signals in being noticed.

Considerations of using different signals to prompt different actions on the part of the driver and of methods of training drivers to make appropriate response(s) to signals will not be included here, although both subjects do have importance and might be dealt with in later reports. It is worth noting, however, that when a person must be ready to expect any one of a set of two or more different signals, each one requiring a different response, the amount of information processing the person's brain must perform at each occurrence of one of the signals is greater than when he must deal only with a single response to a single signal.

This extra processing is manifested outwardly by an increase in the observer's <u>reaction time</u> -- the time between the occurrence of the signal and the making of the appropriate response. It has been repeatedly demonstrated in laboratory studies (Woodworth and Schlosberg, 1954, Chapter 2) that reaction time increases with the number of alternative signal-response pairs for which the observer must be prepared. Moreover, when the signal occurs unexpectedly, and under stressful conditions such as heavy traffic, some people completely forget what the appropriate response is to whichever signal has occurred. This failure can take place even when there is only one signal and one response, but it becomes increasingly likely the more signal-response combinations there are to be remembered. Consequently, a set of signals consisting of otherwise meaningless events that have only arbitrary connections with the expected responses, can be quite dangerous. A multi-signal, multi-response system should employ signals that suggest the response desired either by their very form or by previous familiarity; as for example, flashing arrows or direct voice commands.

Our attention will be restricted largely to the general alerting function of light signals as they affect the driver, with little consideration of the pedestrian. This decision is based on the assumption that the problem of unresponsive drivers has in fact proved far more serious, in terms of both accidents and delays of emergency vehicles, than the problem of unresponsive pedestrians. When, as is common, a sound signal is being used, in addition to lights, the pedestrian has the marked advantage over the driver of not being in a sound-attenuating and noise-generating enclosure, and he should consequently hear the siren or horn well before the driver. Moreover, pedestrians crossing the street, or about to do so, often look down the street in both directions (or, at a corner, in three or four directions) and hence are fairly likely to notice even a far-off light signal. The pedestrian is also often free to observe in any desired direction for lengths of time that would be dangerous for a driver, and even to stop walking and continue to observe if he thinks he might be detecting an approaching emergency signal or other attention-compelling event.

Although we will be considering lights basically as general alerting signals, it must be realized that lights and sounds do carry information more specific than the fact that an emergency vehicle is nearby, such as an indication of the direction of the emergency vehicle relative to the target automobile. One advantage of light signals over sounds is that the ability of human beings to localize the sources of sounds is greatly inferior to their ability to perceive the direction of visual stimuli. Under any ordinary conditions, to see anything at all is to know at least roughly where the seen object is relative to oneself. For example, if a driver sees a flashing light in his rear-view mirror, he knows that the light is behind him; if he sees it through his windshield, he knows it is ahead of him, and which way it deviates (if it does) from being straight ahead. It is only when he does not see the source of the light directly, but rather the pattern created by the light's shining on objects (such as the interior surfaces of his car, or the roadway) that light detection without knowledge of its direction sometimes occurs.

Knowledge of signal direction is of least importance in jurisdictions in which a single response to any emergency-vehicle approach is mandatory, but even there it may be crucial in properly timing the response (as when the emergency vehicle passes on the right). Even in such jurisdictions, the behavioral fact is that some motorists either do not choose to or are not in a position to make the legally prescribed response. Instead, they note the direction of approach of the emergency vehicle and make the response (including "no response" -- maintaining course and speed) that they judge will make it easiest for the emergency vehicle to get through the traffic. The driver, in short, "uses his common sense," and it may sometimes be beneficial for him to do so, although incompatible "ad lib" maneuvers begun by neighboring drivers in a heavy traffic stream obviously can lead to accidents. In any event, the alerting function of the light signal is by far the most important, and the problem of detecting its direction will be dealt with only briefly.

Although the basic purpose of an emergency-vehicle warning signal is to be noticed by drivers, there is an obvious secondary function: to communicate that the signal that has been observed is associated specifically with an emergency vehicle. In other words, the signal must not only attract attention, but must be distinctive; it must not greatly resemble other lights or sounds that occur with significant frequency in the environment. Keeping emergency-vehicle warning signals different from other deliberate signals is a matter of establishing a convention with some legal force and seeing to it that the convention is made known to the public. Although psychological factors are involved in choosing a convention that will be easily remembered, this problem will not be dealt with here. However, choosing a light signal that stands out from the pattern of lights that occurs naturally in traffic is a perceptual problem and will be discussed later.

4.2. The Stage Model of Reacting to a Signal

A signal may be defined as a sensory stimulus that is emitted with the intention of conveying information. In the specific case of a warning signal, the information being transmitted is that a condition of some kind of danger exists in the vicinity. Frequently, the information conveyed to an observer familiar with the signal system also includes a request or demand for action of a particular sort, meant to reduce the danger of the situation. This action is sometimes outwardly visible (for example, slowing of a vehicle), and sometimes internal to the observer (for example, staying alert). A successful signal must be detected by the sensory system of the observer at which it is directed, must be properly interpreted, and must lead to the desired response. In this section, the processes intervening between the emission of a warning signal and the carrying out of the correct response by the observer are analyzed and, with particular application to warning-light signals, a specific set of processes or stages is postulated.

In order for a light signal to be detected visually, it is clearly necessary that some of the light enter the eye. Some of that light must reach the light-sensitive back surface of the eye (the retina), where it must stimulate some of the photoreceptors -- the light-absorbing nerve cells that generate the first stage of the visual response. In order for the photoreceptor system to be triggered into producing a large enough response to result in a sensation of seeing a visual event, a certain minimum number of the photoreceptors, within a certain maximum area of the retina, must be triggered by the incoming light within a certain maximum period of time. The exact numbers are still not known with certainty, but the critical number of receptors, the critical area within which they must lie, and the critical time within which the receptors must be stimulated, all vary with the prevailing light level -- the background -- against which the light signal is appearing; and they vary, too, with the level of light to which the eye has been exposed in the recent past -- the adaptation level. Under the best possible conditions, in which a light signal is presented to a fully dark-adapted eye against a completely black background, the minimum detectable amount of light energy (the threshold -- in this case the absolute threshold) is fantastically small. On the other hand, if the eye has been looking at a very bright surface and the light signal appears against a bright background, the amount of additional energy (above the background level) needed for the visual system to just make out the signal against the background (the differential threshold) can be enormously higher than the absolute threshold.

Let us assume, then, that a light signal has produced enough stimulation within the critical time and critical area associated with the given background level and state of adaptation of the eye to produce a seeing response. We can say that under these circumstances the signal provides an adequate stimulus for seeing. If the signal contained too little energy, or if the energy was spread over too large an area of the retina, or if the energy arrived over too long a period of time -- in any of these situations, even though some response in one or more photoreceptors may have taken place, the stimulus is inadequate for seeing and seeing cannot take place.

However, even though a stimulus is adequate for seeing, it may not in fact be seen. The photoreceptors feed back to higher-level nerve cells, which in turn feed back to still higher-level nerve cells, and so on, until connection is made with cells in the visual area of the highest level (<u>cortex</u>) of the brain. Although there is some evidence that simple detection of light can take place at lower levels in the brain, the recognition of objects and interpretation of a visual scene take place at the highest (cortical) level. The interconnections of the cells within the brain are almost incomprehensibly complex, and things can happen in other parts of the brain that will cause the nerve impulses corresponding to the light signal to be intercepted and suppressed, so that the neural signal never arrives at the visual cortex and the light is not seen. The old proverb "there is many a slip 'twixt cup and lip" is quite apropos to this situation. In more everyday terms, we say that we failed to see the light, even though it did register at the outer end of the visual system, because we were "paying attention" to something else. We do not know in terms of brain physiology what attention is, but we all know from direct experience that one can fail to see something that is in plain sight "right in front of one's nose." Not only can one visual pattern keep us from noticing another less compelling but perfectly adequate visual stimulus, but a sound pattern (such as a radio program) can keep us from noticing a visual stimulus that is in fact registering on our outer visual system. Indeed, we can fail to see anything whatever in our entire visual field because of dominating interference from stimuli generated completely internally; we often refer to such an event as "daydreaming".

Let us assume, then, that a light signal has adequately stimulated the visual system and that the observer was paying attention and actually senses the presence of the light. He must then recognize and interpret the specific pattern that he has perceived in the signal. Every aspect of the stimulus will influence the interpretative process: the sizes and shapes of the illuminated areas, their colors, brightnesses, and the way in which each of the preceding factors change (or fails to change) with time, for each area within the signal pattern. The observer's ability to recognize this signal, or to deduce its probable significance, obviously is strongly a function of his entire past experience. Moreover, the interpretation made also depends on the context -- the overall situation in which the observer perceives himself to be. Thus the detailed characteristics of the entire present environment -- not only the visual aspects -- as well as the characteristics of and changes in the environment over the recent past, will all influence the interpretation chosen for any particular signal. For example, the sudden appearance of a simple red light against a largely dark background is given one interpretation when the observer is out on the lake in a boat, and another interpretation when he is driving a car. In the latter case, the interpretation will differ depending upon the location of the light relative to the driver's automobile -- whether it is directly ahead and below eye level, for example (brake lights of the car ahead), or off to the right and well above eye level (red traffic light).

Once the observer has decided that a visual event that he has noticed is a deliberate signal of some kind, and has also decided exactly what message the signal was meant to convey, he must then make a decision about whether to make any overt response, and, if so, what it should be. The final step is for him to actually carry out the planned response. To a scientist studying the reactions of an observer to signal lights, the only directly observable events are the first -- the occurrence of the signal; and, if it takes place, the last -- the occurrence of the observer's outward reaction. All the intervening mental activity discussed above can only be inferred.

Science does not yet really know very much about these intervening processes. There may be stages that have not been listed above, and some of the stages that have been listed may not really occur as independent activities at all, but may instead be part of the processing that occurs within other stages. Regardless of what the realities of brain functioning eventually are found out to be, it will be convenient in discussing the effectiveness of light signals to refer to the various processes that have been described above. In summary, these processes are as follows:

a) <u>Reception</u>. The adequate stimulation of the outer portions of the visual system by the light stimulus.

b) <u>Noticing</u>. The result of paying sufficient <u>attention</u> to the stimulus to allow the message to get all the way up to the visual perception area in the brain.

c) <u>Interpretation</u>. This stage may have at least two substages: the recognition of the stimulus as a deliberate signal of some kind; and the recognition of the specific meaning or intent of the signal if it is familiar from past experience, or the reasoning out of the most likely meaning if the exact form is not familiar.

d) Decision. The determination of whether an outward reaction to the signal is to be made; if so, what the reaction will be, and when it is to be carried out.

e) Reaction. The actual carrying out of the planned reaction.

It should be understood that the above sequence of stages represents a summary of the processes that occur when everything goes smoothly. In practice, the sequence can be interrupted within any stage or in the transition between any of the consecutive stages. Thus "freezing" might be interpreted as an inability to carry through the decision stage to completion, despite every effort to do so. Stepping on the accelerator when application of the brake was intended can be thought of as difficulty in making the transition from decision to reaction. In such situations, the breaking of the ideal chain may be due to disruption by powerful emotional reactions ("panicking"), or to competition from other perceptually insistent stimuli ("distraction") or other sequences of internal processings ("confusion").

Some of the phrases used in describing the above stages suggest conscious, deliberate reasoning and decision-making. When enough time is available, some degree of controlled analysis of the situation may actually occur. However, the entire sequence from signal to reaction may take place in less than a second, and most or all of the steps may be carried out automatically, without conscious volition. The stages listed here represent conceptually familiar intermediate results in an information-handling process, the detailed workings of which cannot currently be described in detail.

5. The Visual Situation in Driving

5.1. Overall Stimulus-Response Pattern

The driver of a moving automobile is faced with a continuously changing, quite complex pattern of sensory stimulation, especially visual stimulation. Critically important visual information passes from the external environment to the driver's eyes through the windows of the vehicle and also through whatever mirrors the vehicle is equipped with. Visual stimulation of somewhat less urgency, normally, comes from the dashboard of the car. Naturally, all stimulation in an automobile is not conveyed by vision; sounds, too, are of some importance. The smoothness of the mechanical operation of the vehicle is monitored by awareness of the engine noise, tire noise, and body rattles and squeaks; and between glances at the speedometer, the wind noise and tire noise supply information about vehicle speed. External sounds not generated by the vehicle itself often provide information about the movements and planned movements of other nearby vehicles. Finally, the sense of touch also supplies significant information to the driver. Upward and sidewards pressures on "the seat of the driver's pants", on his back, the soles of his feet, and all of his postural muscles, provide clues to the acceleration and deceleration of the vehicle and the curvature and tilt of the roadway. Felt vibrations also provide information about the smoothness of the road surface and the circularity and smoothness of the tires.

As a result of the inputs through all of these senses, but principally through the visual sense, the driver is kept informed of the position, velocity, and acceleration of his vehicle relative to the roadway and to other vehicles and fixed objects on or near the roadway. The driver has a certain notion at each moment of what his position, velocity, and acceleration *ought* to be, relative to all the external objects. Very frequently throughout a ride the deviation between the actual values of these variables and the values considered desirable by the driver will rise above an acceptable level. He then takes the action that he expects will reduce the deviation to an acceptable level: he turns the steering wheel a bit, eases up on the accelerator pedal, or performs other control-related activities. Very shortly after he has taken corrective action, the driver will see evidence of the action in the stream of his sensory impressions. For example, if he has turned the wheel somewhat to the left, he may observe that the vehicle is getting closer to the white line on the left side of his lane. As a result of this sensory *feedback*, he knows whether his corrective action was about right, too much, or not enough. In the latter two situations, he will make a new corrective adjustment and will again note the results by observing the motion of the vehicle relative to outside objects.

Thus a driver's sensory input affects his motor (muscular) reactions, and vice versa. In engineering terminology, we would describe the situation as a continuous <u>feedback loop</u>. Only experience can properly match up the magnitudes of the corrective reactions to the magnitudes of the observed errors. Prolonged undercorrection can lead to an ever-increasing error and, eventually, an accident. Prolonged overcorrection can lead to an oscillation between errors in one direction and in the other; in the case of steering, this oscillation is familiar as the "weaving" characterizing some inexperienced or drunk drivers.

An important part of the process of learning to be a competent driver consists of discovering which kinds of stimuli within the incoming stream of sensory impressions should be selected for attention as important cues to required action, and which kinds can be safely disregarded. External light stimuli are of fundamental importance, of course. A driver who does not quickly recognize traffic lights, and vehicle head, tail, brake, and turn lights, is going to have trouble. At night on a city street, many extraneous lights are present in the environment, some having the same red, green, and yellow colors that characterize the critical signals, and some moving or blinking on and off. Under these conditions, the ability to select out only the relevant lights must be well developed, and it is not surprising that some beginning drivers find such a visual environment overwhelming and are very hesitant about driving at night. On a dark road at night, many of the familiar visual cues that a driver is accustomed to from daytime driving experience are missing, and it is necessary to learn how to get along with a reduced level and different pattern of visual feedback. This experience, too, can be frightening to a beginner and hence even suburban or rural drivers may dislike night driving.

The complexity of the visual stimulation reaching the driver of a moving vehicle is often not fully appreciated, because we tend to perceive the world not in terms of changing clumps of visual stimuli, but in terms of fixed objects that retain stability despite our motion relative to them. Actually, all the visual stimuli that we pick up through the windows of a vehicle are flowing by in a continuous moving stream within which the rate of flow varies greatly, depending upon the distance from the vehicle of the object producing each visual stimulus. At night, objects become harder to make out, and to an inexperienced observer, the visual input consists of a shifting maze of unorganized lights that come flashing by in a partly meaningless jumble.

Every driver must continually scan his visual field, interpreting the pattern in one particular direction as quickly as possible and then shifting his line of gaze --or, sometimes, only his attention -- to another part of the field. The line of gaze and the focus of attention do not always coincide. Thus, it is not unusual for a driver to keep his eyes fixed on the car directly ahead, and yet to be aware at times of cars moving by in neighboring lanes, through peripheral vision. There is a continued scanning of attention, as well as of direction of gaze, and although the focus of attention is often coincident with the direct line of sight, there are frequent temporary divergences of the two. In the context of home or office, the discrepancy is often made evident by a (usually momentary) inability to find an object over which the seeker's eyes may pass repeatedly.

If a visual event intended as a signal occurs in a part of the visual field to which a driver is not currently paying attention, even if he is looking in that direction, it will not be noticed until the driver's attention passes again over that portion of the visual field. Of course, attention is not an all-or-nothing matter. Some parts of the visual field rarely receive more than a minimal level of attention, while other parts are focused on more often and more fully. Thus a visual signal in a portion of the field currently being assigned a low level of priority may not be seen even when some portion of the driver's attention does move back to that area. It takes a signal with an unusual degree of "impact" to overcome a low attention level and intrude itself into the driver's consciousness. One of the determinants of how much time the observer will give to a particular part of the visual field on a given scan, and how much attention he will pay to what is seen during that time interval, is the degree of unexpectedness of the pattern of stimulation detected during the early moments of the time interval. If everything there seems to be as it should be, the inspection interval will be terminated relatively quickly and what is seen will "register" in the observer's awareness at only a low level or not at all. If something is noted in the area that is not consistent with recent past experience -- if some unexpected change has occurred -- the attention will be focused longer and more fully in that direction until the unexpected change has been interpreted and a decision made on whether action is required.

The attention phenomena discussed above may be of particular importance when the "unexpected change" in the visual field is a deliberate signal. The purpose of issuing a signal is to communicate some kind of information to the observer, and obviously no information transfer can occur until the observer has noticed the presence of the signal. The effectiveness of the signal in achieving the desired goal of information transfer is therefore strongly a function of the ease with which the signal can intrude itself into the conscious awareness of the observer. This ability to intrude is known by various names: *conspicuity*, *noticeability*, *perceptual insistence*, *attention-attracting power*, or simply *effectiveness*. In this report, the term "conspicuity" will be favored, but some of the other terms may occasionally be used interchangeably.

5.2. Visual Stimulation From Emergency-Vehicle Warning Lights

The nature of the visual stimulus reaching the "target" driver (that is, any of the drivers for whom the signal is intended) depends strongly on the direction from which the emergency vehicle is approaching. The most important general observation that can be made is that in most instances the image of the warning light does not first appear directly in the line of sight of the driver, but rather it usually appears well away from the central direction -- in the *periphery* of the visual field. As soon as the presence of the light has been noted "out of the corner" of the driver's eye, he will usually shift his gaze to look directly at it, provided traffic conditions in his immediate vicinity safely allow a momentary glance away from the straight-ahead direction.

The critical event is the driver's noticing the light with his peripheral vision; the direct inspection of the signal, which is partly involuntary, is for purposes of confirmation and planning a reaction. The first and later direct glances help to verify that the signal is associated with an emergency vehicle. They also provide the basis for estimates of the route of approach, the time remaining before the moment of closest approach, the distance at closest approach, and the need for (and nature of) a protective reaction.

The considerable implications of the fact that the critical alerting function of an emergency warning signal usually occurs in peripheral vision will be detailed in the following section (6). Here we will merely examine the patterns of stimulation associated with the three basic directions of approach: from a) the rear, b) the side, and c) the front. Because approach from the rear is the most troublesome case, that pattern of stimulation will be examined first, in considerable detail. In this discussion, some general facts about illumination will be introduced.

a) Approach from the rear. When a driver is being overtaken by an emergency vehicle exhibiting a warning light, his only opportunity to detect the light at a safe distance comes through reflections in one of his rear-view mirrors. The inside mirror is the one that most frequently transmits the signal, since it is the only mirror present in some cars, while in others it is the only one properly positioned for use and/or the only one habitually used. When the driver is looking straight ahead, the inside mirror is usually somewhat above the driver's line of vision and quite far off to the right (in angular terms).

Safe driving practice includes frequent direct glances at the inside mirror to monitor the positions and relative movements of vehicles to the rear. However, many drivers neglect such monitoring and even a conscientious driver may have to let quite a few seconds go by between glances if traffic is heavy and driving conditions are difficult.

Fairly frequent use is made of the left outside mirror by some drivers. In comparison with the range of locations of inside mirrors, placement of these mirrors is quite variable. Most are below the mean straight-ahead line of vision, but the type attached to the molding above the window is above or at the same level as this direction of view. The type mounted far forward on the left fender is somewhat to the left of the forward line of gaze, and the other types are considerably further to the left. The presence or use of right outside mirrors is not very common, and need not be discussed beyond pointing out that they are approximately level with or a little below the straight-ahead direction and very far off to the right.

Whichever mirror may be used, and wherever it may be placed, the essential point is that the image of a signal from the rear will not be located near the center of the driver's visual field, except during the small fraction of the time during which he is looking directly at the mirror. Thus these signals are delivered peripherally most of the time.

If traffic is light, the overtaking emergency vehicle has little problem getting through, except on very narrow roads. The problems occur when traffic is medium or heavy. In those situations, while the emergency vehicle is still far from the target driver, there is a considerable probability that intervening vehicles will be physically blocking the image of the emergency vehicle's warning light. Moreover, even if the light is not being blocked at a given moment, there are enough lights (at night) and motions (day or night) being imaged in the target driver's mirror(s) that it becomes harder for the image of the emergency-vehicle warning light to attract his attention, particularly when it is being viewed peripherally.

The brightness that any object is seen to have is determined essentially by the amount of luminous power (flux) per unit area impinging on the retina of the observer's eye (technically, the <u>illuminance</u> of the retina). At long distances, the image of the warning light is seen as a point with no perceptible area. In this case, the illuminance of the observer's retina is inversely proportional to the square of the distance between the light and the observer (if the air is clear), so that the light at long distances is not only tiny but is also not very bright. When the emergency vehicle has come close enough to the target vehicle to permit the image of the warning light to appear as a disc (an <u>extended source</u>), rather than a point, the observer's retinal illuminance ceases to increase as rapidly as the inverse square law would imply, and it increases less and less rapidly as the disc grows larger (the limit being no change at all for an infinitely large disc). Even when the emergency vehicle has come up directly behind the target vehicle, the image of a warning light in a rear-view mirror is not extremely large in an angular sense. Moreover, because many lights are covered by lenses that are not perfect diffusers of light, a small "hot spot" corresponding to the filament or plasma arc is seen superimposed on the disc of the lens. Thus, even a nearby warning light has characteristics intermediate between a point source and an extended source, and some degree of brightening continues to occur even as the light approaches the target vehicle very closely.

When the emergency vehicle is very close behind the target vehicle, either directly to the rear or off to one side in a neighboring lane, another effect may occur. Instead of directly observing the image of the light in a mirror, the target driver may notice a perceptible brightening of non-mirror surfaces either inside or outside the car. If the light is a rotating beacon, the driver may see a broad, diffuse patch of light sweep across the interior roof of the car, the dashboard, the windshield pillars, or the dirt layer on his windshield. If the light is a flash lamp, the effect will be for some or all of these surfaces to be lit with a diffuse light that flashes on and off. It is also possible for the driver to notice illumination from the light falling on the road ahead of him, on buildings a short way down the street, or on the surface of vehicles not far ahead. Shiny surfaces, either inside or outside the car, although not necessarily good image-forming mirrors, may flare up momentarily with bright specular reflections of the light.

It is only when no direct image of the warning light is seen -- when only surface illuminations are noted -- that there may be confusion about the direction from which the warning light is approaching. Drivers in this situation will usually make repeated rapid scans over as much of the visual field as they feel safe in examining, in an attempt to locate a direct or mirror image of the source. They can thereby establish the direction of approach of the warning light and also verify that it is indeed coming from an emergency vehicle. Since nearby drivers may be slowing, stopping, or maneuvering in response to the same warning signal, this visual searching behavior has the potential of leading to collisions.

Because the zone of noticeable illumination of diffuse surfaces does not extend very far in front of the emergency vehicle, especially in the daytime, a driver who has first noticed an emergency-vehicle warning light by surface illuminations will frequently be too late to take evasive action allowing the emergency vehicle to pass without slackening speed. In fact, it is not unusual for a warning light noticed in this indirect way to be coming from an emergency vehicle that is "tailgating" the target driver, waiting for him to notice its presence and get out of the way.

b) Approach from the side. In this situation, the target and emergency vehicles are approaching an intersection at about the same time at right angles to one another. This is a particularly dangerous situation, of course, particularly if the target driver does not hear the emergency-vehicle siren or horn. The light signal from the emergency vehicle will not be seen until the emergency vehicle is very close to the intersection.

The illumination by the warning light of street objects, described in (a) above, might allow the emergency vehicle's approach to the intersection to be sensed before the vehicle itself is visible. If this illumination extends far enough in front of the emergency vehicle, some of it may be picked up on objects more or less directly in front of the target driver.

Once the emergency vehicle clears the corner building line and enters the actual intersection, the warning light itself becomes visible, but it is located about 90° from the target driver's straight-ahead line of sight. If the emergency vehicle enters the intersection first and is moving faster than the target vehicle, the warning light -- and the body of the emergency vehicle itself -- will move rapidly from the side to a position directly ahead of the target driver. By the time the emergency vehicle and light are close enough to the target driver's line of sight to be noticed, it may be too late to avoid a collision.

If the target vehicle enters the intersection before the emergency vehicle, and at a greater speed, the warning light will start out about 90° to the side and will move to larger and larger angles of deviation until, with luck, it passes behind the target vehicle (180°). If the target driver does not notice the light at the moment it first becomes visible off to the side, he may well not notice it at all, unless he happens coincidentally to glance far to the side, or happens to see the illumination of street objects produced by the warning light.

c) Approach from the front. This is rarely a difficult situation. The emergency vehicle is normally on the other side of the road in the first place, so that even if it is never noticed, there may be no problems. Greater danger arises when the stream of traffic ahead of the emergency vehicle is much more crowded than the traffic in the direction that the target vehicle is moving. The emergency vehicle may then move over onto the wrong side of the road and it is then vital that its presence be noted. Fortunately, most drivers are constantly scanning the scene in front of them, taking in at least a moderate angle on all sides of the forward direction. If the emergency vehicle is not hidden by other vehicles as it approaches, most drivers will notice it at quite a long distance, especially at night. In the daytime, however, lights of any kind are harder to see, and some target drivers may fail to notice the emergency vehicle until it is fairly close.

Cases intermediate to the three that have been distinguished above [(a), (b), and (c)] can arise when the roadway is curved or when an intersection at other than right angles is approached. A rough rule for separating the situations is that (a) applies when sighting is through a mirror, (b) applies when sighting is through a side window, and (c) applies when sighting is through any part of the windshield.

It is important to realize that in any large, relatively unselected group of people -- such as drivers -- all abilities will vary over a considerable range. Thus there are usually at least a few people on the road with seriously impaired peripheral vision, either permanently -- due to age, eye disease or brain damage -- or temporarily, due to emotional state, sleepiness, inattention, or intoxication with alcohol or other drugs. Such people can sometimes fail to see even the most obvious object directly in front of them. We must therefore, resign ourselves to the fact that no light signal, no matter how visually effective -- and, of course, no sound signal either -- can be expected to serve its purpose 100% of the time. Some warning lights in use today are undoubtedly more effective than others, and perhaps new lights somewhat more effective than any now in use can be designed, but a totally effective warning-light system is an unattainable goal.

6. Peripheral Functioning of the Eye

6.1. Introduction

As we noted in Section 5.2., detecting an emergency warning light is, except in the relatively unimportant straight-ahead case, a matter of detection in the periphery of the visual field. Many of the standard measures of visual functioning were determined for visual fields about 2° in diameter centered around the line of direct gaze. This central part of the retina is known as the <u>fovea</u>. Our ability to see color and fine detail are at a maximum there. The photoreceptor cells in the fovea are called <u>cones</u> (because of their shape), and are the cells that perform best at reasonably high levels of illumination ("day vision"). A few degrees away from the very center, the density of cone cells begins dropping off and the density of another type of photoreceptor cell -- the <u>rods</u>, begins to increase. The rods have no color vision and poor detail vision, but the rod system responds to much lower levels of light than does the cone system: they are the receptors for "night vision."

The density of cones is greatest in the central fovea, where there are no rods at all. The cone density then drops off very rapidly outside the fovea, although there are still a few cones out near the edges of the visual field. Starting at the edge of the central fovea, the rod density rises rapidly from zero, exceeds the density of cones only a few degrees from center, and continues rising until about 20° out, where the rod density is highest. Further still into the periphery, the rod density drops off again, but remains much higher than the cone density all the way out. The distribution of the two classes of photoreceptors is shown in Fig. 6.1-1, taken from Brown (1965a, p. 49). In the daytime, when we want to see something clearly, we move our eyes until the image is formed on the central fovea, where the cones are most dense; in other words, we look directly at the object. At night, however, a faint light can be seen best by looking about 15 or 20 degrees away from the light, so that the image is formed on the most rod-rich area. Astronomers, sailors, and other night observers are familiar with this effect.

The cone system is able to mediate color vision because, according to the most popular current view, there are three different kinds of cones, one absorbing red light more strongly than other colors, one absorbing green most strongly, and one absorbing blue most strongly. The fall-off in cone density from the fovea out toward the periphery is apparently somewhat different for the three different classes of cones. As a result, the characteristics of our color vision change as we go from the fovea out toward the periphery.

As a general rule, most visual functions vary strongly with the retinal location. They vary also with other factors, three of the most important being the size of the stimulated area, the level of retinal illuminance, and the duration of the stimulation. To review all the ways in which various visual functions change with these parameters would require covering a good portion of the voluminous literature on vision research. We will limit ourselves here to a discussion of some aspects of those visual functions that are most relevant to the detection of emergency-vehicle warning signals.

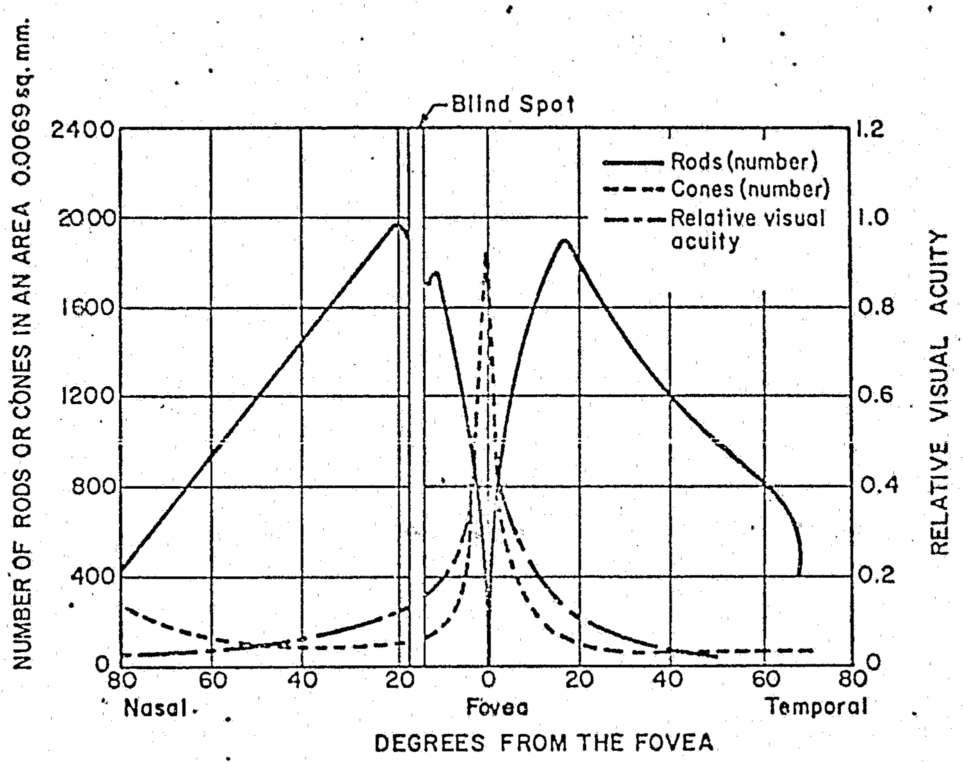

Fig. 6.1-1. Distribution of rods and cones along a horizontal meridian of the retina of a human right eye. "Nasal" refers to the half of the retina lying toward the nose; "temporal" to the half lying toward the temple. The vertical strip centered around 15° in the nasal retina represents the blind spot, in which there are no photoreceptors, and consequently no vision. The dot-dash curve representing relative visual acuity ("resolving power" or "sharpness of vision") is seen to follow the density of the cones fairly closely. [Figure (modified) from Brown (1965a).]

6.2. Luminous Efficiency

The eye is not equally sensitive to different wavelengths of light. Many experiments have been carried out to determine how much physical radiant energy (or power, or areal density of power, or whatever measure is appropriate) of each wavelength of light is necessary to achieve a constant visual effect. The constant effect is often taken to be absolute threshold (bare visibility in darkness), but other experiments are based on various techniques of brightness matching at levels well above threshold. The sensitivity of the eye at each wavelength is then usually defined as the reciprocal of the amount of energy needed to achieve the criterion visual effect. (If you need a lot of energy, sensitivity is low; if you need little energy, sensitivity is high). The curve showing the sensitivity of the eye as a function of wavelength -- the <u>spectral</u> sensitivity -- has been known by various names. Usually, it is only the relative values of sensitivity that are of interest, the peak of the curve being frequently set equal to unity. In that case, the curve is known as the <u>luminous efficiency</u> function, but the terms <u>visibility</u>, <u>luminosity</u>, and relative <u>luminous efficiency</u> are also to be found in the literature.

There are two different standardized luminous efficiency functions: one, the <u>photopic</u>, applying to day vision (the cones in the fovea), and the other, the <u>scotopic</u>, applying to night vision (the rods in the periphery). Unfortunately, many important situations (such as night driving) involve levels of illumination that are lower than the true photopic range, but not so low as to be truly scotopic. Such intermediate levels are referred to as *mesopic*. The key distinction between photopic and scotopic is that the cones see color, but the rods do not. Therefore, in any situation where there is enough light to distinguish any color at all, the level is not truly scotopic. It is rare for night driving to involve strictly scotopic levels, since an automobile's own headlights normally illuminate the road to a level in which some color can be seen, up to a certain distance.

Mesopic vision, since it involves response by a mixture of rods and cones, should be characterized by a luminous efficiency function intermediate between the photopic and scotopic curves, the relative weightings being a function of the level of illumination. No series of such mesopic luminous efficiency functions has been standardized as yet, but there have been experimental determinations made (Kinney, 1958).

Both the photopic and scotopic curves are characterized by maximum sensitivity toward the middle of the visible spectrum, and minimum sensitivity toward the ends. The wavelength of maximum photopic sensitivity is about 555 nm; of maximum scotopic sensitivity, about 510 nm. (The nanometer, abbreviated nm, is a billionth of a meter, or about 40 billionths of an inch.) This shift of the eye's sensitivity toward shorter wavelengths as the level of illumination drops is call the *Purkinje shift*. Figure 6.2-1 (Wyszecki and Stiles, 1967, p. 383) illustrates the two standard response functions. It is important to notice that these are *relative* functions, each one normalized to be unity at its peak, and give no information on the sensitivity of the rods relative to that of the cones. The fact is that at all except long wavelengths (the red end of the spectrum), rod vision is much more

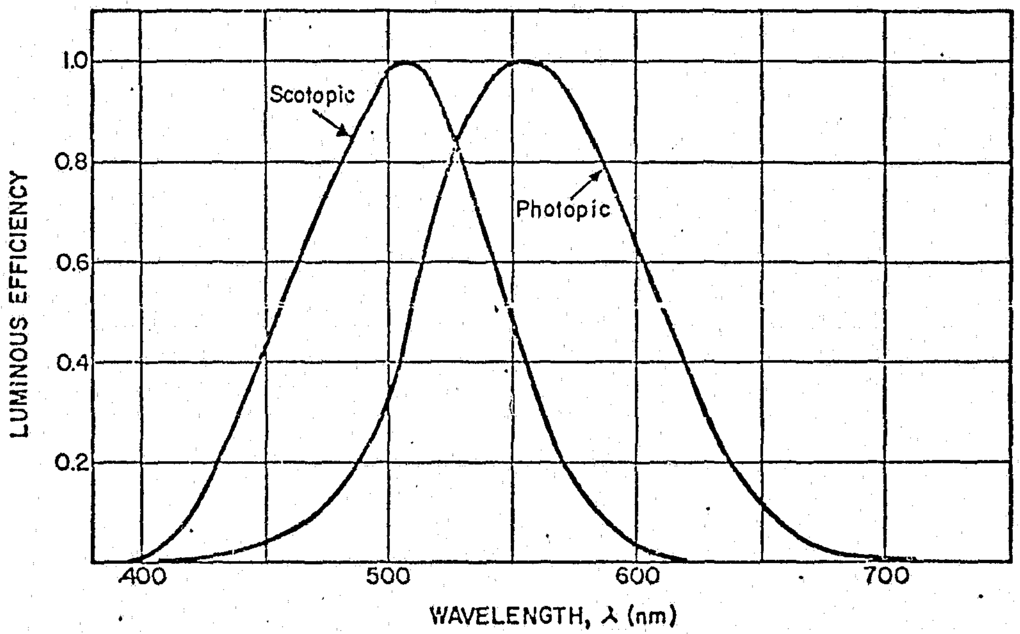

Fig. 6.2-1. Standard (CIE) spectral luminous efficiency functions for photopic and scotopic vision. The peak of each function is assigned the value 1.0. [Figure (modified) from Wyszecki and Stiles (1967).]

sensitive than cone vision. This is illustrated in Fig. 6.2-2 (Graham, 1965a, p. 72), which shows threshold energies (reciprocally related to sensitivity) on a more or less absolute basis. The figure caption explains that the exact vertical positioning of the scotopic curve relative to the photopic curve is a function of all the viewing conditions.

The experiments on which the standard luminous efficiency functions are based were done with fairly large fields, about 2° of visual angle in diameter (about four times the angular size of the moon). There are, of course, many cones or rods in such a sizeable area of the retina; the photoreceptors have diameters of only a few micrometers (microns). It should not be assumed that the thresholds shown in Fig. 6.2-2 reflect the absolute sensitivities of a single rod and a single cone; rather they represent the sensitivities of the rod and cone *systems* over an area containing thousands of receptors. Some vision scientists believe that individual rods and cones have approximately equal sensitivities; the greater responsiveness of the rod system is due to the richer neural interconnections among rods.

In determining thresholds for rods, it is necessary either to use very large central fields or else to use fields located in the periphery, since there are no rods in the fovea. The second procedure is more common, and was used by Kinney (1958) in determining her mesopic luminous efficiency functions. At low light levels, the periphery shows pure rod luminous efficiency, but with enough increase in the retinal illuminance, the luminous efficiency function begins to show changes in the direction of the photopic sensitivity curve.

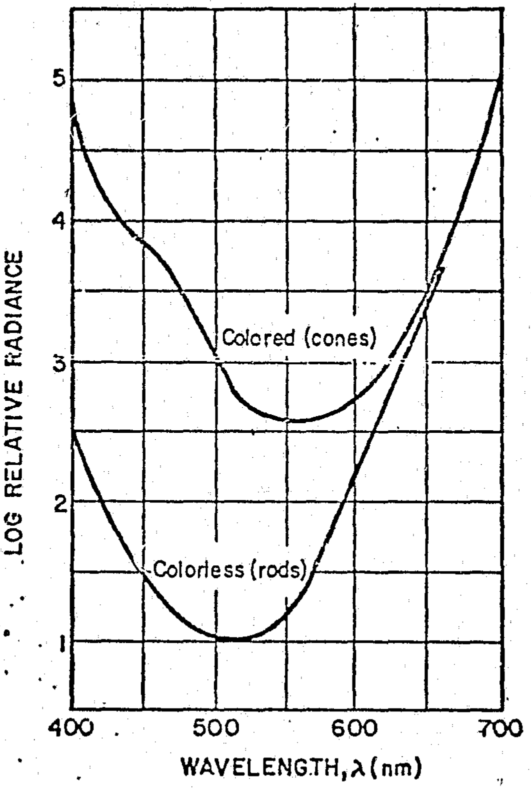

Fig. 6.2-2. Relative radiance required for rod and cone vision at different wavelengths. The absolute radiance required, the detailed shapes of the two curves, and their relative positioning on the radiance axis, all vary with the duration of exposure, the area, and the retinal position of the stimulus. The particular curves in this figure apply to conditions that give minimum thresholds for each type of receptor. [From Graham (1965a).]

It is to be expected that the detailed shape of the luminous efficiency function would vary with the area (in angular terms) of the stimulus. Bedford and Wyszecki (1958) have shown that area has an effect, but a small one, in foveal vision. We have not yet located data on the effect of area on peripheral luminous efficiency, but the greater degree of neural interconnection of rods would suggest that the effect of area in the periphery would be more marked than in the fovea.

The fundamental point that needs to be stressed here is that the conditions applying to the perception of emergency-vehicle warning lights at a distance include peripheral vision and small areas, and we do not really know in detail what the sensitivity of the eye is under those conditions.

In the formula [Eq. (10.6-4)] for the "effective intensity" of a flashing light, (see Section 10.6), the intensity that is integrated over time is not a physical (radiant) measure, but rather a visual (luminous) measure.* The luminous intensity is obtained from the radiant intensity

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* The term intensity is often used in a careless way to refer to almost any measure of the physical, psychophysical, or perceived "strength" of a light. Technically, however, 'intensity' refers specifically to the output of a light in terms of power (flux) per unit solid angle. 'Radiant intensity' is raw physical intensity (measured, for example, in watts per steradian), while 'luminous intensity' is intensity weighted unequally over different wavelengths in a pattern corresponding to the relative sensitivity of a typical human eye to light of different wavelengths. An attempt has been made to include in the Glossary (Section 13) definitions of most of the technical terms used in this report. The most widely recognized authoritative source for strict technical definitions of terms used in the fields of lighting and color is the CIE International Lighting Vocabulary (CIE, 1970).

by weighting (multiplying) the radiant intensity, wavelength by wavelength, by the luminous efficiency function, and adding the results for all the wavelengths together to obtain a single overall measure of total luminous intensity. The standard unit for luminous intensity is the candela (formerly, the "candle"). The spectral radiant intensity -- the intensity of the light at each wavelength -- can be measured by a photoelectric device, and is related to the energy impinging on the observer's eye. The luminous intensity, being based on the radiant intensity and the spectral response of the eye, is related to the energy absorbed by the eye (in the photoreceptors) and hence available for creating sensations of seeing in the brain.

Calculations of effective intensity for light signals are normally carried out using the standard photopic luminous efficiency curve (Fig. 6.2-1) because no better information is available. It might be worthwhile to determine experimentally a luminous efficiency function for the specific conditions we consider typical of emergency-vehicle warning-light perception. Such a study would necessarily be a long-term activity, but it might be worth the cost to develop a luminous efficiency function more realistically suitable for calculating the effective intensities of flashing lights seen in the periphery as point sources.

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1 OF 4

6.3. Color Perception

The intensity of a light can be specified by a single number, but it takes three numbers to specify color. The necessity for three specifying numbers is a reflection of the fact that color is a three-dimensional attribute. There are infinitely many ways of chosing the three single variables into which color can be analyzed. One common breakdown is into <u>hue</u>, <u>saturation</u>, and <u>lightness</u>. (See the Glossary, Section 13, for definitions.) From another perspective, equally valid, color can be analyzed into amount of redness, amount of greenness, and amount of blueness. There are many conceptual and mathematical complications that arise in a full explanation of the details of color measurement, and no such exposition can be attempted here. We will simply point out the computational procedure.

Instead of the single spectral weighting function used to convert spectral radiant intensity into spectral luminous intensity, three different weighting functions are applied to the spectral radiant intensity to derive a color specification. These weighting functions, which are internationally standardized (by the CIE, the International Commission on Illumination), are denoted $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, the subscript λ indicating wavelength. Figure 6.3-1 (Wyszecki and Stiles, 1967, p. 270) is a graph of these three weighting functions, which are known as the <u>1931 CIE color-matching functions</u>, and also by other names such as <u>tristimulus values of the spectrum</u>, <u>distribution coefficients</u>, and <u>color-mixture functions</u>.

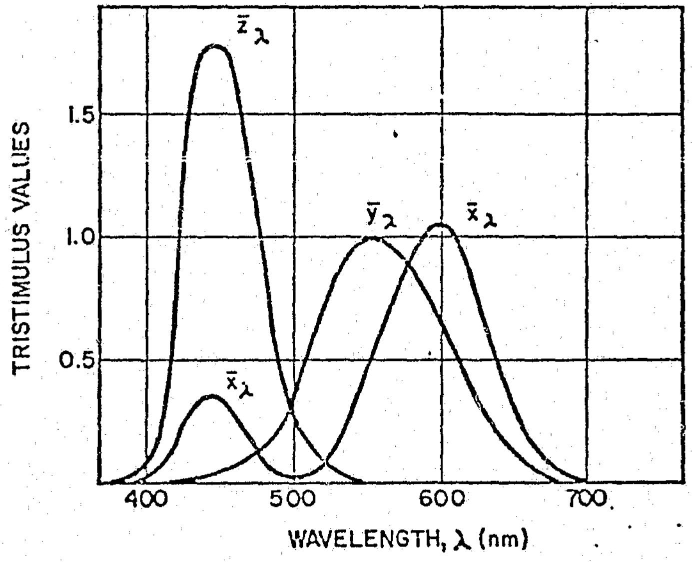


Fig. 6.3-1. The 1931 CIE color-matching functions. The $\bar{x}_\lambda$ ("red") curve does not quite reach zero in the neighborhood of 500 nm and has a secondary peak in the blue wavelength region. [From Wyszecki and Stiles (1967).]

For any given light, when the spectral radiant intensity is weighted by $\bar{x}_\lambda$ and the products summed across the entire spectrum, the resulting quantity is denoted X and can be thought of in an approximate way as the amount of redness in the light. Similarly, the sum of the $\bar{y}_\lambda$-weighted intensities is Y, roughly the amount of greenness; and the sum of the $\bar{z}_\lambda$-weighted intensities is Z, the amount of blueness. The three quantities X, Y, and Z are called the <u>tristimulus values</u> of the light and constitute a full specification of the color of the light. A comparison of Figs. 6.2-1 and 6.3-1 reveals that the $\bar{y}_\lambda$ function is precisely the same as the photopic luminous efficiency function. Consequently, the Y tristimulus value is directly equal to the luminous intensity of the light as well as being an indicator of the amount of greenness. A somewhat more intuitively acceptable way of stating this situation is to say that the size of Y relative to the sizes of X and Z is a measure of the percentage greenness in the color, while the absolute size of Y is a measure of the luminous intensity. Note that the technical meaning (that is, the CIE definition) of the word <u>color</u> includes the intensity as well as the aspects usually referred to in the everyday usage of the term, so that two lights that have the same color in this sense are a complete match. However, in the field of signal lighting, color and intensity are traditionally treated as separate, as in everyday usage. To avoid conflict with other signal-light literature, we will therefore sometimes use 'color' in this report in the sense that excludes the intensity (or whatever other measure of the "amount of light" may be appropriate).

Two lights match each other perfectly if and only if the lights have the same tristimulus values. Hence the basic information embodied in the functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ is the answer to the question of what lights -- as measured by the spectral radiant intensity distributions -- match each other and what lights do not match. This is the reason for the name "color-matching functions". Personal color-matching functions can be determined for any given observer, by means of very time-consuming experiments carried out with very elaborate apparatus. The standard functions of Fig. 6.3-1 represent an adopted average of a number of such personal sets of functions.

We have presented the color-matching functions above as a logical extension of the luminous efficiency function -- an extension of a one-dimensional concept to all three dimensions of color. In an analogous fashion, it is tempting to propose (for the first time, as far as we know) the extension of the concept of the effective intensity of a flashed light (detailed in Section 10.6) to the <u>effective color</u> of such a light. Just as the perceived brightness of a steady light changes when the light is briefly flashed, the chromatic (color) appearance of the light similarly changes (Ball and Bartley, 1971). In close analogy with the definition of effective intensity, we might define <u>effective tristimulus values</u> by the expressions:

$$X_e = \frac{\int_{t_1}^{t_2} X\,dt}{a_x + t_2 - t_1}, \qquad Y_e = \frac{\int_{t_1}^{t_2} Y\,dt}{a_y + t_2 - t_1}, \qquad Z_e = \frac{\int_{t_1}^{t_2} Z\,dt}{a_z + t_2 - t_1}. \qquad (6.3\text{-}1)$$

We have allowed above, through the use of subscripts, for the possibility that different values of the constant a (which has the dimension of time) will be found appropriate for the three different color channels. It is in fact believed (Cohen and Gordon, 1949) that the red, green and blue cone systems do have different temporal response characteristics for transient stimulation. It should be noted that no effort has yet been made to determine whether the form of Eqs. (6.3-1) allows for realistic predictions of the colors of short flashes of light.

Note that the quantities X, Y, and Z in the expressions (6.3-1) above represent the instantaneous, time-varying tristimulus values of the flashed light, in analogy with the meaning of I [sometimes written explicitly as I(t)] in the usual definition of effective intensity. Since, as we have indicated, Y for a light is equal to the luminous intensity I, the equation for Y_e above is, except for notation, the customary expression for effective intensity I_e [Eq. (10.6-1)]. The quantity Y (=I) can be measured directly by a phototube in front of which has been placed a filter (a piece of colored glass or plastic) having a spectral transmittance curve which, when multiplied by the spectral response curve of the phototube, gives the $\bar{y}_\lambda$ (luminous efficiency) function. With this arrangement, the electrical response of the filtered phototube to any light is proportional to the spectral radiant intensity of the light weighted by the $\bar{y}_\lambda$ function and integrated over wavelength; in other words, to the total luminous intensity. For a brief flash of light, the fluctuating electrical output of the photocell is a more or less faithful representation of the changes in the luminous intensity during the course of the flash (provided the photocell and the associated circuitry possess a rapid, linear response characteristic). By using other filters to give the filter-photocell combination a spectral response curve mimicking the $\bar{x}_\lambda$ function and the $\bar{z}_\lambda$ function, the quantities X and Z can be similarly studied as a function of time during the light pulse.

Color-matching functions have been measured for 10° fields centered on the fovea. The outer portions of such a field contain a great many rods as well as cones and the color-matching functions obtained differ somewhat from the 1931 CIE 2° functions. It would certainly be expected that if color-matching functions were obtained for a field of any size centered at a retinal location out in the periphery, these functions, too, would differ from the 1931 curves. In order to best predict color perceptions for emergency-vehicle warning lights, it would be highly desirable for data to be collected on the color-mixture functions in very small peripheral fields.

6.4. Color Discrimination

The term discrimination in the psychophysical context refers to the ability to distinguish differences between stimuli. With regard to color, there are people who have no ability at all to distinguish chromatic aspects of color; they can discriminate colors only on the basis of light-dark differences. Such people are usually referred to as being "totally color blind." More technically, their vision is called monochromatic (one-color).

Normal color vision is, as has been mentioned earlier, three-dimensional, or <u>trichromatic</u>. There is a group of color-defective people whose vision is <u>dichromatic</u> (two-dimensional). Both of the two most common types of dichromats have trouble discriminating colors over the range that a normal sees as red-yellow-green. These "color-blinds" in fact do not perceive the qualities of redness or greenness at all; all colors appear to them to be blues or yellows of varying degrees of strength or paleness (technically, <u>saturation</u>). One of these two classes of dichromats, the <u>deuteranopes</u> (popularly, the "green-blind"), despite their color-discrimination difficulties, have normal luminous efficiency functions, or, in some cases, show somewhat less than normal sensitivity to green and blue light. The other class of red-green defectives is the <u>protanopes</u> (popularly, the "red-blind"). They have a marked loss of luminous efficiency in the red. Thus a colored object that looks vivid red to a normal observer may look medium brown (brown being dark yellow) to a deuteranope and brownish black to a protanope.

Only about 1% of males are protanopic and 1% deuteranopic. There are also people who have trichromatic vision that differs from normal in ways tending more or less toward protanopia or deuteranopia. Such people are known as <u>anomalous</u> <u>trichromats</u>. The most common form of color blindness, affecting 5% of males, is <u>deuteranomaly</u>, the type of anomalous trichromatic vision that tends toward deuteranopia. A deuteranomalous observer, unlike a deuteranope, can see red and green as qualitatively distinct hues, but his ability to discriminate different shades of color is inferior to normal in the red-yellow-green range of hues and he may show a very slight loss of luminous efficiency in the green-blue spectral range. Protanomaly affects about 1% of males and involves the same basic features listed above for deuteranomaly, except that the luminous efficiency loss is in the red and is quite definite, being similar to the loss in full protanopes.

The four types of color defect listed in the preceding paragraph affect a total of about 8% of males. Only about 1/2% of females have these color defects. All other types of color vision impairment are rare, even in males, but a third type of dichromatism, called tritanopia, is important despite its rarity. Tritanopes cannot perceive the qualities of blueness or yellowness, and to them all colors are red or green, the only variations being in lightness and saturation. Their luminous efficiency curve is nearly normal, but may show some loss of sensitivity in the blue. The significance of tritanopia, and its associated form of anomalous trichromatism, tritanomaly, is that normal human vision becomes tritanomalous and, finally, tritanopic, as the size of the stimulated area of the retina becomes smaller and smaller. This effect is known as small-field tritanopia. Moreover, it appears to be true that if the total energy delivered to the retina by the visual stimulus is low enough, normal vision will tend toward tritanopia regardless of what factor is causing the energy to be low. Specifically, the effect has been found not only in connection with small fields, but also when the retinal illuminance is low or the presentation time of the stimulus is restricted to a brief flash (Weitzman and Kinney, 1967).

Most of the experimental work establishing these effects has been for viewing in the central fovea, but several experimenters have obtained similar results in the periphery. The application to the perception of flashing signal lights at a distance is clear: unless the lights are extremely intense, the small areas and quick flashes should lead to somewhat tritanomalous color responses in the observer. Tritanopes confuse certain shades of blue and green, so one problem that might be anticipated is that some blue and green signal lights would be difficult to distinguish even for perfectly normal observers. Tritanopes also confuse yellow and white, so again we might anticipate a problem with using both yellow and white in a signal-light system for color normals. The confusion of yellow and white is in fact familiar to those concerned with long-distance signal lighting, and both colors are used in the same signal system only when the difference between them can be emphasized by having them appear close together in space or in time (Breckenridge, 1967).

6.5. Flicker Perception

The eye cannot follow the ons and offs of a flickering light to very high frequencies of flashing. Instead, as the frequency increases beyond a certain point, the on portions of the cycle (the light flashes) do not seem to go all the way on (that is, look dimmer than slower flashes), and the off portions do not seem to go all the way off (that is, look brighter than complete darkness). Thus, the difference between the light and dark phases appears to grow less and less, and finally, at a high enough rate of flicker, they appear the same; that is, the light appears to be steady. The frequency at which *fusion* -- the disappearance of flicker -- first occurs is called the *critical flicker frequency* or sometimes the *critical fusion frequency*; in any case, the abbreviation *CFF* is standard.

Among many other variables, CFF depends on the area of the stimulus, the *luminance* level (the intensity measure that is used for stimuli large enough to be seen as having a definite area), and on the portion of the retina on which the area is imaged. Unfortunately, as is true for many sensory functions, the effects of these variables on CFF show *interaction*; that is, the effect of one variable differs depending on the values of the other variables. As a result, when two experimenters both study the effect of systematically changing the values of one variable -- for example, retinal location -- while keeping the other variables fixed at particular values, they may get startlingly different results if they happen to select different particular combinations of fixed values of the other variables. As a result of strong interaction among the variables affecting any sensory function, the earlier publications on the subject may seem to contradict each other, and only later, when the interaction effect has been realized, does it become possible to encompass all the different results in a unified description.

The situation described above did in fact arise in the study of the effect of retinal location of CFF [see Brown (1965b) for a discussion]. It is now understood that for large areas, having angular diameters of more than a degree or two, the periphery can see flicker up to higher frequencies than the fovea. Thus, even though a relatively large area may look quite steady when gazed at directly, flicker may be detected when looking off to one side. Some people have been annoyed by fluorescent lights in this way, especially near the ends of old bulbs, where the rate of flicker may be slower than the 60 cycles per second of the alternating current.

On the other hand, it is now known that for small areas, less than a degree in diameter, the fovea is better than the periphery at seeing flicker. In a small area seen well into the periphery -- as for example in the image of an emergency-vehicle warning light appearing in the rear-view mirror of a driver looking straight ahead -- sensitivity to flicker is far <u>poorer</u> than in the center of the eye. This is another reason, in addition to the lower retinal illuminance, that a flashing emergency light may not be noticed at long distances when the emergency vehicle is approaching from the rear. As the emergency vehicle comes up close to the target automobile, the angular size of the flashing light grows and so the "corner of the target driver's eye" becomes more and more sensitive to the flickering taking place in the mirror.

6.6. Movement Perception

Sensitivity of the eye to movement has been subjected to less systematic analysis than has flicker sensitivity, and much of the work is old. Interaction effects between variables appear to be significant with respect to movement, too, but explorations of these effects have been sketchy. The existing evidence indicates that movement perception in the periphery is inferior to that in the fovea. Two different types of movement thresholds have been studied: sensitivity to speed changes, and sensitivity to position changes. The periphery appears to be inferior in both aspects of movement perception. A study by Aubert in 1886 (discussed by Graham, 1965b, p. 575) found that the lowest speed at which any motion can be noticed (the absolute threshold) is twenty times higher 9° out in the periphery than in the fovea.

The popular notion that the "corner of the eye" is exceptionally sensitive to movement is, according to the evidence, a severe misconception. One possible reason for this false impression is that the motion sensitivity of the periphery may be relatively better than other kinds of peripheral sensitivity, such as the ability to make out fine detail (visual acuity). The fact that movement can be clearly detected in retinal regions in which vision is generally very foggy may give us the impression that the movement sensitivity is absolutely good. The acuity and most other visual functions of the fovea are so good that we are not especially impressed by the movement sensitivity there, even though it is in fact unequalled elsewhere in the retina.

A second factor that probably contributes to the mistaken impression that the periphery is more sensitive than the fovea to the perception of movement is the simple fact that much more of the retina's area is periphery than fovea, so that on a probabilistic basis most motions would first appear in and be detected by the "corner of the eye." It may be useful to point out that high as it is relative to the foveal threshold, the just noticeable speed of motion 9° in the periphery was found by Aubert to be 18 minutes of arc per second of time, so that many movements familiar in everyday life are quite visible in the periphery. (A cloud that drifts across the moon in a second and a half, for example, is traveling at an angular speed greater than 20 minutes of arc per second.)

PART III. PERCEPTUAL AND PHYSICAL ANALYSIS OF WARNING SIGNALS AND DEVICES

7. Effectiveness of Signals: Perceptual Variables

7.1. Primary Role of Effective Intensity

There is no question about what single variable plays the greatest role in determining the conspicuity of a light signal: it is the effective intensity. It is obvious that if a light is so weak that it lies below the observer's detection threshold, it will not matter what its color, flash rate, etc., might be; it will not be seen at all. At the other extreme, a light so intense as to burn out the observer's eyes (such as from a high-powered pulsed laser or a hydrogen bomb explosion) will certainly be noticed, again regardless of the value of any of the other variables.

The effective-intensity measure (discussed in Section 10.6) relates to the output of a light source, the quantity with which we have to be concerned in setting specifications for warning-light hardware. Visually, however, the relevant variable is <u>effective retinal illuminance</u>: the areal density of effective luminous power reaching the retina. An ideal point source putting out a million candelas of intensity at a distance of one mile from an observer is visually outshone by an ideal point source putting out only one candela at a distance of five feet from the observer. (This is a simple consequence of the inverse square law.) If we specify that for adequate effectiveness a warning light must put out at least some particular number of candelas, we are setting this floor under the intensity because we want to insure that at some particular distance (selected on the basis of giving a target driver enough time to maneuver after he notices the light), the light should deliver to the target driver's retina at least a certain amount of illuminance that corresponds to a selected reasonably high probability of detection.

Although effective intensity is the dominant variable in determining conspicuity, a number of other parameters of the light signal have definite importance. The role of these other parameters becomes increasingly important as the background against which the signal is viewed becomes more complex. When the background is filled with lights of various colors, moving and flashing, the role of the noticing and interpretation stages (see Section 4.2) becomes more important relative to the reception stage. The problem becomes one of distinguishing the signal light from all the other lights in the background. The conspicuity of the signal light is maximized by making it as perceptually different as possible from some kind of average of the background lights. Every aspect that can be varied can contribute to establishing this distinctiveness. These other aspects are discussed in the remaining sections of Chapter 7.

7.2. Flash Rate

As pointed out in Section 6.5., the human eye is not capable of following the individual flashes in a train of flashes occurring at a high enough frequency. At very high frequencies, no impression of flashing remains at all, and the light is seen as steady. The flash rate at which this complete fusion of the individual flashes occurs -- the critical flicker frequency (CFF) -- is a strong function of luminance, area, retinal location, and other variables, but values of 20-50 Hz (hertz: cycles per second) are fairly typical in the midranges of these variables. At extremely low flash frequencies, if the light is on half the time and off half the time, the appearance is of a steady light that burns for a while and is turned off for a while. Thus the impression of conspicuous flicker is maximum at some intermediate frequency within the range 0-20 Hz.

Interestingly, several visual effects connected with flickering lights have their peaks at about 9 or 10 Hz. It has been known for a long time that lights flickering at frequencies from about 2 to 20 Hz appear brighter than the same lights shone steadily; this phenomenon is known as brightness enhancement. Much of the modern work on this effect has been done by Bartley and coworkers (see Bartley, 1961) and it is often referred to as the Bartley effect, although Bartley was not the discoverer of the phenomenon. The greatest degree of brightness enhancement occurs at frequencies near 10 Hz, although the frequency yielding maximum effect depends on luminance and other variables.

There might be good reason to use frequencies near 10 Hz to maximize conspicuity, but unfortunately there is another effect that peaks in the same frequency range. The electrical activity of the human brain has certain characteristic frequency components. Most prominent among these components is the alpha rhythm, which has a frequency in the neighborhood of 10 Hz. It is found that when a human subject looks at a light flickering at a frequency of about 9-12 Hz, the alpha component of his brain waves is increased; this effect is known as photic driving. The subjective experience that accompanies photic driving is usually unpleasant, and may include dizziness, nausea, nervousness, and strong urges to escape the situation. The essential nature of the disease known as epilepsy is an instability of the brain's electrical activity. When epileptics are exposed to lights flickering near the frequency range of 9-12 Hz., it is common for the resultant photic driving to trigger an attack, including convulsions in the more serious cases.

The use of light signals flickering at frequencies anywhere near 10 Hz (600 flashes per minute) is thus not practical because of the unpleasantness of photic driving to almost everyone and the dangerous (especially in traffic) triggering of epileptic attacks in those susceptible to such seizures. Above 15 Hz, flicker may begin to blur toward fusion, particularly with dim lights. It was necessary, therefore, for warning-signal designers to turn to frequencies below the disturbing range, and most flashing signals have been designed for operation at flash rates inside the range 1-3 Hz (60-180 flashes per minute). For psychological reasons, speed and urgency are associated in most people's minds, and it is found that very slow flash rates up to about 1 Hz do not communicate a sense of warning to many people. In aviation, the frequencies that have proved most popular are in the range of 1.2-1.5 Hz (72-90 fpm).

7.3. Duty (On-Off) Cycle

This parameter is also known by a variety of other names such as light-time fraction, pulse-to-cycle fraction, and light-dark ratio. What is meant is either the fraction of a complete cycle or period of a flashing light during which the light is on; or, in many other cases, the ratio of the time within the cycle that the light is on to the time that it is off. Unfortunately, there is no generally accepted convention about which of these two measures is preferable. Readers of the technical literature must therefore be prepared to encounter either of them (or sometimes both) in the work of different authors.

It will be useful to introduce distinct symbols for the two measures. If we let

$$a = \text{time on} / \text{time off} \qquad (7.3\text{-}1)$$

and

$$b = \text{time on} / (\text{time on} + \text{time off}), \qquad (7.3\text{-}2)$$

corresponding (in reverse order) to the two definitions above, then a and b are expressible in terms of each other in accordance with the relationships

$$a = \frac{b}{1 - b}, \qquad b = \frac{a}{1 + a}. \qquad (7.3\text{-}3a,b)$$

When the periods of light and dark are equal, then $a = 1$ and $b = 1/2$, and it will be seen that these values check in the interconversion equations (7.3-3) above. This particular duty cycle represents the middle of the scale. At one extreme, there are flashes consisting of extremely short pulses of light, followed by a dark interval; the duty cycle (a or b) approaches 0. At the other extreme, there is a light that remains on most of the time, and "negatively flashes" off for a brief period within each cycle (a very large, b almost unity). Such lights are called occulting lights and are used in some lighthouses but have not been used much for signaling on land.

It has been alleged (Symposium, 1971, pp. 163-165) that the visual effects of occulations -- negative flashes -- are quite similar to the effects of positive flashes with the inverse duty cycle. That is, a flashing light with a light-dark ratio of a has a visual effect (in terms of threshold or of conspicuity) equivalent to that of an occulting light with light-dark ratio $1/a$. (In terms of the light-time fraction b, the equivalence is between b and $1-b$.) Perceptually, then, a 1:1 light-dark ratio is actually at one extreme, with the other extreme being ratios approaching either 1:0 or 0:1. It may be of some use to define an actual scale reflecting this perceptual symmetry between light and dark flashes. One possibility, presented here for the first time as far as we know, is a quantity c we might call light-dark symmetry. We define c as 4 times the light-time fraction multiplied by the dark-time fraction, or, explicitly, as:

$$c = 4 \times \left[\frac{\text{time on}}{\text{time on + time off}}\right] \times \left[\frac{\text{time off}}{\text{time on + time off}}\right]. \qquad (7.3\text{-}4)$$

The relationships of a and b to c are specified by

$$c = \frac{4a}{(1 + a)^2}, \qquad c = 4b(1 - b). \qquad (7.3\text{-}5a,b)$$

It is easy to check algebraically that the quantity c is unchanged if a is replaced by $1/a$ or b by $1-b$, as required.

The intuitive significance of the name 'light-dark symmetry' for c can be appreciated by noting that for a 1:1 on-off ratio -- the case of perfect symmetry -- c=1; and for both the on-off ratios 0:1 and 1:0 -- the cases departing maximally from light-dark symmetry -- c=0. Whether c or any similar measure will prove useful in the representation of actual visual data, is not yet known.

Some consideration should be given to the possible usefulness of occulting lights as emergency warning signals. It is worth finding out whether the symmetry in the visual effects between flashing and occulting lights might not break down when the signals are presented against visually complex backgrounds. It is conceivable that an occulting light differs more from the average of the other lights in a night urban street scene than does a corresponding flashing light, in which case the occulting light may be more conspicuous.

Data on both thresholds and dark-background conspicuity judgments suggests, however, that the optimum on-off cycle for a light of fixed intensity is 1:1, the case of light-dark symmetry. This finding should also be checked with visually complex backgrounds.

7.4: Pulse Shape (Waveform) and Flash Duration

The eye integrates light input over short periods of time, which range from about 0.01 sec. at high luminances to 0.1 sec. at low levels. Within the critical duration, as these integration times are known, it does not matter how the light is distributed in time; it is only the total luminous energy that counts in determining whether the flash will be seen by the eye. These considerations hold rigidly for single brief presentations of light. When the light presentations are repeated cyclically, however, new factors appear to enter the picture and the matter becomes rather complicated. Early flashes in the train affect the response to later flashes, even when the cycle time is shorter than the critical duration for a single flash. When the repetition period is longer than the critical duration, as it is for flashing slower than 10 Hz (as in warning lights), still further complications arise. Experiments on critical flicker frequency have shown that for some viewing conditions, the detailed waveform of the stimulus is of no consequence -- only the fundamental frequency is significant. However, for other viewing conditions, effects from the temporal shape of the light pulse have been detected. Brown (1965b) has reviewed comprehensively the data and theory on waveform effects. In general, it can be stated that considerable further work will be necessary to clarify the matter fully and permit predictions applicable to practical questions such as the conspicuity or even the visibility of emergency warning lights.

In the case of flashing emergency lights, the primary consideration in the pulse shape -- aside from the total flash duration -- is the rise time of the light flash and possibly also the fall time. The facts concerning the rise and fall times and total durations of the light flashes produced by the different basic types of lights are summarized briefly below.

Gaseous discharge lamps. Gaseous discharge lamps have extremely rapid rise times and fall times, with the fall times comparatively prolonged with respect to the rise times. However, since the entire pulse from such a source usually lasts much less than the critical duration (well under a thousandth of a second), the waveform can be presumed with confidence to be irrelevant to the visual effect.

Flashed incandescents. An electrically flashed incandescent lamp has a considerably slower rise time than a gaseous discharge lamp, and the fall time is about twice as rapid as the rise time. A flashed incandescent lamp produces light pulses lasting on the order of 0.1-0.2 sec., longer than the critical duration, so that the detailed pulse shape could well have some effect.

Some authorities on flashing lights have the informal impression that among lights of equal effective intensity, a rapid rise time increases conspicuity. The more sudden shock to the eye relative to the dark condition caused by a rapidly rising flash might intuitively be thought to increase conspicuity, but experimental tests are called for.

Rotating incandescents. A rotating incandescent beacon produces at a given point in space a relatively symmetric light pulse with rather slow rise and fall times. The duration of the flash from a rotating lamp depends on several factors (discussed in Section 10.5), but typical values for emergency-vehicle warning beacons are in the range 0.01 to 0.05 sec. If the lights are bright enough, these times may just exceed the critical duration, so that pulse shape may or may not be a factor.

With respect to both types of incandescent warning lights, new experimental work will be necessary to answer the decisive question: if all other variables besides the pulse shape (particularly color and effective intensity) are kept the same, are there differences in conspicuity among different waveforms?

7.5. Spatial Sweep of the Beam

When a stationary, electrically flashed lamp of any type sends out a light pulse, the illuminance it produces at a given point in space has a course of variation with time (the pulse shape), but there is no actual spatial movement taking place (other than the propagation of the light beam). On the other hand, a continuously burning, rotating beacon light not only produces a comparable variation of illuminance with time, but also a directional sweep through space. As the edge of the beam of light from one of the rotating lamps moves past the point of observation, the illuminance rises from zero (or from some minimal level if the edges of the beams from, say, four lamps in the beacon overlap somewhat), reaches a peak at the center of the beam, and drops again to the minimal level as the beam's other edge moves by. If the beacon is close enough to have a perceptible area, it may be possible to notice that, let us say, the right side of the area begins brightening while the left side is still dark. The right side remains brighter as the entire area increases in brightness, but decreasingly so. As the peak of brightness is reached, the area appears homogeneous; and after that point, the left side becomes brighter and continues increasingly so until the bright crescent disappears at the left edge and the whole area reaches the minimal brightness level. In such a case, we interpret the spatio-temporal pattern as a right-to-left sweep of a beam.

If the beacon is far enough away to appear as a point source, the spatial cues described above are lacking, and the rotating light may be indistinguishable from a flashed light. Frequently, however, even at long distances, other spatial cues are present that permit recognition of the spatial sweep taking place. If the haziness of the atmosphere is sufficient, the entire length of the light beam may be visible as a long cone, and the motion of the beam can be seen directly by the scattered rays even when the point of observation is entirely outside the beam itself.

A second source of information about beam rotation comes from the observation of non-mirror surfaces near the observer, illuminated by the beam. The circular or elliptical patch of light representing the intersection of the surface with the cone of the beam can be seen, moving from one side of the surface to the other, if the motion is not extremely rapid. The surface can be a somewhat diffuse (light-scattering) reflector, or a somewhat diffuse transmitter. An example of the latter that sometimes does serve to reveal the sweep of a light beam is a dirty or scratched automobile windshield.

When a rotating beacon comes close enough to the observer, it is sometimes possible to make out the internal structure of the unit, provided that the dome is not a very good diffuser. The rotating of the turntable and lamps within the dome may then be directly observable.

Since rotational motion is still another dimension in which a warning light may differ from the lights in the background, it would be expected that, everything else being equal, such rotation would increase conspicuity relative to a stationary flashing light. Unfortunately, everything else is rarely equal; for example, if the effective intensity of a gaseous discharge lamp considerably exceeds that of a rotating incandescent lamp, the flash lamp would be expected to be more conspicuous. It would be useful to compare experimentally for conspicuity two lights that produce identical variations of illuminance with time at a given point in space, but only one of which is rotating.

7.6. Color

It is frequently alleged that one color is more visible or more conspicuous (attention-attracting) than another. For example, it might be claimed that a red light having an intensity of 1000 candelas can be seen further away than a blue light of equal intensity. As was pointed out in the last paragraph of Section 6.2, the calculation of the intensities of the lights in candelas will most likely be carried out with the use of the standard CIE photopic luminous efficiency function that applies to vision in fields of about 2° diameter. We can anticipate, however, that for lights seen as point sources, a somewhat different luminous efficiency function will actually apply (Bedford and Wyszecki, 1958).

In order to give the two lights an equal chance in a visibility comparison, we naturally have to present equal luminous intensities of the two colors. We must therefore use the luminous efficiency function appropriate to the specific viewing conditions to be used. How do we determine the luminous efficiency function for pure spectral (single-wavelength) lights appearing as point sources? By one of several methods of comparison, we determine the relative visibilities of the various wavelengths, either by determining absolute thresholds or by equating brightnesses at levels above threshold. Thus, by definition, if we are using the correct luminous efficiency function, steady lights of equal luminous intensity (or luminance, for extended sources) must appear equally visible.

Actually, it has been discovered that some methods of comparing visibility lead to different results than other methods. Thus, the only meaning that can be attached to a claim that light of one color is more visible than light of another color, is that the method of comparing visibility used in the determination of the luminous efficiency function (employed in the calculation of luminous intensity) differs from the method of visibility judgment used in the final test.

On the other hand, the conspicuities of colored lights properly equated in simple visibility need not necessarily be equal. Again, it depends on the specific operational test we establish for determining conspicuity. If we decide to test conspicuity by measuring reaction times to sudden presentations of various lights, then it is conceivable that we may get different reaction times despite equality of the luminous intensities, since the luminous efficiency curve used in calculating the intensities will probably not have been derived using an equal-reaction-time criterion.

Here, too, we must allow for the possibility of interactions among variables. Thus, although steady-burning lights of the same, properly calculated luminous intensity would be equally visible at a distance regardless of color, if those same lights were flashed we could no longer be sure that the visibilities or the conspicuities would remain equal. The existing evidence on this particular question, incidentally, is contradictory (Sharma and Yorke, 1971).

When special backgrounds are introduced, conspicuity can depart sharply from simple visibility. For example, if the background consists mostly or entirely of red lights, with no blue background lights present, it would certainly be expected that a blue signal light would be more conspicuous than a red signal light if the luminous intensities of the two were at all comparable. In such a case, obviously, it is not really the color of the blue light as such -- its blueness -- that makes it more conspicuous, but rather its differentness from the background.

Although it is not properly a perceptual problem, it is important to point out that there are physical effects that may arise in long-distance viewing that depend strongly on color. Tiny particles suspended in the air -- and, in fact, the gas molecules comprising the air, themselves -- tend to scatter light rays that strike them away from the directions they were originally traveling. The degree of this scattering is a strong function of wavelength, when the particles are small enough, with short-wavelength (blue) light being scattered most and long-wavelength (red) light being scattered least. The clear sky in daytime is seen entirely by light scattered out of the sun's rays, and as a consequence of the wavelength dependence just mentioned, it appears blue. (Above the atmosphere, in space, where there is no scattering, the sky is invisible; that is, it appears as black as the night sky.) Larger particles, such as the water droplets that make up clouds, scatter all wavelengths equally; hence clouds appear white.

In a hazy or foggy atmosphere, scattering will divert portions of the beam from an emergency warning light in directions away from the location of the observer. Since many hazes and fogs contain particles of a variety of sizes, some wavelength dependence often characterizes the average scattering, and the loss of apparent intensity under these circumstances will be greatest for a blue light, and least for a red light. That is, if the actual luminous-intensity outputs of a red and a blue light are equal, the illuminance of the observer's retina by the red light seen through a haze containing fine particles will be greater than the retinal illuminance produced by the blue light. Since, as pointed out earlier, the retinal illuminance determines the brightness seen, it is clear that red lights have an advantage over blue lights of the same intensity when the viewing is through an atmosphere that scatters significantly over the distance of view. If the use of a blue light is considered desirable in any particular situation, it is only necessary to use a light of higher intensity in order to allow for the delivery of the desired level of illuminance to the retina of an observer viewing through haze. It will generally take a greater consumption of current to produce a higher intensity, so economic considerations enter into the situation.

7.7. Number and Spatial Pattern of Lights

If we have available several identical lights, it is obvious that a display consisting of two of the lights, presented simultaneously, will be more conspicuous than a display consisting of only one of the lights. If the lights are so far away as to appear as point sources, and if the lights within the two-light display are close enough together as to be unresolvable visually, then the two-light display is optically equivalent to a single light of double intensity, which is certainly more conspicuous (although there is no reason to believe that it is twice as conspicuous as a light of the original intensity).

When the two lights are presented with considerable separation -- far enough apart that the retinal areas on which they are imaged have negligible neural interconnection -- then the lights will act independently as far as the probability of simple detection is concerned. If the chance of detecting a single light within a given period of observation is 1/2, for example, then the chance of detecting one or both of the lights in a two-light display with wide separation between lights is given by the rules of probability as 3/4 [$= 1 - (1/2)^2$].

When the lights are close enough together that some neural interaction can be expected -- and this is likely to be the situation for a real warning-light display -- then the simple detectability will be greater than that associated with independent probabilities, but less than that associated with complete fusion of the lights into one double-intensity light. Experimental data exist on all these relationships when the criterion is simple detection.

When the criterion, however, is conspicuity -- the rapidity of noticing when a signal above the detection threshold appears at an unexpected point in both space and time -- then nothing very quantitative can be said. The two-light display will surely be more conspicuous than the one-light display, but not only because of the extra stimulation reaching the eye. Instead, there is the additional factor of the geometric form of the total display. The occurrence of two lights in rather close proximity is a considerably more improbable event than the occurrence of a single light, and the spatial pairing would be expected to contribute to the likelihood of the display being noticed. If the two lights are arranged in a precisely vertical or precisely horizontal line, the event becomes more improbable and hence more striking.

When the display consists of three, four, or more lights, the geometrical figure in which the lights are arranged would reasonably be expected to affect the conspicuity, everything else being equal. Moreover, when the lights are close enough to the observer for each one to have a definite shape, this shape, and its relationship to the pattern of the total display, would presumably also affect conspicuity.

The guiding principle, as noted earlier in this report, is that conspicuity is maximized by making the display differ as much as possible, in as many ways as possible, from some kind of average of the background. Now that the concept of improbable events has been introduced, we can take the principle a step further. In vehicular traffic, it is not only the background that is visible at a given moment that counts, but some type of weighted average of the ever-changing background scene over some period of time. More than that, the conspicuity of a signal is also clearly affected by some type of average of other similar backgrounds that the driver has encountered on past occasions. In the last analysis, it seems evident that what counts is the expectation of the observer -- the probability that he assigns to the appearance of a given stimulus pattern at a given time and place. His estimate of probabilities will of course be strongly influenced by what he sees in the background at the present moment and what he has seen in the past few moments, as well as by his entire previous experience with comparable situations. The goal, then, is to make a signal a maximally improbable event, in a specified context. In the case of emergency-vehicle warning devices, the context is the vehicular traffic scene, in its various phases such as daytime driving, nighttime country driving, and nighttime city driving.

In regard to shape, we might speculate that triangular lighting configurations or triangular lights, for example, are rarely encountered in any context, so perhaps a triangular cluster of three lights, each itself triangular in shape (achievable by masking) might prove exceptionally conspicuous. The only way to determine the actual conspicuity of this or any other such complex arrangement is by empirical test, since no data, theory, or model is available to permit prediction.

7.8. Illuminated Area

<u>Lights</u>. If a signal consisting of a uniformly illuminated patch is increased in area, with the luminance remaining fixed, the signal will be more easily detected (at least up to a large limiting area), and will surely also be more conspicuous in any reasonable context. In short, everything else being equal, the larger the signal the better (but with diminishing returns beyond some large area). If luminance must be sacrificed in order to achieve a larger area, then the effect on conspicuity cannot be predicted with confidence. Even for simple detection, the relative importances of changes in luminance and area are functions of the initial area, the retinal location, and other variables.

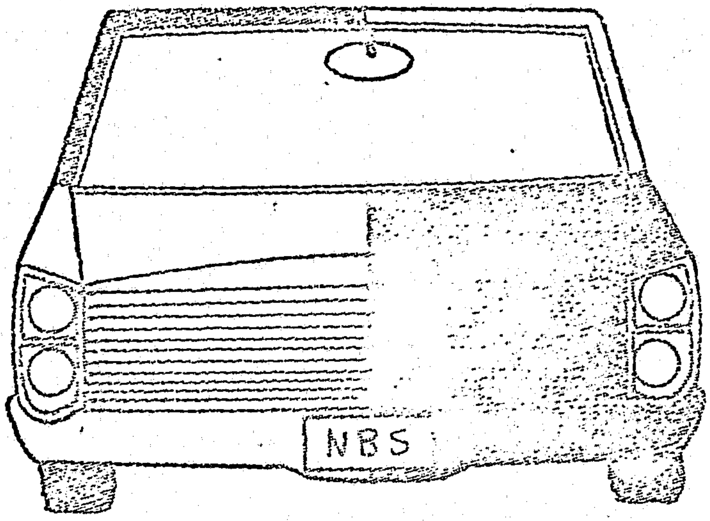
<u>Surfaces</u>. It appears impractical to expect the warning lights carried by emergency vehicles to be made much more than a foot in diameter. However, the surface of the emergency vehicle itself can be regarded as an auxiliary visual signal, and in bright sunlight the surface signal could under some circumstances prove more potent than any light signal used. Esthetic considerations presumably have had a strong influence in the past on the colors and patterns used in the painting of emergency vehicles. Another factor has been the desire for distinctiveness among different categories of emergency vehicles (fire engines red, ambulances white, etc.) In any event, visibility and conspicuity have not been the exclusive concerns of those responsible for the decoration of emergency vehicles.

At night, and against dark backgrounds such as earth or foliage in the daytime, light colors such as white or yellow are more visible, and some fire departments have started painting their engines white or yellow for that reason. (Night visibility of emergency vehicles is of some concern, because the vehicles sometimes do not use their warning lights, as when returning from emergency runs.) Unfortunately, with snow on the ground a white vehicle is all but invisible, and the noticeability of a yellow vehicle is not much better. Only dark colors show up really well against snow, or, for that matter, bright sky. A vehicle of intermediate reflectance, such as medium gray or tan, is not strikingly visible against either light or dark backgrounds, and is poorly visible against backgrounds of intermediate lightness, such as the road surface itself, on many occasions.

The solution appears to be to make the vehicle both very light and very dark simultaneously. Obviously, there is no way of arranging this for the vehicle as a whole, but it is certainly possible to make half the vehicle light and half dark. It would be wrong to paint the left half light and the right half dark, or the front half light and the rear half dark. It is important that large areas of both light and dark be visible regardless of the direction from which the vehicle is viewed. A fine checkerboard pattern would not serve well; although certainly conspicuous at close range, a checkerboard vehicle would appear to have a uniform, medium lightness at distances beyond which the individual squares could be resolved. The optimum arrangement would appear to be a "harlequin" pattern in which each major surface of the car (sides, rear, hood, roof) is divided into two to four rectangles painted alternately light and dark; in other words, an extremely coarse checkerboard.

A harlequin-painted vehicle, regardless of the angle of view, contains a large area that contrasts maximally in lightness with any background whatever. If the background is dark, the light area of the vehicle has maximum contrast with it; if the background is light, the dark area of the vehicle has maximum contrast with it; and if the background is medium, both the light and dark areas of the vehicle contrast with it about as much as anything can.

Sketches of several harlequin-type patterns were produced, and in Figs. 7.8-1 to 7.8-3, there are presented six views of an automobile painted according to the one best pattern discovered. The pattern is simple, follows the natural divisions of the vehicle, and exhibits substantial areas and edges of both black and white regardless of the angle of view. Since the pages are white, the view simulates the appearance of the harlequin-painted car in snow. Immediately following Figs. 7.8-1 to 7.8-3 are duplicate copies. Readers wishing to examine the appearance of such a vehicle on various backgrounds are invited to cut out the images of the cars from the duplicate figures and place them on black, gray, forest green, and other backgrounds of interest. Note that the pattern shown in Figs. 7.8-1 to 7.8-3 may be slightly preferable to the inverse (negative) pattern, in that the black area of the hood may somewhat reduce glare in the driver's eyes during driving in sunny weather.



Other view on following page.

Fig. 7.8-1. Front views of a harlequin-painted automobile, showing contrast with a white background. Upper view, from below the roof line; lower view, from above the roof line. This series of illustrations is presented twice in order to allow for cutting out of one set of car outlines to test appearance on black and other backgrounds.

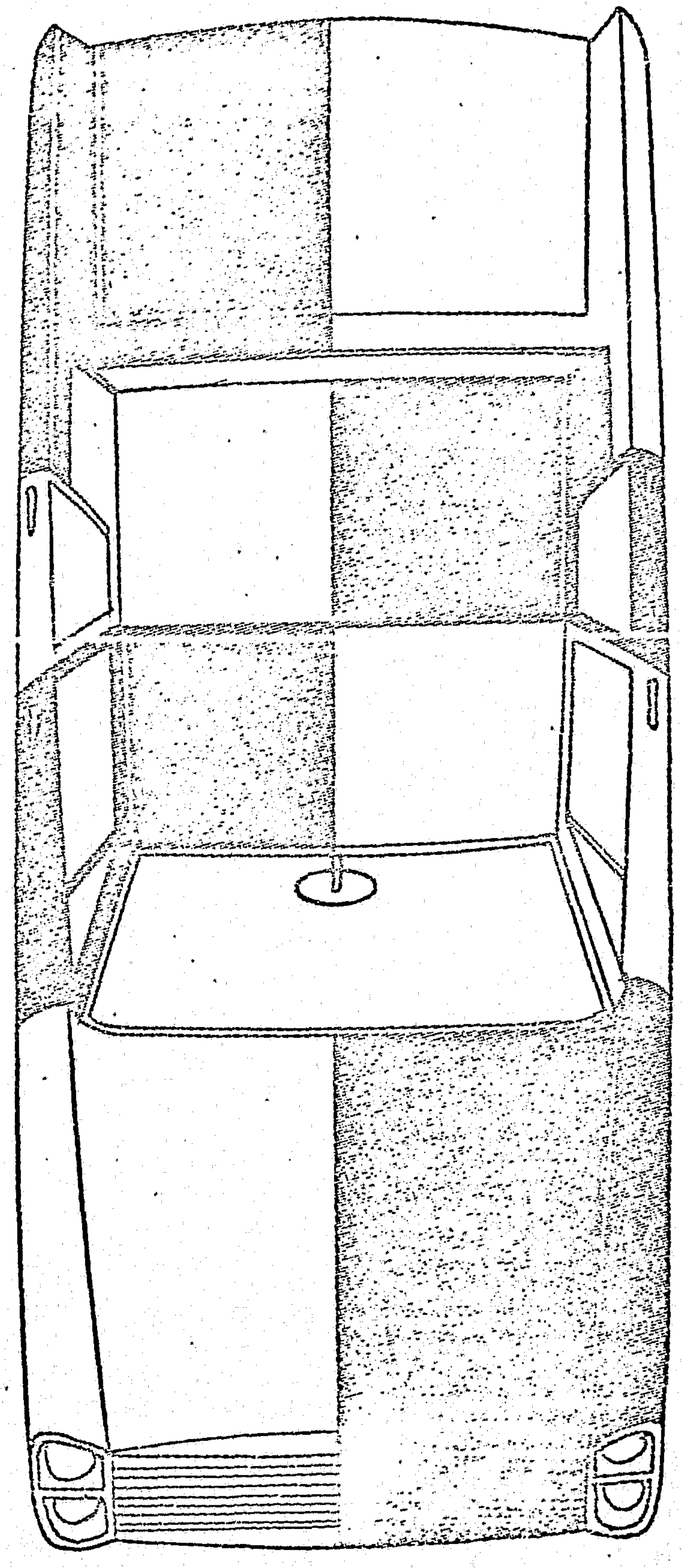
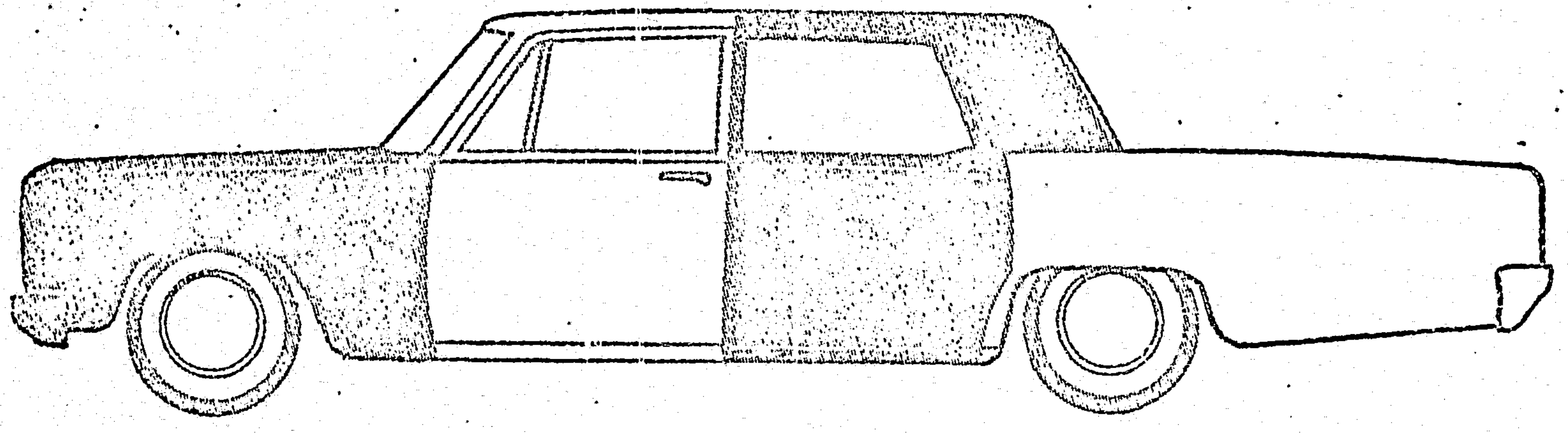


Fig. 7.8-1

View From Above



O-ther view on following page.

Fig. 7.8-2. Side views of a harlequin-painted automobile, showing contrast with a white background. Upper view, from below the roof line; lower view, from above the roof line. This series of illustrations is presented twice in order to allow for cutting out of one set of car outlines to test appearance on black and other backgrounds.

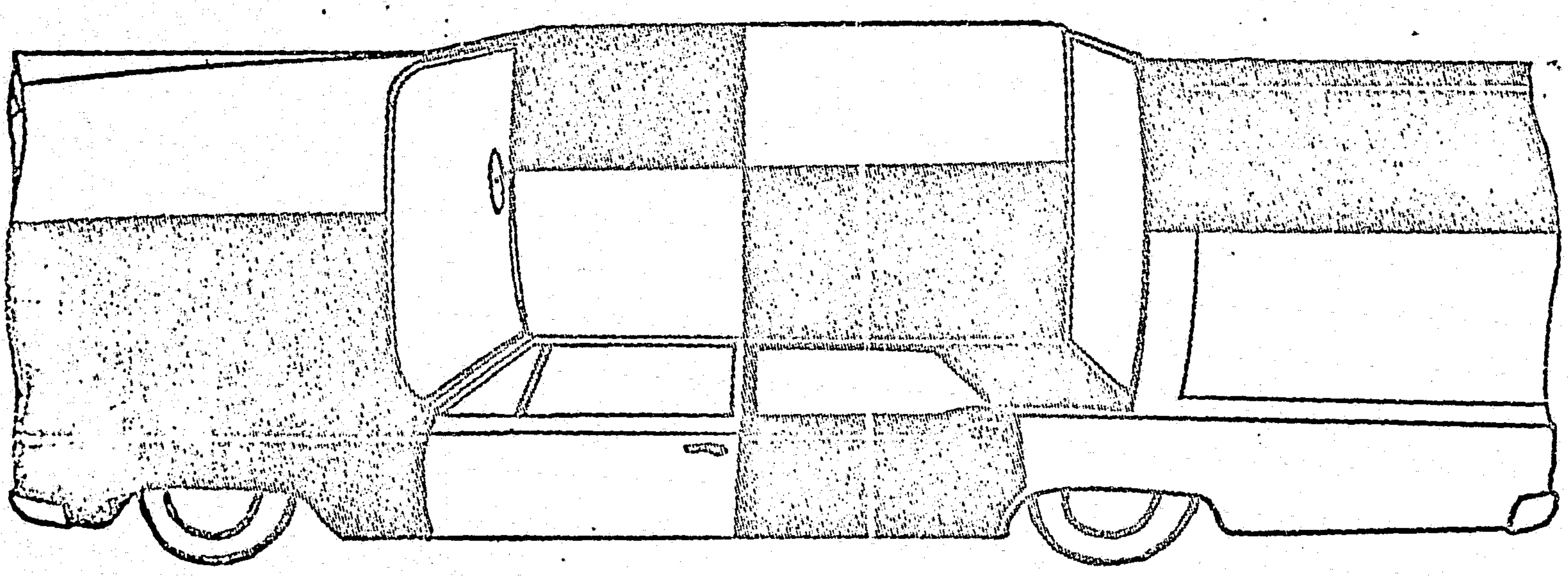
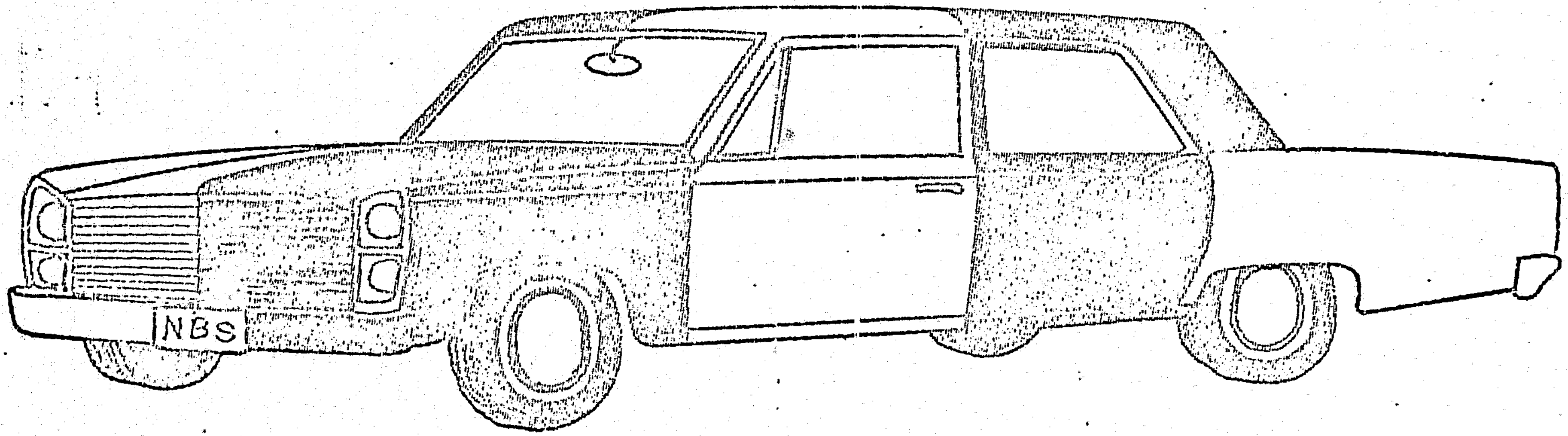


Fig. 7.8-2

View From Above



Other view on following page.

Fig. 7.8-3. Diagonal views of a harlequin-painted automobile, showing contrast with a white background. Upper view, from below the roof line; lower view, from above the roof line. This series of illustrations is presented twice in order to allow for cutting out of one set of car outlines to test appearance on black and other backgrounds.

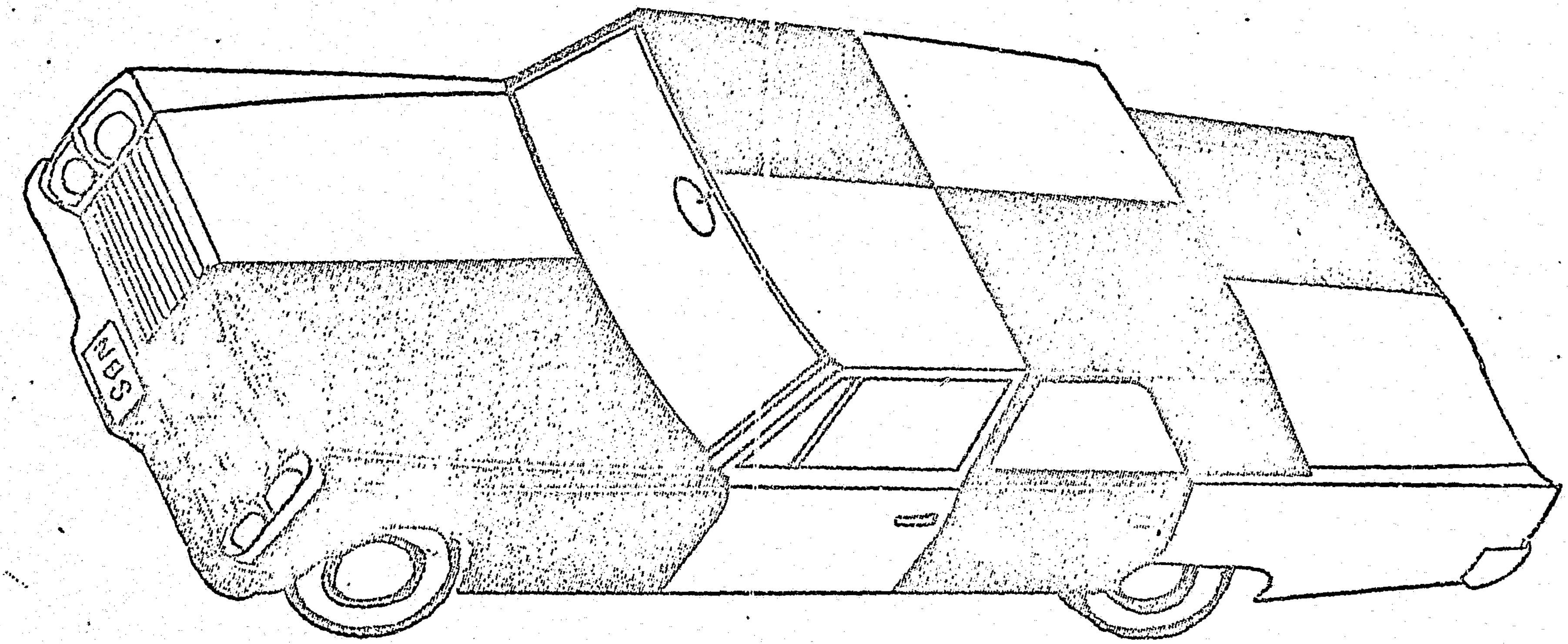


Fig. 7.8-3

View From Above

On the following pages, Figs. 7.8-1, 7.8-2, and 7.8-3 are presented again in order to allow interested readers to cut out the car outlines and view them against black, gray, and chromatic backgrounds, while still leaving a full set of figures in the report.

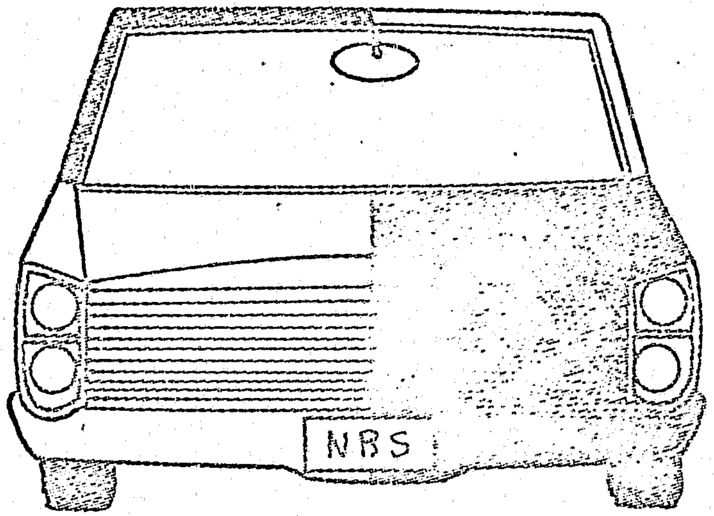


Fig. 7.8-1

Level View

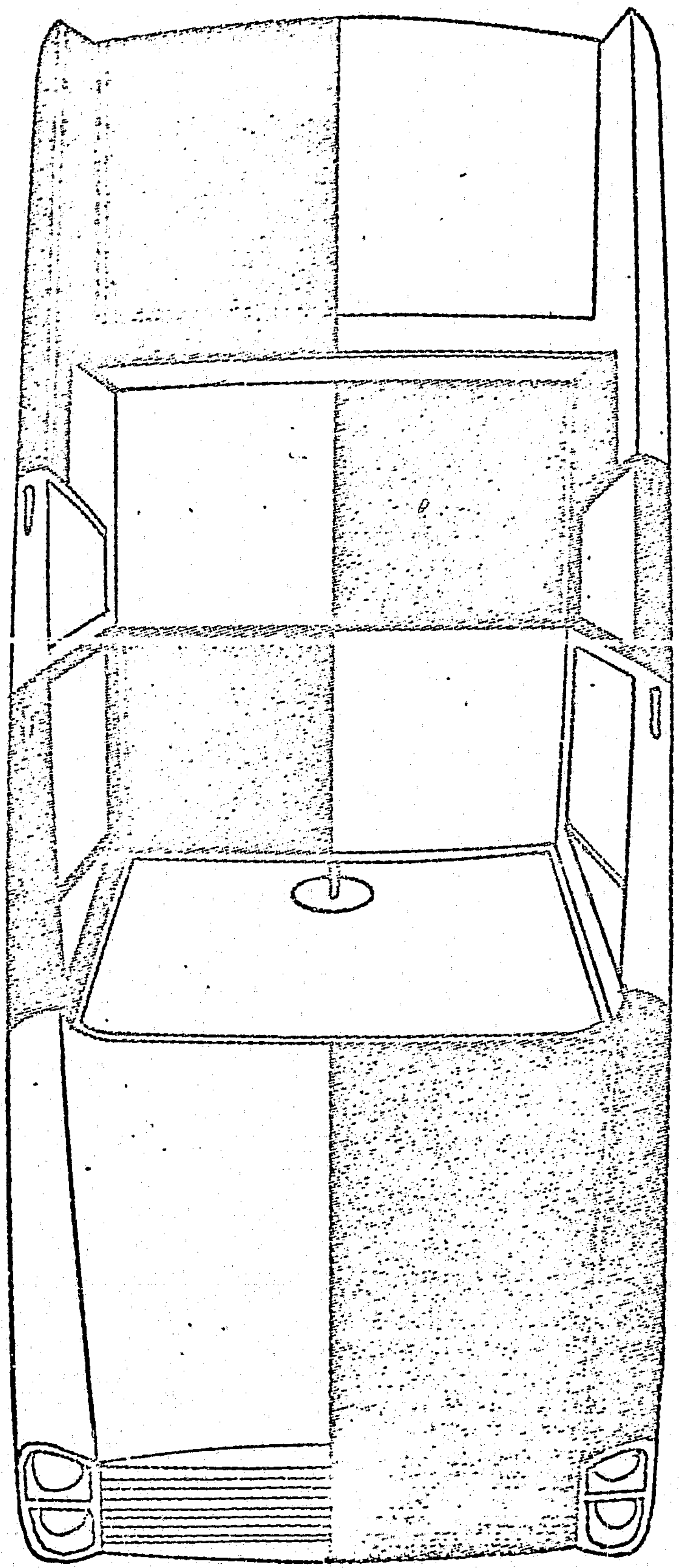


Fig. 7.8-1

View From Above

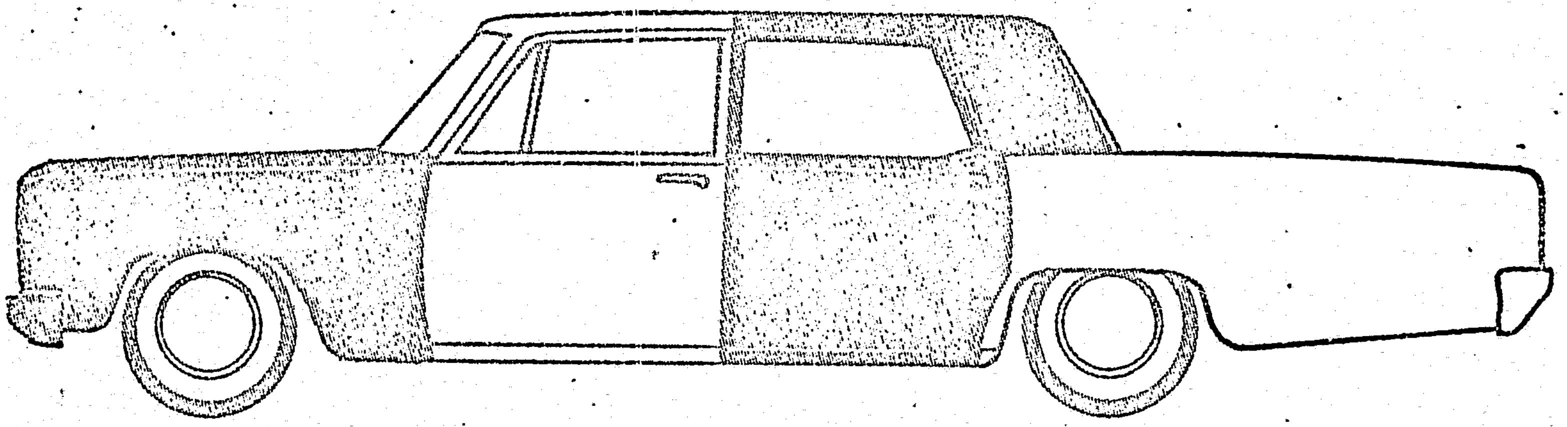


Fig. 7.8-2

Level View

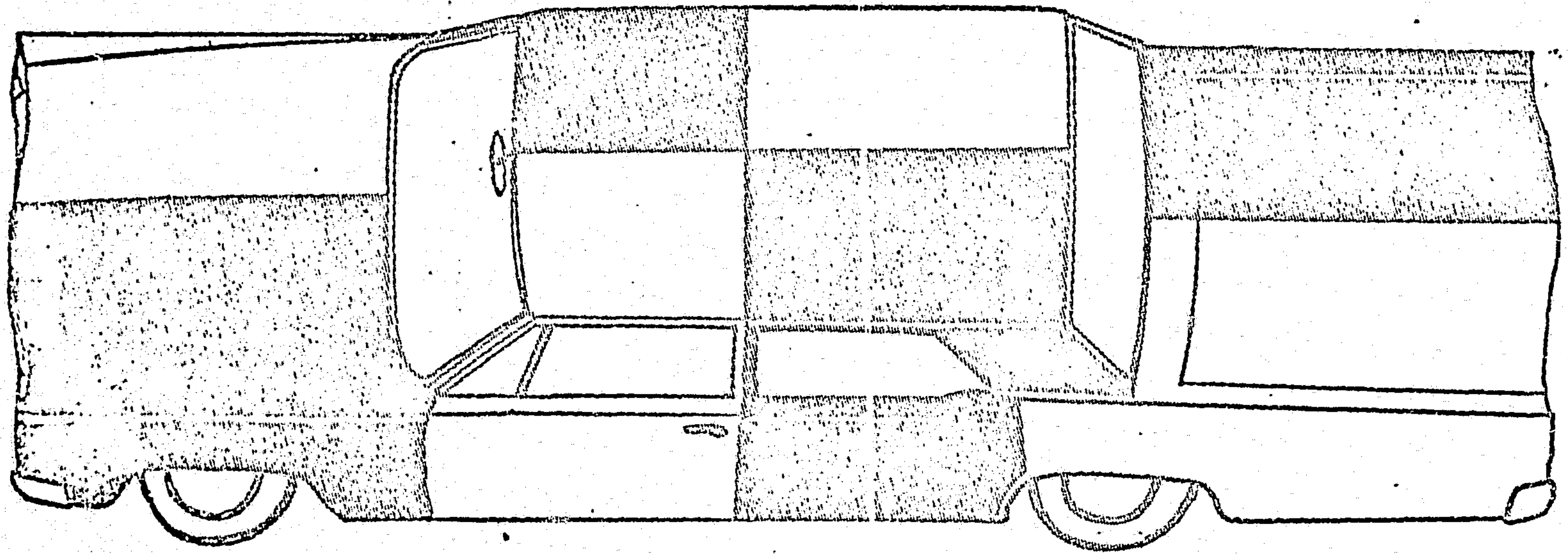


Fig. 7.8-2

View From Above

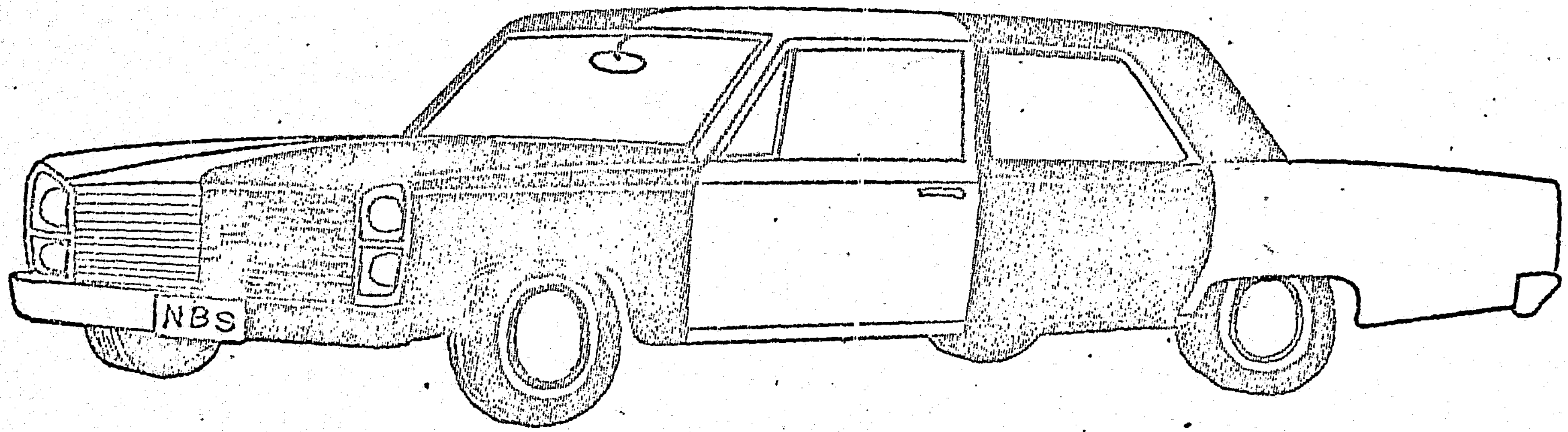


Fig. 7.8-3

Level View

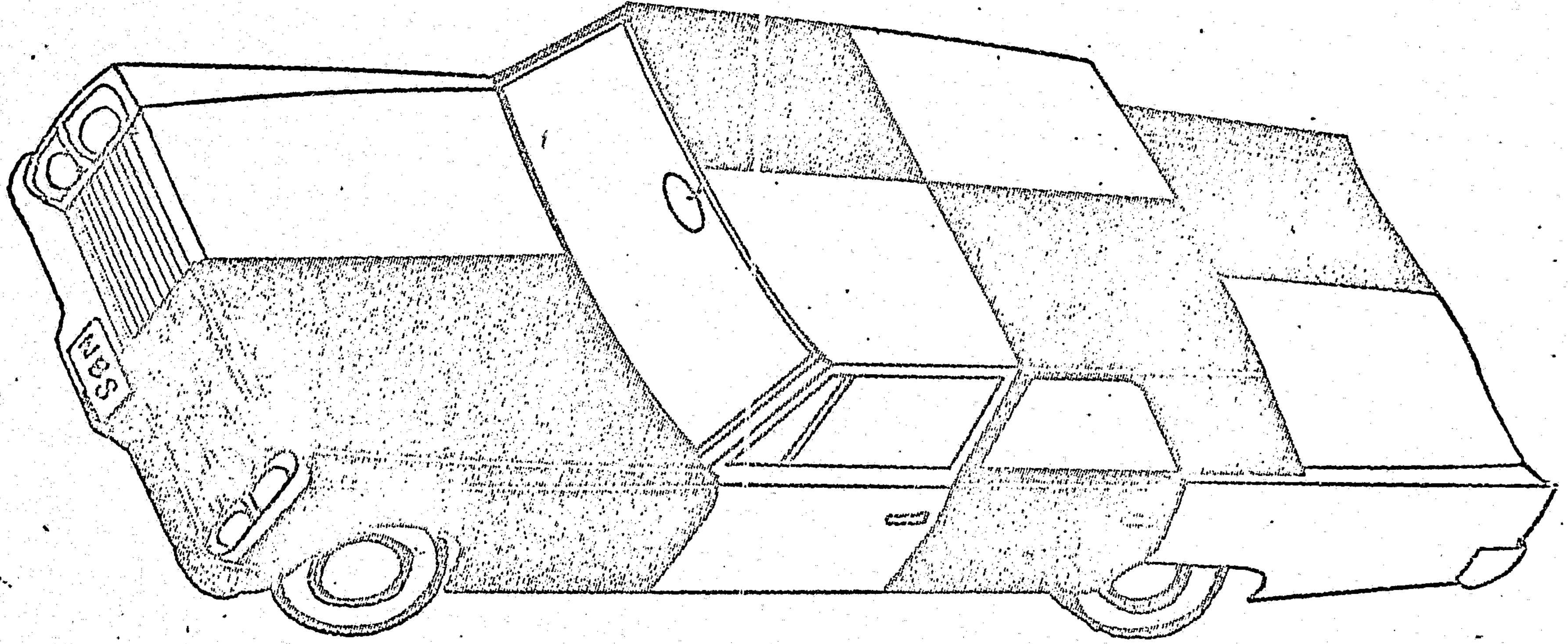


Fig. 7.8-3

View From Above

An extremely important fact about color contrast, to which designers of all kinds should pay much more attention, is that for many practical purposes, only lightness contrast counts. When one or both of the contrasting areas subtends a small angle at the observer's eye, differences in hue and saturation do not add as much to the overall impression of difference between colors, as does a substantial lightness difference. At very long viewing distances, the contribution of the hue and saturation differences fades toward zero. As a result of this rule, it is possible to retain color coding for close-up identification in harlequin-painted vehicles. For example, ambulances could be painted black and white, fire engines dark red and reddish white, and police cars navy blue and pale blue. In each case, the presence of the basic hue (or its absence, in the black-white combination) will permit the same kind of identifiability of function that we have now, but the chromatic content of the colors will not significantly affect the ability of any of these vehicles to stand out against any background.

Particularly because of the difficulty of seeing lights in the daytime, it is a definite waste not to make use of the vehicle's large surface as a signal. If there were any objection at all to painting emergency vehicles in a harlequin pattern, it would probably come from the crews of the vehicles, who might at first feel somewhat self-conscious about riding around in vehicles that were so--conspicuous. The conspicuousness, of course, is just what is needed for safety. Moreover, the light-heartedness traditionally associated with a harlequin pattern might possibly make a small contribution toward having members of the public accept the presence of the vehicles in good humor. Needless to say, the principle of maximum contrast with the background requires that if harlequin painting becomes customary or standard for emergency vehicles in any jurisdiction, the use of such a pattern on any other vehicle should be forbidden.

There are instances in which the police authorities in a given jurisdiction prefer to have some or all of their police cars painted inconspicuously, in order to permit covert surveillance activities. The suggestion for harlequin patterning naturally is meant to apply only to vehicles for which high noticeability is desired.

7.9. Motion of the Light Source

Electrically flashed lamps contain no moving parts; they simply go on and off. Rotating beacons, on the other hand, involve actual motion. Either the lamp is rotated or oscillated on a turntable or else the lamp is left fixed and a lens is moved in front of the lamp or a mirror in back of it. In more complicated units, both lamps and mirrors may be in motion. At long distances, when the entire unit is seen as only a point, the rotating beacon may be indistinguishable from a flashed lamp. However, when the unit is close enough to be seen as having a definite size and shape, the motion of the moving parts or of the light beam itself may become noticeable.

The increased noticeability of a moving light in circumstances when most lights in the environment are steady has always been well known. People signaling to boats offshore traditionally swing their lanterns back and forth, and railroad workers also swing their signal lanterns at night. Even when there are people and vehicles bearing lights moving across the background, a swung lantern is relatively conspicuous because its localized, repetitive motion is markedly different from the steady, unidirectional motion of a man or vehicle progressing in a particular direction.

Once again, we see that the best signal is one that differs as much as possible, in as many ways as possible, from the normal background stimuli; that is, one that is as improbable as possible under the total set of circumstances in which it appears. Several designs that apply this principle through the use of light-source motion are feasible. An emergency-vehicle warning light might be made more conspicuous by oscillating it back and forth across the width of the vehicle, or bobbing it up and down a few feet, or both together. Another approach might be to impart some even more complicated but repetitive motion, such as moving the light around and around a large triangular track standing upright on the roof in an orientation corresponding essentially to that of the windshield (but straight up, like old-fashioned windshields).

The larger the excursions of the moving light (as for example, across the entire width of the vehicle's roof), the greater will be the distance at which the motion will be visible and will contribute to conspicuity. Such gross motion of the entire unit would be conspicuous at far longer range than the small internal motions characterizing most of the present rotating beacons. As is most often true, a price must be paid for conspicuity added through gross motion. The cost of the unit would increase, there would be more frequent mechanical failures, air resistance might be increased, and if vertical motion were included, there would be some possibility of collision with low-hanging tree branches. Fortunately, as will be discussed in the immediately following section (7.10), actual mechanical motion can often be replaced by illusory motion produced by flashing lights in sequence with proper timing.

7.10. Temporal Phase Relations Among Lights

Some emergency-vehicle warning-light displays consist of two or three separated lights mounted across the width of the roof. If, to consider the two-light case, both lights are flashing with the same frequency, is it more conspicuous for the lights to flash on and off together (in phase) or for one to go off as the other comes on (out of phase)? With a center light and two side lights, should all the lights have the same frequency, and, in any case, what should the phase relationships be among the three lights to maximize conspicuity?

In some situations, people's perceptions correspond closely to the objective physical pattern. For example, suppose that an observer is watching a display consisting of two lights flashing at the same frequency with a 1:1 on-off ratio, but with one light lagging a little behind the other in phase. What is seen might be as follows: left light comes on and stays on (for a while); right light comes on a moment later and stays on; left light goes off and stays off; right light goes off a moment later and stays off; then repeat.

Now suppose that we leave everything else as above, but change the timing to put the two lights fully out of phase. Now what is occurring is objectively as follows: left light comes on and stays on; left light goes off and stays off, and simultaneously right light comes on and stays on; right light goes off and stays off and left light comes on and stays on; then alternate the last two steps. Human perception being as complex as it is, the observer may now see something quite different from the reality of the situation: he may see a single, continuously burning light that hops suddenly back and forth from side to side. In other words, he may see motion that is apparent or illusory.

Apparent Motion. This particular illusion is not very surprising, for consider what the observer would see if there were in fact a continuously burning light that hopped very quickly from side to side with a regular rhythm: he would see precisely the pattern of stimulation described above, except that in addition, he might see a faint blur of light along the path of the rapid motion. When the motion is quite rapid, the blur of light as the lamp passes from one position to the other is quite faint; the principal events are the alternate appearances of the bright light on the left and on the right. Thus the perceived patterns for a single light jumping back and forth and a pair of lights blinking alternately are very similar, and it is not difficult to believe that the two could be confused. Since we do tend to expect the faint intervening blur when we interpret our perception as a moving light, it is common for observers to see the blur even when it is not there; that is, when the motion is illusory.

In the illusion of motion described above, it is not necessary that the flashing of the two lights be repetitive; a single flash of each light with a suitable time lag between the flashes may be enough to trigger the illusion. The appearance or non-appearance of the illusory motion is a function of a number of variables. Among these variables are the durations of each of the flashes and of the dark interval between them. If there is no dark interval -- that is, if the flashes overlap temporally -- then the relevant variable is the interval between the starting times of the flashes. Other factors that have been shown to influence the perception of illusory motion are the intensities, colors, sizes, and shapes of the two lights, and the spatial separation between them. Finally, the attitude ("set") of the observer, including his guess as to what he is looking at and his expectations concerning whether movement is to be anticipated, can influence whether he will in fact see movement.

In its crudest form, the type of apparent motion discussed above is seen in the sequential turn signals used on the rear of some automobiles. What is actually the repeated sequential lighting or brightening of, usually, three lights, is seen as the movement of something -- perhaps a blob of light -- in the direction of the later brightenings. In more elaborate form, the phenomenon is seen on older theater marquees in the strings of incandescent bulbs that produce sensations of a flow of light around and around or back and forth. In still more elaborate form, the phenomenon is seen in Times-Square type traveling message signs or animated advertising signs. In the ultimate forms of illusory motion, namely movies and television, real and apparent motions are combined. The images in both media actually consist of a succession of still pictures. There is real motion in the sense that the image corresponding to a particular moving object shifts its position on the screen from one still shot to the next. The image, however, never actually occupies any of the intervening positions; they are filled in perceptually by the observer so that the motion is seen as smooth and continuous in most instances.

A different motion illusion is often seen when a single light is flashed. The illumination seems to burst radially outward from the center of the light; that is, something (perhaps a pattern of rays or spikes of light) seems to be expanding out from the center. When the light goes off, the "rays" may be seen to be sucked back into the center of the light, in an inward contraction. This illusion does not seem to require separate attention in considerations of warning-light design, since it is a function of the same variables -- intensity, pulse duration, and possibly pulse shape (time course) and color -- that are already known to be determinants of the conspicuity of signal lights.

The first kind of apparent motion, however, involving two or more lights, could quite possibly be made to play an important part in improving the conspicuity of a multi-light unit. The real motion discussed in the preceding section (7.9) can probably be replaced advantageously by apparent motion with fewer of the disadvantages mentioned in (7.9) as being associated with real motion.

8. Influence of the Background

8.1. Characterization of the Background

When a signal light appears against a background of other lights, the characteristics of the background lights influence the conspicuity of the signal. The same variables discussed in Chapter 7 for the signal lights are also the relevant ones for the lights appearing in the background. A reasonably complete specification of a particular background viewed from a fixed vantage point would include the following: (a) the position of each light within the field; (b) a statement of the intensity, color, size, and shape of each light; (c) a statement of the flash rate, on-off ratio, and pulse shape, for each flashing or sweeping light (rotating or oscillating around a point); (d) for each moving (position-changing) light, a statement of the path of motion and the time course; (e) if there is more than one flashing or sweeping light, a statement of the phases of all such lights at a specified moment in time; and (f) where there is more than one moving light, a statement of the phases of all such motions at a specified moment in time.

In city driving, the background does not ordinarily consist of a set of isolated lights seen against an overall curtain of blackness. There is usually enough prevailing light to illuminate ordinary objects, so the background consists of a gigantic mosaic of small patches of light, each patch representing a more or less uniform portion of an object. For such a background, the same type of specification would serve as was described above for the case of isolated lights embedded in darkness; there would simply be enormously more stimuli to specify.

The discussion of background specification to this point has been based on the idea of a stable background viewed from a single observing position. In moving traffic, however, the background is continuously changing. It is clear that no adequate description of the actual background encountered in driving can be supplied in the form of a few or even many numbers. The closest thing to an adequate statement of a real traffic background would consist of a roll of color movie film or videotape shot from an actual moving vehicle.

Despite the practical impossibility of accurately specifying the background encountered in the driving situation, some of the more important aspects of real backgrounds could be abstracted out and quantified in a statistical sense. For example, it would be helpful to know the relative frequencies of occurrence of lights of different colors. Also directly relevant to the emergency-vehicle warning-signal problem would be a specification of how many flashing lights of different colors are encountered per minute.

One possible procedure for actually generating the required information would involve repeatedly snapping color photographs of the rear-view mirror of an automobile driving through actual traffic, at intervals of about 20 or 30 seconds. In order to identify lights that are changing in intensity with time, each photographic record could actually consist of two pictures, snapped in very rapid succession. Statistical counts of colors and time-varying lights could then be made from the photographs.

In order to obtain information of really general national applicability, it would be necessary to make counts such as those described above in many different locations within many different cities across the country. Quite possibly, the knowledge gained would not add enough to what can be learned from the overall subjective impressions of experienced drivers to warrant the considerable expense of the objective measurements.

8.2. Controlling the Background

To a considerable extent, the visual background encountered by motor vehicle drivers is a given aspect of the world that must be taken account of in the design of optimum light signals. Fortunately, however, affecting the visual environment on the roads is not totally beyond our capacity. Because most emergency signal lights are flashing, some jurisdictions have banned from the streets all flashing lights other than emergency signals. The emergency signals are thus made to differ more from the background, and this increases conspicuity.

Similarly, in a jurisdiction that uses red emergency lights, their conspicuity can be increased by banning all red lights on the streets that are not emergency or traffic signals. Banning anything is a serious step for which society pays some price, and the gain in emergency-signal conspicuity must be weighed against the loss of freedom, if nothing else. Some jurisdictions that have become concerned with "visual pollution" have banned all garish, flashing, or moving commercial signs. Although it may not have been intended in every case, the same bans that reduce unpleasant visual clutter also contribute to the conspicuity of most of our present warning lights.

One step that can be taken without the need for legal proceedings is to improve the immediate backgrounds of signal lights. The background that differs most from any sufficiently bright light is total darkness. Consequently, instant improvement in at least the daytime conspicuities of all warning and traffic lights could be obtained by surrounding the lights with areas that are painted black. We are unaware of any actual realization of this principle in connection with vehicle-borne emergency warning lights, but black surrounds are being used around some school-bus flashers, and some jurisdictions have begun a program of installing black backgrounds around their traffic signals.

8.3. The Crucial Role of the Background

In a series of laboratory experiments studying reaction times to peripherally viewed lights, Gerathewohl (1953, 1957) established that under some circumstances, a flashing light is more conspicuous as a signal than the same light left burning steadily. In Gerathewohl's studies, the signal lights appeared against a background of steady "distraction" lights. Some time later, Crawford (1962, 1963), in a generally similar series of experiments, introduced various percentages of flashing lights into his backgrounds. No one who has read the earlier sections of this report should be surprised to learn that Crawford found flashing light signals to be less conspicuous when some of the background lights were flashing than when the background lights were all steady. What is surprising in Crawford's findings, however, is that if even a single one of the background lights was flashing, the advantage of a flashing signal light over a steady signal light was lost; and if at least 10% of the lights in the background were flashing, steady signal lights became unequivocally superior to flashing signal lights.

Because there were quite a few differences in the detailed conditions of the Gerathewohl and Crawford studies, the two sets of results may or may not be directly comparable. Moreover, both series of studies used configurations highly simplified with respect to the real-life traffic situation (although resembling it more than the configurations in any other laboratory studies of which we are aware), so that the direct, quantitative applicability of the findings to the design of emergency-vehicle warning lights is open to some question. It is nevertheless quite clear, even from the internal results of the Crawford experiments, that the nature of the background plays a critical role in determining the conspicuity of a signal light.

9. Assessing Conspicuity

9.1. Introduction

In this section, attention will be paid to the problems of conspicuity assessment both for existing warning-light devices and for light signals produced as part of laboratory experiments. In many attempts to evaluate the perceptual effectiveness of hardware of one kind or another, unsophisticated experimenters have produced useless results because variables that have a major influence on effectiveness have been left uncontrolled. The following section, 9.2, is included as a caution to those interested in experimenting not only on emergency warning lights, but on any category of sensory devices.

9.2. Sources of Differences in Effectiveness: A Caution

Lights are used on all types of vehicles and in some fixed installations such as lighthouses and airport runways both to indicate mere presence and also to signal the occurrence of important events, such as the application of brakes in a motor vehicle. Lights that are maximally effective in one of these situations need not necessarily be best in any of the other contexts, so repeated attention has been given to the problem of conspicuity by investigators working with each of these specialized contexts in mind.

One problem that arises in almost every case is the question of which color is most effective. There are three different classes of variables that contribute to the final answer to such a question. These will be reviewed now with respect to the specific issue, used as an example, of whether red or blue lights are more effective.

(a) Physical outputs of devices. There is no meaning at all in the unqualified question: which is more effective, red or blue lights? It is necessary to specify exactly which red and blue lights are to be compared. If we are concerned only with the effect of color, it is clearly necessary to give the lights an equal chance at being effective in every respect other than color. In particular, the intensities of the lights are crucial. No one could believe that a fair test was being conducted if a blue glass were installed as the lens of an antiaircraft searchlight and that beam were compared in effectiveness as a signal to the beam from a pocket flashlight with a red lens installed. As a first step in making an unbiased comparison, we might think of using two identical pocket flashlights, containing identical light bulbs, one equipped with a red lens, and one with a blue lens.

Such a comparison would in all probability still not be fair, however. In fact, it would not be fair even if a representative selection of different commercially available blue glasses and plastic filters were tested against a similar selection of red filters. The problem has to do with the typical characteristics of commercial blue and red filters. A blue filter, in order to appear strongly blue, must transmit light within the fairly narrow band of wavelengths that appear blue, and must not transmit very much light of other wavelengths. As a result, only a small percentage of the total energy emitted by a white source such as an incandescent lamp passes through strongly blue glass or plastic. The percentage of incandescent lamp light passed by a typical blue filter is about 3%, in luminous (visibility-weighted) rather than radiant (energy) terms; this fraction is known as luminous transmittance.

On the other hand, the entire long-wave end of the spectrum appears red, so that a glass can appear strongly red by passing all wavelengths beyond a certain point in the spectrum, and no wavelengths below that point. As a result, a typical red filter passes a broader band of wavelengths than a saturated blue filter. Moreover, incandescent lamps emit more long-wave (red) than short-wave (blue) energy. The combination of a broader range of transmitted wavelengths and a greater level of energy within that waveband leads to a typical luminous transmittance of about 20% for red signal-light filters transmitting incandescent lamp light.

Thus, even if identical light sources are used for comparisons carried out with a selection of red filters and a selection of blue filters, there will be typically seven times as much luminous power in the red light as in the blue light. In order to be fair to the blue light, then, the lamp used with the blue filters should have about seven times the luminous intensity of the lamp used with the red filters. Comparisons made using several commercial red-light units and several commercial blue-light units reveal only the performance of those specific red units relative to those specific blue units. If the issue is the generic question of the relative effectiveness of redness and blueness as qualities of a signal, then the requirement is that the units tested should deliver to the retina of the observer equal illuminances of red and blue light, regardless of what kinds of light sources and filters are used to produce the lights.

(b) Sensitivities of the observers. Usually it is some measure of observer sensitivity alone that is really sought in comparisons of effectiveness. The "physical" output discussed in (a) above cannot properly be considered independently of observer sensitivity. It is retinal illuminances that must be equated for a fair visual comparison, and illuminance is obtained by weighting irradiance -- a physical energy-related measure -- by the luminous efficiency function of the observer. The luminous efficiency function appropriate to the viewing conditions (the angular size of the lights, the irradiance level of the light entering the eye, and the portion of the retina on which the light is imaged) must be used, as discussed in earlier sections (6.2 and 7.6).

What we need to do, then, is to deliver to the observer's eye red and blue lights that appear to him, under the viewing conditions being used, to be equally bright. Any differences in conspicuity that may exist between red and blue light must then be a function of aspects of the observer's response other than his impression of simple brightness. For example, it is conceivable that differences in the rapidities of response of the different color channels of the visual system might make flashing red lights attract attention to a greater or lesser extent than flashing blue lights, even though the lights are equally bright when steady.

(c) Familiarities. Many people live in jurisdictions in which red and perhaps yellow lights are used for all emergency signals, and blue lights are not used at all for signaling. When such people serve as observers in an experiment in which they are asked to respond to red and blue lights in some manner, it is possible that the quickness or strength of their responses will be influenced by their long familiarity with red as an emergency-warning and stop-signal color and their unfamiliarity with blue in the same contexts.

Since there are now jurisdictions in which blue is widely used as an emergency-warning color, people from those areas would be expected to yield results showing less of an advantage for red relative to blue as a signal color. A test of whether familiarity does in fact contribute significantly to the measured effectiveness of a signal can be arranged by using two (or more) groups of observers with different histories of exposure to the classes of signals being tested. Thus, in the example we are using, we might use two large groups of observers, chosen randomly from among long-term residents of jurisdictions using mainly red and no blue warning lights, and of jurisdictions using mainly blue and a minimum of red warning lights. Perhaps more efficiently, we might use two smaller groups chosen not at random but by matching pairs of members on characteristics such as age, sex, driving experience, and other variables that might affect the results of an effectiveness or conspicuity study.

Although in a comparison of red and blue the role of familiarity may be in sufficient doubt as to require a direct test, there are other comparisons in which it is obvious that familiarity plays a major role, at least comparable to the contribution of the perceptual variables. An example is the question of the relative effectiveness of pictorial as opposed to verbal road signs. Unfamiliarity with the language in which a highly visible verbal sign is written will render the sign totally ineffective. Similarly, unfamiliarity with the accepted meaning of one of the less self-explanatory pictorial signs will also render it ineffective, regardless of how clearly it can be seen.

9.3. Basic Experimental Approaches

(a) Direct subjective ratings. In this type of experiment, each observer is asked to look at the signals and give some kind of rating corresponding to his or her impression of how effective the signals would prove to be in actual use. Several variations are possible. The signals can be presented one at a time and the rating might then be in the form of a number -- say, from 0 to 100 -- representing the observer's subjective scale of effectiveness. Alternatively, the signals can be presented in pairs, and the rating might take the form of a simple judgment as to which of the two signals being simultaneously judged appears to be more effective. With the latter procedure, the numerical ratings of effectiveness for each signal would be derived by established statistical techniques [see, for example, Guilford (1954)].

When the comparison is specifically of the conspicuities of emergency-vehicle warning lights, it would obviously be important to present the lights with viewing conditions as comparable as possible to the conditions under which real lights are seen on the road. Thus the lights should be viewed from a distance giving the test lights an angular size at the observer's eye comparable to the angle subtended by a typical commercial unit at a distance long enough to allow a normal driver to take necessary action in time. (Note that an 8-inch dome seen at 382 feet subtends an angle of 1/10 of a degree -- 6 minutes of arc.) There is little importance in conspicuity ratings made from close up, because the practical interest is in maximizing the probability of the signal's being noticed at distances that will allow the emergency vehicle to move smoothly through traffic.

Even more important is the fact that, in this context, there is relatively little interest in direct (foveal) viewing of the signal lights, because the difficult situation is attracting a driver's attention when the signal-light image is coming from the rear-view mirror, from the right side of the windshield, or through a side window. It is not unusual for the center of the rear-view mirror in a full-sized American automobile to be 35° or 45° to the right of the driver's straight-ahead line of sight, and the right edge of the windshield can be about 70° away.

The basic format of a "comparison-within-pairs" experiment might therefore involve having the observer fixate (steadily look at) a relatively unobtrusive target directly ahead, while the two lights to be compared in conspicuity appear symmetrically perhaps 35° - 45° to the right and left of the fixation target. The lights are thus separated from each other by something on the order of 70° - 90°. As we have discussed in earlier sections, an observer can see little detail 35° or 45° into the periphery of his field of view, but some color discrimination and a good deal of sensitivity to flicker and motion are retained, so that the observer is quite capable, with a bit of practice, of focusing his attention on the conspicuities of isolated lights very far from his direct line of sight.

A final variable important in these conspicuity comparisons (see Section 8.3) is the background against which the signal lights appear. A black (dark) background is of some interest as an approximate representation of conditions on low-traffic unlighted roads at night. More useful is a background that is basically dark but which contains a selection of "distraction" lights of various colors and intensities. Ideally, the distraction lights should move and an occasional one or more should flash on and off. This background represents a city street at night or a road with heavy traffic. Perhaps the most critical test is with a high-brightness background, corresponding to the condition of driving in daylight or sunlight, which strongly interfere with the noticeability of light signals.

Recently, a laboratory experiment of the direct-rating "paired" comparison type was carried out by Edwards (1971). Edwards explored the relative conspicuities of lights having different combinations of flash rate and on-off ratio. The viewing conditions were not ideal from the point of view of emergency-vehicle warning lights because each light of the pair being compared was only 2°50' to the side of the fixation point. The Edwards study does establish, however, the basic soundness of the method.

Any method of testing conspicuity other than collecting real-life statistics involves some assumptions relating the measure used experimentally to the kind of conspicuity that operates in the practical situation. The direct-rating method involves the rather strong assumption that an observer examining lights in a static viewing situation can correctly estimate from what he sees the degree to which the different lights would be able to attract his attention if he were not expecting their appearance and was concentrating on other matters (that is, if he were driving a car). If it could be established that this assumption is realistic, then confidence in direct-rating studies would be justified. It would consequently be desirable to show a high correlation between direct ratings and other measures of conspicuity that are more objective or closer to the real-life situation. Two such measures are discussed in (b) and (c) below. Exploration of the latter two measures will require a relatively long-term experimental program. In the absence of ample resources of time and funds, method (a) appears to be the procedure of choice.

(b) Eye movements. There now exist devices, known as "eye-movement recorders," that can make an accurate record of the positions of both of an observer's eyes over a period of time. Suppose an observer is fixating a foveal target and comparing the conspicuities of two lights located in symmetrical positions in the periphery, as described in (a) above. The observer is trying to fixate the foveal target rigidly, but there will inevitably be small involuntary movements of his eyes to one side or the other of the fixation point. An eye movement recorder sufficiently sensitive to pick up the small involuntary eye excursions might well show that, for two particular lights, the observer's gaze has a significant tendency to start to move slightly toward one light more than toward the other. It would be necessary to show that the same tendency was retained when the two lights were interchanged left for right, since the tendency for the eyes to move to one side could be a positional bias of the observer rather than a genuine preferential attraction toward one of the lights. The same precaution is necessary in a direct-rating experiment or any other procedure involving comparisons within pairs. (Such procedures are known in the jargon of experimental psychology as paired comparisons or pair comparisons.)

Another precaution that is desirable in studying eye movements with two flashing lights present simultaneously is to avoid having one light consistently flash before the other, since the eyes may tend to turn toward the earlier light, rather than the more conspicuous one. The only sure solution, where feasible, is to synchronize the lights to flash simultaneously. If the lights have different flash rates that cannot be adjusted, it may be possible to average out the effect of flash ordering by simply running the eye-movement recorder for a long enough time. It must first be established, however, that in a long series of flashes of the particular lights being compared, each light flashes first very nearly half the time, regardless of the times of occurrence of the initial flashes when the units are turned on. Even when unbalanced flash ordering cannot be avoided, the eye-movement method could still prove informative if it turns out that the average magnitudes -- not simply the frequencies -- of involuntary eye movements are related to conspicuity.

The basic assumption of an eye-movement study is that if an observer is paying attention to the stimuli of the experiment (see Section 5.1), his gaze is drawn more strongly toward a more conspicuous light. This is an assumption that many people would consider less risky than the assumption underlying the direct-rating approach [see (a) above]. It would not be unreasonable, therefore, to use eye-movement recording as a method for validating, at least partially, the direct-rating procedure. Fortunately, since the experimental arrangements are the same, it is easy to combine the two procedures; the eye movements are recorded while the observer considers which light to rate more conspicuous.

A considerable amount of preliminary work would probably be necessary in order to make the eye-movement method practical. We know of no experiments applying eye-movement recording to the specific problem of signal-light conspicuity. An important element of the preliminary work would be finding a suitable measure, derivable from the recordings, that correlates well with gross differences in conspicuity (that is, conspicuity differences so obvious as not to require assessment through another type of experiment). For example, it might be that the fraction of the time that the observer's gaze lies on one side of the fixation point is a better or a worse measure than the average size of the eye excursions in that direction. It might even be found that rigid fixation is not the best condition to use in studying eye movements. A simpler procedure would be to tell the observer to fixate only before the test lights appear and then to look freely back and forth at both lights as soon as they come on. It might turn out that the light toward which the observer first turns his gaze is, with high probability, the more conspicuous. It could conceivably be found that some aspect of the eye-movement statistics measured when only one light was presented at a time (still peripherally, of course) would correlate better with obvious differences in conspicuity than any measure obtainable with paired presentation. Finally, it could unfortunately turn out that no eye-movement measure at all could be found that had any significant association with differences in conspicuity, but that result seems unlikely.

Both the eye-movement method, if it proves feasible, and also the direct-rating method, are applicable either to the testing of actual commercial warning-light units, or to simulated laboratory displays. There might be occasions when the effectiveness of commercial units is of specific interest. For example, a police or fire department contemplating the purchase of new warning-light units would undoubtedly like to see a graph showing some reliable measure of effectiveness as a function of the selling price of the unit, for all units on the market. However, if the factors determining conspicuity are ever to be explored quantitatively in such a way that the conspicuity of a unit will be accurately predictable from physical measurements made on it, it will be necessary to use simplified, fully controllable lights in the laboratory. The building of a quantitative predictive model for conspicuity will require the use of equipment permitting variation of each of the relevant variables separately over a considerable range of values, and such control is not available when only commercial units are studied.

(c) Reaction time. In studies based on reaction time, a signal light is turned on at randomly chosen moments, and the time that the observer consumes in reacting to the signal -- that is, carrying out the required response -- is measured. This procedure is not well suited to comparisons between lights presented simultaneously in pairs, but provides an absolute measure for lights presented one at a time. The lights should still be presented peripherally, and each light should be presented at least twice: once to the left of the fixation point and once equally far to the right (preferably a number of times on each side), thus averaging out any tendency the observer may have toward greater sensitivity on one side or the other. With flashing lights, the reaction time should be measured from the moment the first flash occurs, not the moment that the "on" button is pressed.

When a single light is presented at a location known to the experimental subject, and a single reaction is always expected, and there are no distracting stimuli deliberately introduced, then the situation is referred to as a simple reaction time study. Reaction times are minimal under these conditions; for lights, the times are typically in the neighborhood of 1/5 of a second for reasonably bright lights viewed foveally. Thus, very accurate measurement of time is necessary in a reaction time study. An electric clock capable of measuring to the nearest millisecond (thousandth of a second) is desirable.

It is impossible to measure simple reaction times to low-frequency flashing lights, because the subject reacts to the onset of the first flash and the second flash occurs too late to affect the outcome. The solution is to abandon simple reaction time and to go instead to disjunctive (also known as discriminative or choice) reaction time, in which the subject does not know which of several stimuli will occur on each presentation, and must make a different response depending on which stimulus appears. Other complications can be introduced, such as distracting stimuli and randomization of the place as well as the time of appearance of the stimuli. As described in Section 8.3, Gerathewohl (1953, 1957) and Crawford (1962, 1963) studied the reaction times to steady and flashing lights with this sort of complex experimental procedure, and Gerathewohl refers to the method by the name "complex reaction time." With sufficiently complicated patterns of background lights and ongoing demands on the observer's attention, reaction times of several full seconds were achieved by these experimenters, so that the later flashes of the flashing stimulus lights had a chance to affect the observer's reaction.

Although considerably simplified, the type of experimental configurations used by Gerathewohl and by Crawford have an obvious resemblance to the real-life situation. There are still assumptions involved in extrapolating their results to the real situation, however. Their patterns of background lights were much simpler than the background seen on the road; in particular, no "flowing past" motion was simulated. Moreover, the observers knew they were experimental subjects and were braced for the regular appearance of stimulus lights at random, but relatively brief, intervals of time. The practical emergency-vehicle warning-light situation involves the unexpected appearance of the warning light at time intervals that may run to hours or even days.

With enough time and money, the real-life situation can be simulated even more closely than Gerathewohl and Crawford represented it. The subjects can be seated in a driver trainer or even a real automobile, surrounded by optical equipment capable of presenting lights that flow past, as when a car is in motion on a road. The visual scene can be made to change in response to the subject's manipulation of the steering wheel, brake, and accelerator. The subject can be left in the experimental situation for hours, with random appearances of dynamically changing ("approaching") warning lights at intervals of minutes rather than seconds. Unfortunately, the cost of a highly realistic dynamic vehicle simulator can be extremely high. Some such devices exist, but they were primarily constructed for special training purposes and would not be likely to be released for research on warning-light conspicuity. It may be a long time, therefore, before any experimenter goes very much beyond Gerathewohl and Crawford in achieving realism.

10. PHYSICAL CHARACTERIZATION OF LIGHTS AND LIGHT SIGNALS

10.1. Physical Measures, Conspicuity, and Standards for Warning Lights

The ultimate purpose of the research effort of which this report is a part is to propose standards for emergency-vehicle warning lights that will assure that lights meeting the standards will have a certain minimum level of conspicuity. A relatively traditional approach to deriving such standards would be to test a variety of lights for conspicuity, and also to measure all the relevant physical values characterizing the outputs of the lights. From an analysis of such data, the hope is that those physical aspects of the light signal that affect conspicuity can be identified, and a function of all these variables derived such that it correlates highly with conspicuity. In other words, we would like to learn how to quantitatively describe and then predict conspicuity from a knowledge of the purely physical characteristics of a light.

A standard for warning lights derived on the basis of physical measurements would be phrased in terms of permissible limits on each of the relevant variables. For example, the intensity would be required to be above some minimum level for conspicuity purposes, and below some maximum level for the purpose of preventing damage to the eyes of nearby observers. Such a <u>physical performance standard</u> would similarly impose upper and/or lower limits on the flash rate, the flash duration, and other instrumentally measurable aspects of the output of the light units. In former times, these physical requirements might have been translated into specific restrictions on hardware; that is, detailed specifications of light sources, lenses, domes, circuitry, mounting brackets, etc. Today it is becoming increasingly accepted that performance standards -- indicating the functions that the device must perform, but not how the performance is to be achieved -- are desirable because such standards encourage the continuing development of new technology. A complete physical performance standard for warning lights might include not only limiting values for the basic parameters of the light signal, but also minimum requirements for the service life of the device -- of whatever kind -- and for its ability to function under adverse environmental conditions, such as temperature and humidity extremes, precipitation, and perhaps the presence of atmospheric pollutants such as dust, sand, and salt.

A still more performance-oriented approach to writing a standard for signal lights is possible, and, from some points of view, preferable. This is the specification of a perceptual performance standard, in which we indicate the ultimate function we expect the light units to perform, and how well we demand that the units perform this function. The physical means used to achieve the required level of performance are not mentioned in such a standard; any configuration of lights that meets the behavioral criterion is acceptable. The primary function we are interested in having the lights perform is, of course, attracting attention; more specifically, being conspicuous when seen away from the direct line of gaze -- that is, in peripheral vision. A highly simplified example of how a perceptual performance standard for warning lights might be phrased is as follows:

> An emergency-vehicle warning light, viewed at a distance of 1000 feet, must be visible at least 60° into the periphery of the (binocular) visual field by 85 percent or more of licensed drivers. An intermittent light shall be deemed 'visible' when each individual flash can be perceived.

NOTE THAT THE ABOVE SAMPLE STANDARD IS A SIMPLIFIED EXAMPLE ONLY AND IS NOT BEING PROPOSED AS AN ACTUAL PERFORMANCE STANDARD FOR LIGHTS.

The specific numerical values used in the above sample standard may be reasonably appropriate, but should not be taken too seriously. Moreover, a complete perceptual performance standard would have to spell out a number of additional requirements, such as the viewing conditions under which the visibility test is to be conducted (night or day, against what background, etc.); the procedure to be used; how large a group of observers is demanded; how they should be selected; and so on. (The number and type of observers selected must be such as to assure with high probability that the test group is representative of all the licensed drivers in the jurisdiction concerned; the problem is similar to choosing the sample for poll-taking.)

The sample standard on the preceding page is an indirect perceptual performance standard; that is, a type and level of performance are demanded that are not in themselves the end result desired, but which are thought to guarantee that end result. What is really desired in an emergency-vehicle warning light is that it be noticed sufficiently soon by some specified fraction of drivers when it appears in the rearview mirror, or off to the side, during a time when the driver is in a traffic situation requiring a specified high level of attention in the forward direction. The development of a direct perceptual performance standard would involve creating a driving simulator that permitted a standardized test to be run that closely approximated the conditions just described.

The use of a standard based on physical variables involves the tacit assumption that the dependence of the ultimate perceptual variable (such as conspicuity) on the physical variables, separately and in combination, is understood well enough so that no substantial improvement in perceptual performance could be achieved (within the restrictions of safety) by going outside the specified limiting ranges of the physical variables. Thus a very substantial body of psychophysical experimentation is presupposed. On the other hand, the use of a perceptual standard presupposes only that a practical and acceptably accurate technique for measuring performance in the criterion perceptual variable has been developed. Even where recourse is had to an indirect perceptual standard, such as the one exhibited above, a similar assumption is implicit, because unless the ultimate criterion variable (conspicuity) can be measured, it cannot be established that some simpler perceptual variable (peripheral visibility) correlates highly with it. The measuring technique for conspicuity could, however, be elaborate and expensive, in the case of an indirect standard, since the technique would be used only in research and not on a routine production basis; the indirect test must then be the practical one.

It should be noted that although a perceptual performance standard for only the conspicuity of lights might prove feasible, a complete standard for emergency-vehicle warning lights would probably still be expected to place restrictions on the service life and harsh-environment performance of the physical device, even though the standard did not otherwise discuss the device. Moreover, if the lights were to serve secondary functions beyond the primary function of attracting attention -- such as identifying the vehicle type or indicating the action expected of the target drivers -- some arbitrary physical codings might then have to be written into the standard, such as requiring the light to be red on a fire engine, or to have greater intensity in the forward direction than to the rear or sides. A pure perceptual performance standard is therefore not realistic; the question is whether some items of perceptual performance should be mixed in with the physical performance requirements. No recommendations concerning standards will be made in this report; the purpose of this section is to call attention to some possible alternative approaches.

10.2. Angular Intensity Distribution

A star of the ordinary variety, viewed from far away, is a source of light that is essentially uniform, to within a practical margin of accuracy; that is, the intensity of the light is the same regardless of the direction in which the observer is located relative to the center of the star. Except perhaps as an expensive and impractical stunt, no artificial source of light can possess this degree of uniformity. Thus, an incandescent lamp obviously delivers less light directly below its opaque base than in other directions, and fluorescent lamps, gas glow tubes, matches, kerosene lanterns, natural gas mantles, and other sources suffer from similar non-uniformities, caused mainly by the necessities for physical support and for delivery of energy to the actual luminous element. The non-uniformity is often not thought of as undesirable, and in many situations -- such as those in which spotlights or floodlights are used -- the concentration of the light output in a limited range of directions is positively desirable.

For any light source, a complete specification of the intensities in all directions from the center of the source is referred to as the <u>intensity distribution</u>. Since the directions from the center are usually specified by a pair of angles measured from two reference directions (such as latitude and longitude on the surface of the earth), the more specific phrase is <u>angular intensity distribution</u>. Because intensity is a concept applicable to a point source, the observer -- or, actually, the photoelectric measuring device used by the observer -- must be carried far enough away from the lamp so that the lamp is effectively a point source at the "viewing" distance used. The quantity measured directly by an ordinary photocell is flux: the light power striking the photosensitive surface. Since the area of the photocell's receiving aperture is fixed, the flux detected is proportional to the illuminance (flux per unit area) of the usable photosurface. The inverse square law of illumination states that the illuminance of a surface produced by a point source is inversely proportional to the square of the distance from the source to the surface. Thus, when the intensity of a point source is determined by measuring illuminance, the distance from the source to the receiving surface must be known. Moreover, when the intensities of a source in different directions are compared by measuring the illuminances produced by the source on receiving surfaces located in those directions, it is convenient to keep the distance from the source to the receiving surface the same in each of those directions, so that no correction of the illuminance values for viewing distance is necessary. Ideally, then, the photocell used to measure the intensity distribution of a light source would be carried around to different positions on the surface of a sphere centered at the source. In practice, it is easier -- and fully equivalent -- to leave the photocell and source in fixed positions and to vary the direction of view by rotating the source around its own center point.

In these measurements, the line joining the center of the light source to the center of the active area of the photosensitive surface is referred to as the <u>photometric axis</u>. The light source is mounted in an instrument, called a <u>goniometer</u>, that allows the source to be independently rotated about two perpendicular axes, and that permits accurate measurement of these angles of rotation. (The prefix "gonio-" is Greek for "angle".) Goniometric measurements are made in the following way. In most measurements, the lamp is initially aimed directly along the photometric axis; that is, the axis of the bulb is alined with the photometric axis, which is normally approximately horizontal (parallel to the floor). This is the reference position (0°, 0°). The primary axis of rotation of the goniometer permits up and down tilting of the lamp (corresponding in some instruments to latitude angle or elevation angle), and the secondary axis permits sideways swings (corresponding to longitude angle or azimuth angle). The procedure normally is to set the vertical ("latitude") angle to some fixed value, and then to rotate the lamp horizontally through a series of "longitude" angles, making measurements at each of these positions. When that series of measurements, called a <u>traverse</u>, is completed, the goniometer is tilted up or down to a new "latitude" setting, and another traverse is carried out. If the readings in each traverse are made at the same fixed set of horizontal (longitude) angles, the complete results can be represented in the form of a matrix (a rectangular array of numbers), in which each row represents a vertical angle setting, and each column a horizontal angle setting; this is known as an <u>(angular) intensity distribution matrix</u>.

Since the interest in the case of a signal light is normally in luminous (visible) rather than radiant (physical) intensity (see Section 6.2), the photocell used has a filter in front of it having a spectral transmittance curve designed to make the spectral response of the filter-photocell combination closely match the CIE luminous efficiency function. The readings are thus automatically corrected for the (standardized) sensitivity of the human eye to light. The readings obtained from the photocell output constitute a set of relative intensity values. If absolute intensities in candelas are desired, the system must be calibrated by replacing the test lamp by a special standard lamp of known luminous intensity. Chapter 12 is an appendix describing in detail the equipment and the measurement and calibration procedures used at the National Bureau of Standards for determinations of angular intensity distribution.

The measurements described above apply to steady-burning lights. When the light of interest flashes on and off, as many warning lights do, the intensity in any direction varies cyclically as a function of time. However, it is convenient to be able to specify a single number to represent an equivalent fixed intensity for a flashing light in a given direction. The quantity most commonly used for this purpose is the so-called <u>effective intensity</u>, discussed in detail in Section 10.6. Essentially, the effective intensity assigned to a flashing light is meant to represent the actual intensity of a steady light that has the same <u>visual range</u>; that is, that can just barely be seen at the same distance. The intensity distribution matrix for a flashing light can then be specified in terms of effective intensities.

The two most significant traverses made in determining the angular intensity distribution of a light are the horizontal traverse at 0° vertical position, which indicates how the intensity varies when the direction of observation is moved off axis sideways only; and the vertical traverse at 0° horizontal position, which indicates how the intensity varies when the direction of observation is moved off axis in only the up-down sense. References to the "horizontal intensity distribution" of a light denote a curve representing the first type of traverse; and "vertical intensity distribution" refers to a curve representing the second type of traverse.

(a) Incandescent Lamps

Fig. 10.2-1 shows the horizontal and vertical intensity distributions of an incandescent sealed-beam floodlamp. Such lamps have parabolic reflectors built into the rear of the bulb, and are also known as PAR. lamps for this reason. The front face of the bulb may also have a built-in fresnel lens to further concentrate, or spread out, or redistribute the light beam. The intensity values in Fig. 10.2-1 are not absolute -- that is, are not given in candelas or other units of luminous intensity -- but are relative values determined by taking the peak intensity of the horizontal distribution as unity (1.0). There is frequently little interest in the faint intensities that exist at angles far from the beam axis, so curves of this sort are often not carried all the way down to zero intensity. It is clear from the figure that the useful spread of the beam (the beamspread) in the horizontal direction is broader than the vertical spread. It is convenient to be able to refer

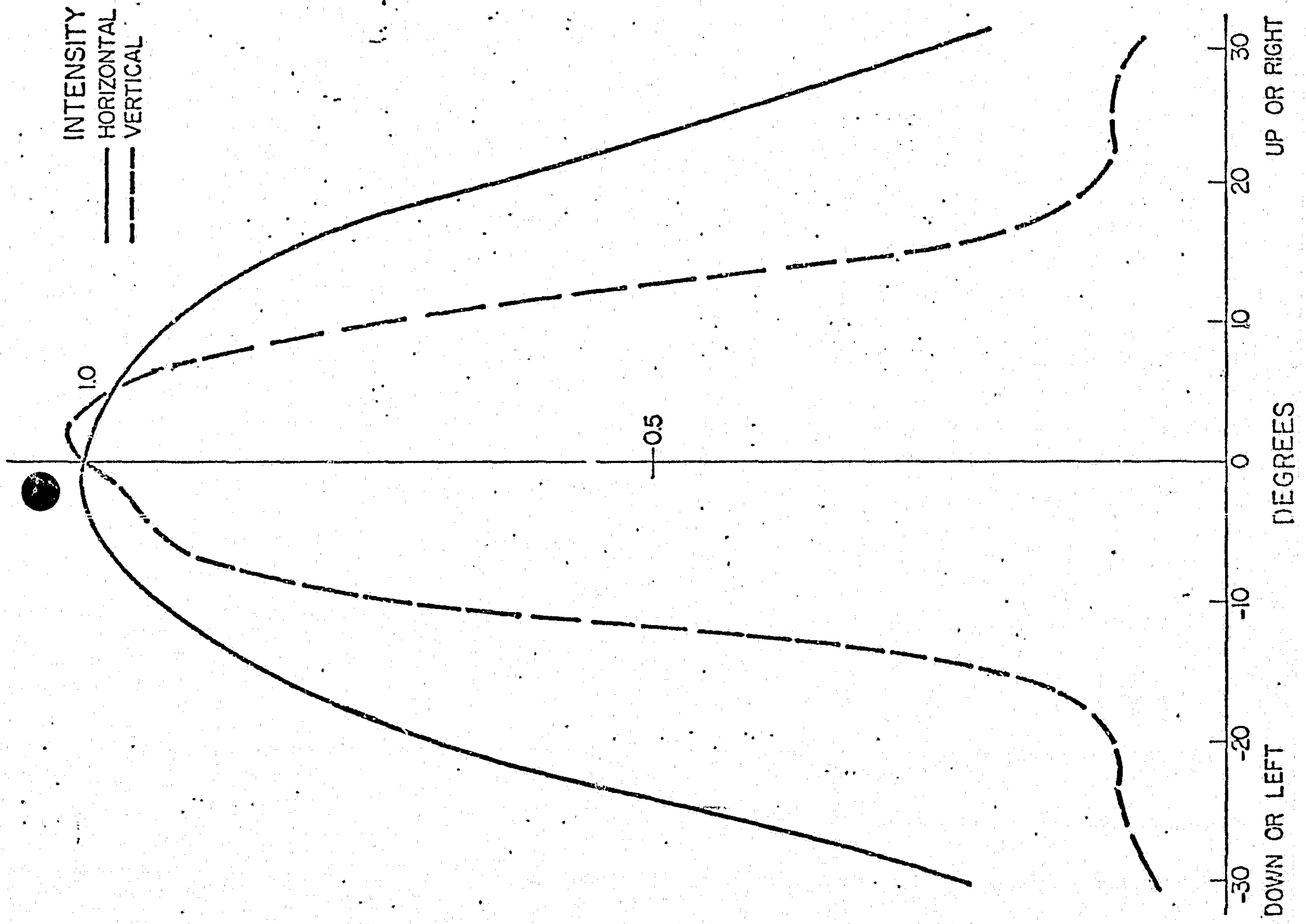


Fig. 10.2-1. Variation of the light intensity from a sealed beam floodlamp as a function of direction. The curves are examples of horizontal and vertical angular intensity distributions. Intensity values on both curves are normalized relative to the maximum value in the horizontal plane (taken as unity).

to the useful beamspread in quantitative terms, and the most common convention concerning the end of the useful core of the beam is that the points at which the intensity has dropped off to one-tenth (10 percent) of the peak intensity delimit the edges of the portion of the beam in which there is practical interest. (This is the definition used by the Society of Automotive Engineers -- the SAE.)

Since the peak of the horizontal distribution in Fig. 10.2-1 is set at 1.0, the beamspread is determined by the angle range within which the intensity is greater than 0.1, according to the 10%-point convention. For this lamp, the shape of the horizontal distribution curve is quite symmetrical about the beam axis, and the 10-percent points are at about ±35°. Thus the horizontal beamspread is approximately 70°. This symmetry of intensity distribution curves is quite common, but small deviations from symmetry are not unusual, and, in fact, can be seen to exist in the vertical distribution curve in Fig. 10.2-1. From that curve it can be seen that the peak of the vertical distribution is slightly above the direction taken as the center of the beam (0°), and also that the intensity at the vertical peak is slightly higher than the intensity at the horizontal peak. Both of these features result simply from the common circumstance that in doing the distribution measurements, the direction taken as the axis of the bulb or the beam (0°,0°) did not happen to coincide precisely with the direction in which the intensity of the beam is maximum. The 0°,0° direction is the only direction included in both of the traverses determining the horizontal and vertical intensity distributions, so that the two distributions must always show the same intensity at 0°. If, in addition, the true peak of the beam's intensity were exactly in the 0°,0° direction, both the horizontal and vertical distributions would have their (equal) peaks at 0°.

The horizontal line representing the 10-percent-of-peak intensity for the vertical distribution in Fig. 10.2-1 should be a bit higher than the line used for the horizontal distribution, but for rough estimation there is little difference, so we note that the points at which the line at intensity 0.1 cuts the vertical distribution curve lie at about -20° and at +21° or +22°. The total beamspread of the slightly asymmetrical vertical distribution is thus about 41° or 42°. A beamspread on the order of 70° horizontal by 40° vertical is not unreasonable for a floodlamp that is meant to provide general illumination over a broad but limited area, but much narrower beams are appropriate for use in emergency-vehicle warning units. The most typical PAR lamp (PAR-36, #4416) used in such signaling units has a beamspread of only 4.5° horizontal by 11° vertical.

(b) Gaseous Discharge Lamps

Another type of light source used in some kinds of emergency-vehicle warning units is the gaseous discharge lamp. Fig. 10.2-2 shows the horizontal and vertical distributions of effective intensity for a common type of flash lamp containing xenon gas. Such lamps cannot be operated continuously, but are flashed at regular intervals, so that the intensities specified in the distributions are "effective" and not actual. As in Fig. 10.2-1, the intensities are relative, and are normalized to the peak of the horizontal distribution as 1.0. For the flash lamp that yielded the measurements in Fig. 10.2-2, the beamspread both horizontally and vertically is in the neighborhood of 40°. The two distributions are very nearly the same, with the vertical beamspread being a few degrees wider than the horizontal. Unlike the continuously operating incandescent lamp on which Fig. 10.2-1 is based, the flash lamp characterized by Fig. 10.2-2 does not have a single direction of maximum intensity, with a smooth dropoff from the peak in all directions. Instead, the curve exhibits "structure" around the beam axis; that is, there are significant variations of intensity in the immediate neighborhood of the axis. Although these variations are rather irregular, the fact that both distributions have approximately equal peaks about 8° or 9° on either side of the axis suggests that the peak intensities of the overall angular distribution lie on an approximately circular ring surrounding the center of the beam about 8° or 9° out.

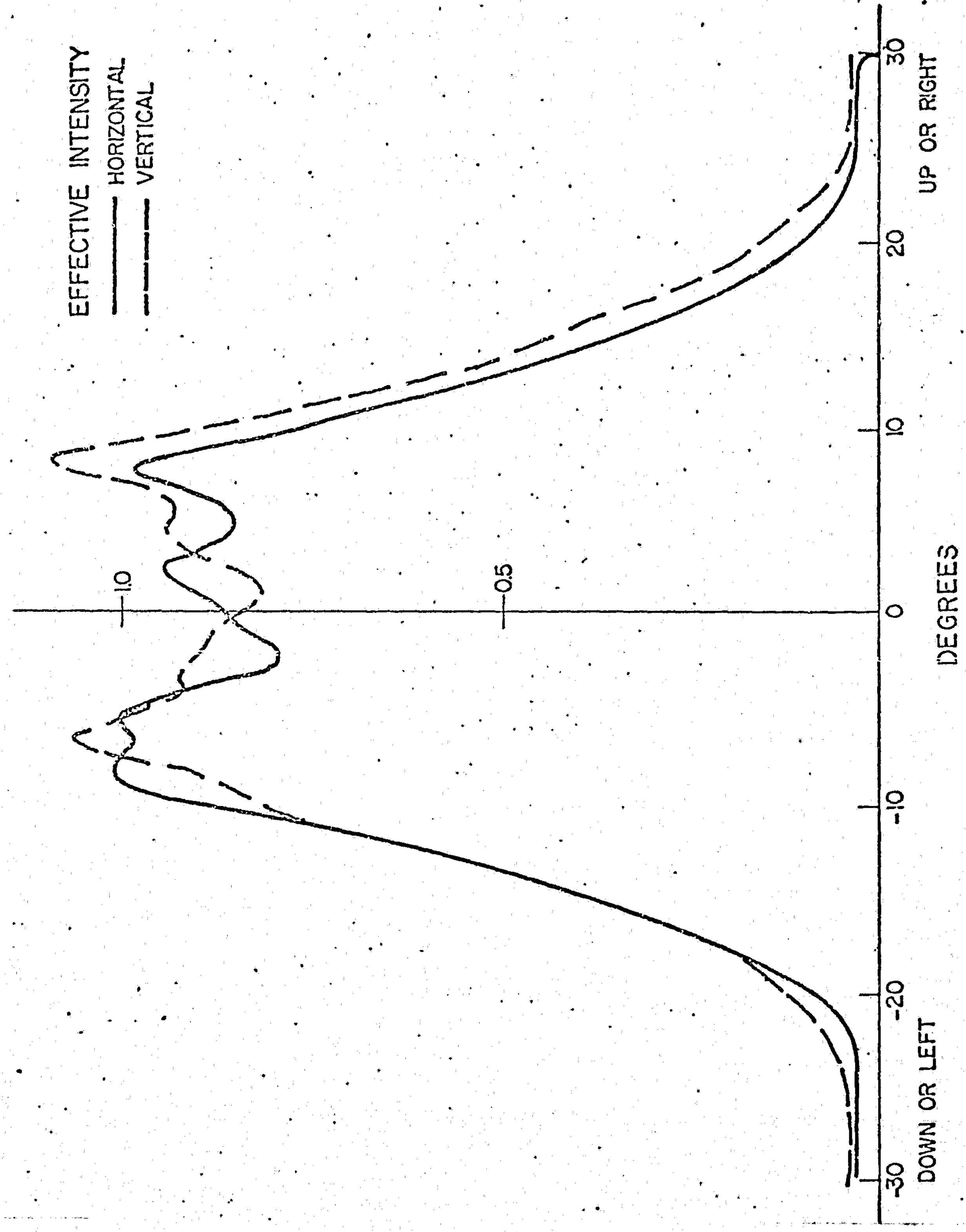


Fig. 10.2-2. Variation of the effective (Blondel-Rey-Douglas) intensity of the light pulses from a xenon flash lamp as a function of direction. The curves are examples of horizontal and vertical angular (effective) intensity distributions. The effective intensity values on both curves are normalized relative to the maximum value in the horizontal plane (taken as unity).

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2 OF 4

The lamp on which Fig. 10.2-2 is based is a sealed-beam flash unit of the general type shown on the ends of the bar in Fig. 3.5e. The center lamp in that figure is a 360° gaseous-discharge source for which the horizontal distribution curve would be approximately at a constant level all the way across -- that is, from -180° all the way around to +180° (the two angles ±180° denoting the same direction -- namely, directly backward).

(c) Notation

In graphical or tabular presentations of angular intensity distributions, angles on one side of the beam axis (0°) are regarded as positive, and on the other side as negative, both in the horizontal and vertical directions. Normally, up and right are taken as the positive directions, with down and left taken as negative. There is, of course, an ambiguity regarding which direction should be regarded as right and which as left. A viewpoint could be adopted corresponding either to that of an observer looking at the lamp from a point along the beam axis, or to the reversed viewpoint of an observer located behind the lamp, looking out along the beam in the opposite direction. It is the latter convention that is customarily adopted; one might call it the user's viewpoint, as exemplified by the driver of an automobile looking out at the pattern of intensity made by his headlights on a wall in front of the vehicle.

The SAE, and many of the police and traffic codes based on SAE practice, observe this same directional convention but use a different notation for the four primary directions. In SAE terminology, U denotes up, D denotes down, L denotes left, and R denotes right. A direction that is neither upward nor downward is denoted H for horizontal; and a direction that is neither leftward nor rightward is denoted V for vertical (that is, lying along the vertical axis of the beam's cross-section). Thus in most automotive lighting literature, the direction that would be referred to in a photometry laboratory as -3° vertical, -2° horizontal, is denoted 3D-2L, and the direction 0°,0° (the beam axis) is denoted H-V. Fig. 10.2-3 illustrates the two systems of notation, with the SAE notation given in parentheses. Contrary to the convention in pure mathematics, the <u>vertical</u> coordinate is usually given first in goniophotometric (angular-intensity) specifications, presumably because of the procedural primacy of the vertical angular setting, as described earlier in this section.

10.3. Flash Rate

Many emergency-vehicle warning-light units produce a regular series of identical flashes, with a constant time interval between flashes. Other units produce more complicated patterns, such as regularly spaced flashes of two alternating types, which often differ in color and intensity and sometimes in other characteristics such as location or duration. We will confine attention here to the simple type of unit with regularly repeating identical flashes.

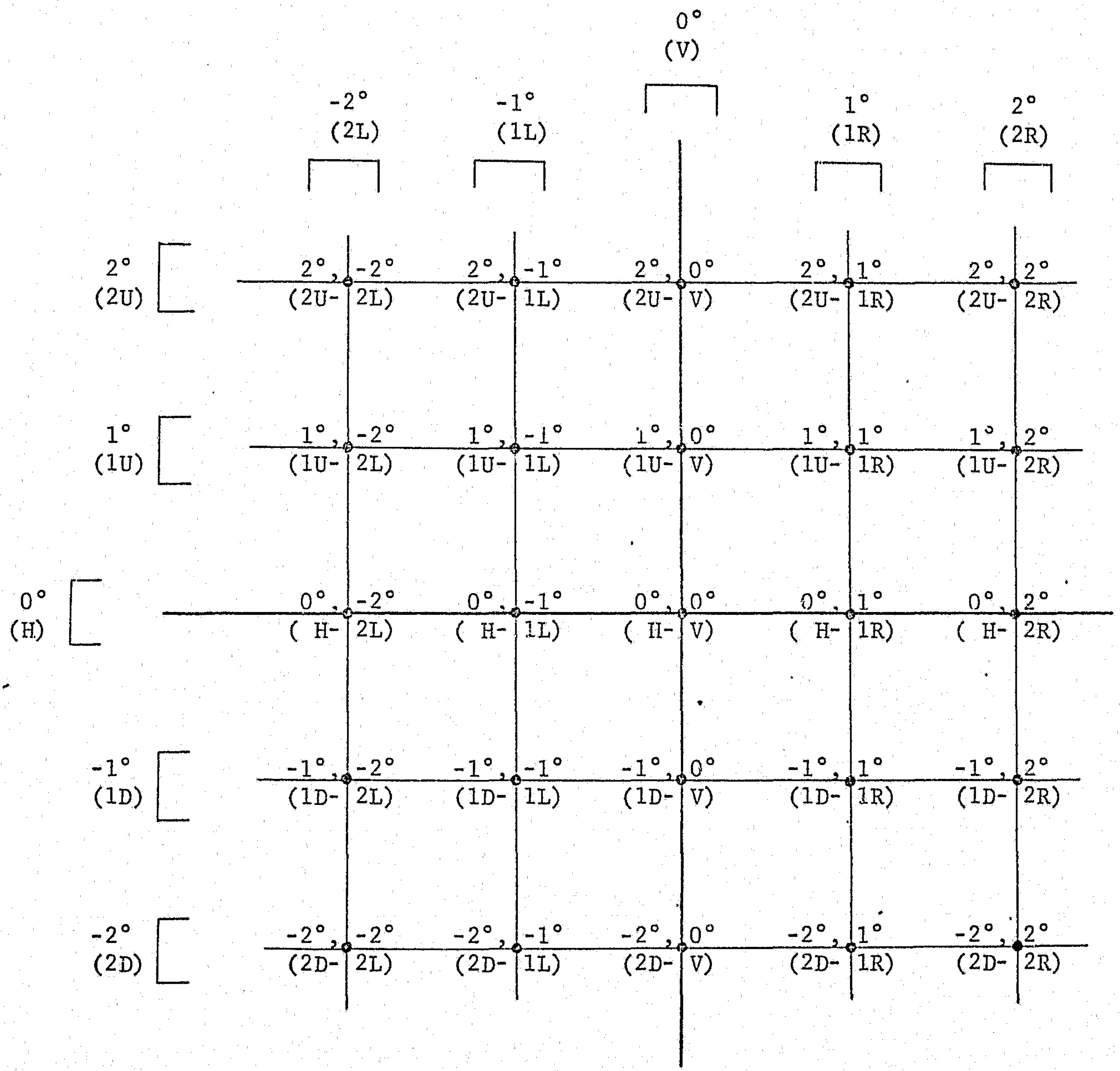


Fig. 10.2-3. Notation of angular directions in the specification of intensity distributions. The upper notation is that used in general photometric work; the lower notation is common in automotive applications (SAE). In both systems, the vertical coordinate is given first. The symbol in the middle of each SAE notation is not a minus sign, but a dash, which is sometimes replaced by a double dash, blank space, or some combination of spaces and dashes. The directions are not as seen by an observer looking at the light source, but as seen by an observer behind the source looking at a wall illuminated by the light beam.

The <u>flash rate</u> for such a light is the number of flashes that occur within some specified interval of time. The most convenient units for expressing the flash rate of warning lights is the number of flashes per minute (fpm). The Society of Automotive Engineers (SAE) recommends rates between 60 and 120 fpm (SAE Standard J595b). A flash rate is, of course, a special case of a frequency, for which the internationally accepted (SI) unit is the <u>hertz</u> (Hz), formerly referred to as the <u>cycle per second</u>. The rates of 60-120 fpm correspond to 1-2 Hz.

For flash rates in the rather slow range indicated above, it is possible to time the interval between two successive flashes with considerable accuracy, by means of electronic timing circuitry acting on the output pulses of a photocell exposed to the flashes. This is the method of choice when high accuracy is important. For many practical purposes, however, a good stopwatch is accurate enough. All that is necessary is to measure the time required for a substantial number of complete flash cycles, and then to divide the number of cycles counted by the total time, to obtain the mean flash rate. For example, if a light is flashing at 90 fpm, the time between flashes (the <u>period</u> of the light) is 2/3 sec. To time -- let us say -- 30 flash cycles will then require measuring a time interval of 20 seconds. If the stopwatch can be used to an accuracy of 1/10 sec, the 20-sec period, and the flash rate, can thus be measured to within 1/2 percent. An incorrect elapsed time of 19.9 sec or 20.1 sec for the 30 flash cycles will lead to respective flash rate estimates of 90.45 fpm (1.508 Hz) or 89.55 fpm (1.493 Hz) instead of the correct value of 90.00 fpm (1.500 Hz). Note that in order to time 30 inter-flash periods, with the starting point taken as the moment of the peak of one flash, 31 flashes must be observed. The simplest technique is to start the stopwatch as a flash occurs, counting that flash as number 0, and to stop the watch as flash number 30 occurs.

Counting the number of flashes within a fixed period of time, as opposed to measuring the amount of time for a fixed number of flashes, is a significantly less accurate technique and should be resorted to only when a stopwatch is not available and a rough estimate is satisfactory. The source of the difficulty is that the count of flashes changes by whole units only. The count within a specified interval of time for a particular flashing light may vary by 1, on repeated attempts, depending upon where in the flash cycle the timing period is started on each occasion. Conversely, lights flashing at somewhat different rates can produce the same count within a particular interval of time, if the time interval begins at suitable, different points (<u>phases</u>) within the respective flash cycles.

As a numerical example, consider a light with an inter-flash period of 0.6453 sec. The flash rate of this light is 92.98 fpm (1.550 Hz). Assume the clock is started for a 20-second timing period and the first flash occurs 0.6421 sec later, the preceding flash having been just missed, by 0.0032 sec. The 30th flash will then occur 19.3558 sec (= 0.6421 + 29 x 0.6453) into the timing period and will be counted, but the 31st flash will be just after the end of the timing period, at 20.0011 sec (= 0.6421 + 30 x 0.6453), and will not be counted. On the other hand, consider a light with a longer period of 0.6896 sec. This light has a flash rate of only 87.01 fpm (1.450 Hz). Assume the clock is started for a 20-second timing period and the first flash occurs only 0.0013 sec later. In this case, the 30th flash occurs just inside the timing period, at an elapsed time of 19.9997 sec (= 0.0013 + 29 x 0.6896). Both lights have produced a count of 30 flashes within a period of 20 seconds, and both would be taken, on the basis of the measurement, to have equal flash rates of 90 fpm (1.5 Hz). Since the actual flash rates are 3 fpm off above and below this measured rate, it is seen that the error can be as much as 3 1/3 percent when, as here, the worst possible cases occur, even with absolute accuracy in both the timing and counting.

It can be shown in general that if the number of flashes counted during a fixed interval of time is n, the flash rate calculated (as n divided by the length of the time interval) can, in the worst cases, be off by the percentage 100/n. This result is independent of the time interval used. In the numerical example given above, n was 30, so the 100/n formula gives a maximum percent error of 3 1/3, coinciding with the result exhibited. Obviously, the accuracy of the measurement can be increased by making n larger. For a given light, this is accomplished by extending the timing period appropriately. Similarly, when the method involving measuring the time for a fixed number of flash cycles is used, the accuracy can be improved by lengthening the timing period, a result achievable for a given light by appropriately extending the number of flash cycles. Both measurement procedures are subject to errors in the watch accuracy and in the performance of the human timer (who in one case must synchronize his pushing of the stopwatch button with a light flash, and in the other must decide whether a flash occurred inside or outside the timing interval), but only the flash-count-for-fixed-time procedure is subject additionally to the uncertainty due to phase described above.

10.4. Temporal Pulse Shape and Flash Duration

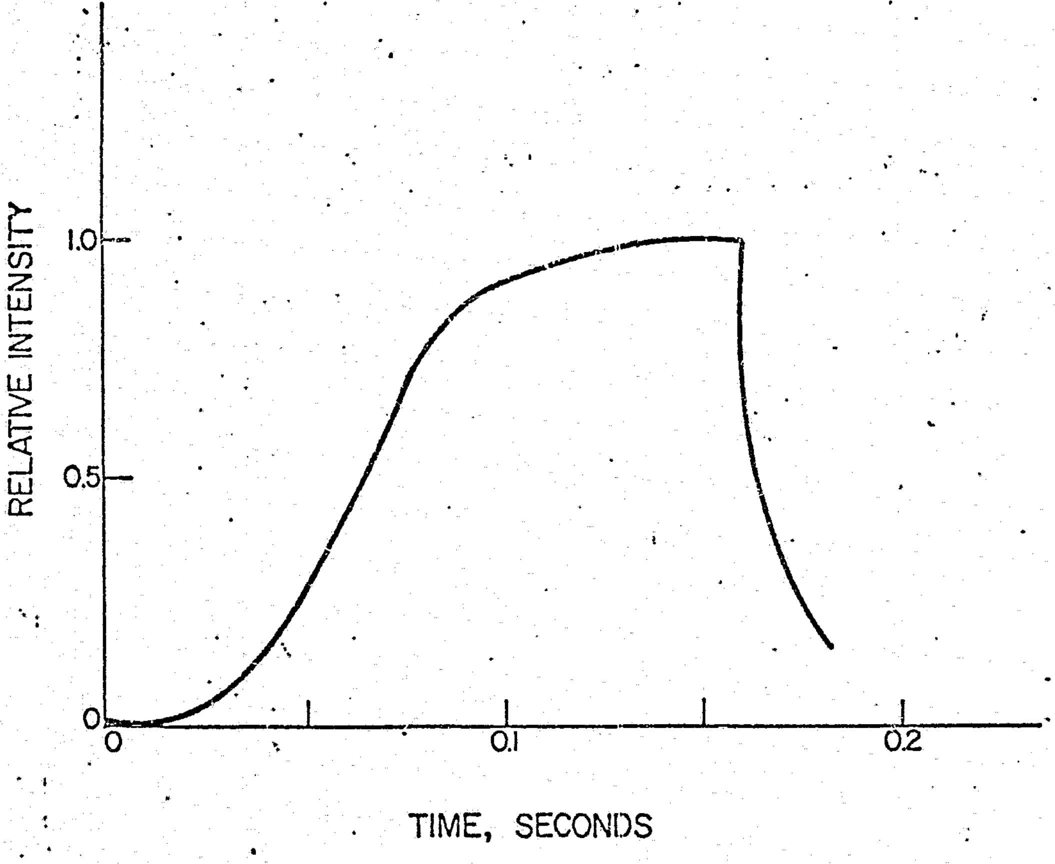
(a) Flashed Incandescent Lamps

No light source can turn on literally instantaneously, or turn off instantaneously. The filament of an incandescent lamp that is electrically flashed on and off has to heat up from a relatively low temperature (well above the ambient temperature, after the first few flashes) to white heat (about 3000K or 4700°F), and when turned off, has to cool down to the lower temperature again. These thermal processes, known as incandescence and nigrescence respectively, require time, on the order of a tenth of a second. Fig. 10.4-1 illustrates the typical time course (variation of intensity with time) of the light pulse from a flashed incandescent lamp. The phrase "pulse shape" is often used to refer to the form of the curve representing the temporal variation, and does not connote the geometric shape of the light source or light beam.

(b) Gaseous Discharge Lamps

In gaseous discharge lamps, on the other hand, there is no solid element being heated and cooled. The applied surge of voltage serves to propagate a wave of ionization across the gas in the tube, permitting the pulse of current to flow across the resultant plasma arc, thus exciting the ionized gas into emitting visible light. Current can flow at nearly the speed of light, which is approximately one foot per nanosecond (billionth of a second), and both the initial ionization process and the decay of the excitation of the gas once all current flow has stopped, are comparably rapid. Since the on and off processes consume negligible time (for most practical purposes), the

Fig. 10.4-1. Example of time variation of light intensity from an incandescent lamp flashed on and off by current interruption. The intensity values on this curve are normalized relative to the maximum value (taken as unity), which occurs at the moment the current is shut off.



duration of the light pulse emitted by a gaseous discharge lamp is determined essentially by the duration of the pulse of electrical current. By choosing suitable electrical circuitry (including, for example, a choke or self-inductor), the duration of the light flash from ordinary discharge lamps of the type used in warning signals can be varied from the order of <u>microseconds</u> (millionths of a second) up to the order of <u>milliseconds</u> (thousandths of a second). The total energy in the emitted light pulse is determined by (but is of course less than) the total energy in the electrical pulse, which is usually generated by charging up a large capacitor (condenser) and then permitting all the stored energy to discharge suddenly. It can be seen, therefore, that the longer the time over which the discharge of a given quantity of electrical energy is spread, the lower will be the <u>rate</u> of electrical current flow during the discharge, and hence the lower will be the instantaneous intensity of the light during the course of the light flash. Fig. 10.4-2 illustrates a typical pulse shape for the flash of a discharge lamp.

(c) Rotating Incandescent Lamps

The third common method of producing emergency warning flashes is rotation, either of one or more lamps around a central point, or of one or more mirrors or lenses around a stationary lamp in the center. In such devices, the intensity of the beam rises smoothly as the moving component rotates toward the observer's line of view, reaches a maximum when the moving component is pointed directly at the observer, and drops off smoothly as the moving component rotates past the observer's line of view. (See Fig. 10.4-3.) The duration of the flash produced by the rotating beam at the eye of the observer is a function

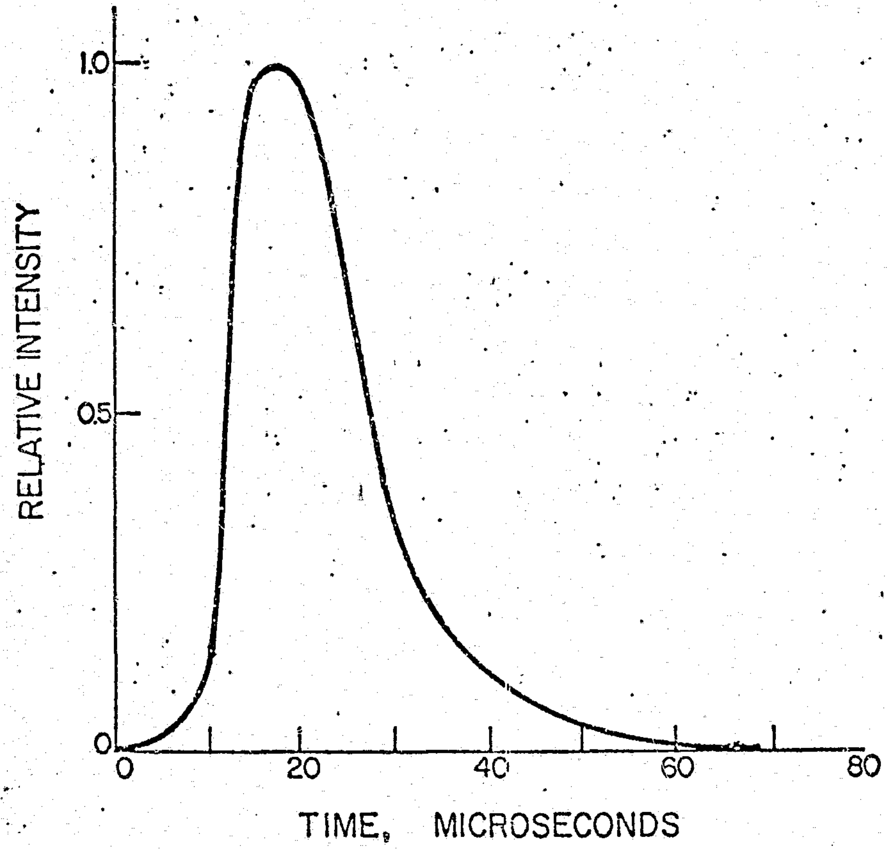


Fig. 10.4-2. Example of time variation of light intensity from a krypton flash lamp. The intensity values on this curve are normalized relative to the maximum value (taken as unity). Note that the units of the time axis are microseconds (millionths of a second).

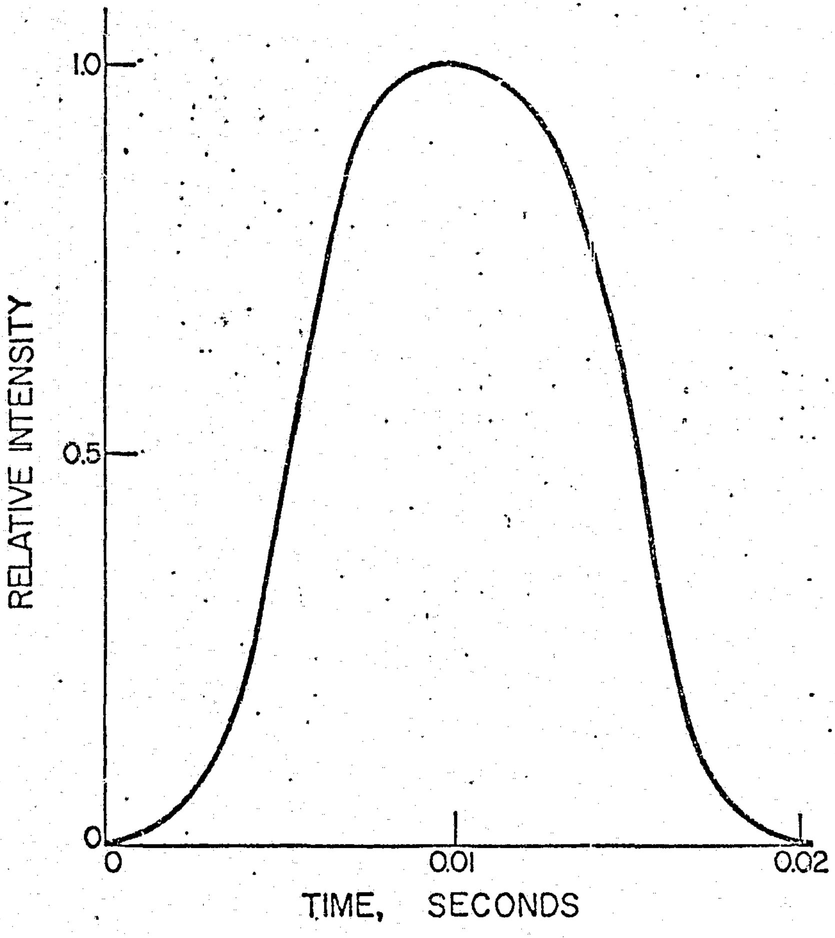


Fig. 10.4-3. Example of time variation of light intensity from an incandescent lamp, rotated past the detector. The intensity values on this curve are normalized relative to the maximum value (taken as unity).

of the angular spread of the beam and the rate at which the rotation is occurring. The duration of such flashes is typically in the range of hundredths of a second.

In a unit producing flashes by rotation, the curve indicating temporal pulse shape at an observation point on the axis of the beam is identical to the horizontal angular intensity distribution, if the scales of angle and time are suitably adjusted. The mathematical details of the adjustment will be discussed in the next section (10.5), but the basic fact of the equivalence ought to be intuitively clear from a physical point of view. The sweep of the beam past the eye of the observer is precisely a horizontal traverse in the context of measuring the angular intensity distribution (Section 10.2), with the observer's eye serving as the photosensitive device. As a particular lamp rotates across the line of sight of the observer, he is progressively exposed to successive angular directions of the lamp's output, and the changes in intensity over these different directions are the source of the changes in intensity over time at the fixed position of the observer's eye. The intensity of the lamp at its maximum value in the time course of the pulse is the same as the maximum (on-axis) intensity of the stationary beam, since the instant when the intensity of the flash is at its maximum is precisely the moment when the lamp is in the on-axis position with respect to the line of sight from the observer to the unit. Fig. 10.4-3 shows a typical pulse shape for the common type of incandescent lamp with a symmetrical angular intensity distribution such as that shown in Fig. 10.2-1.

(d) Measuring Instrumentation

In order to obtain graphs of the intensity of a light pulse as a function of time, such as Figs. 10.4-1 to 10.4-3, it is necessary to use both a photocell with a very rapid response capability, and a recording device that can follow comparably rapid fluctuations in electrical current. Any recorder using a mechanical arm bearing the writing device is slowed by the inertia of the arm. A certain amount of time is required to accelerate or decelerate even the relatively small mass of a recorder arm, and most ordinary "strip-chart" or "X-Y" recorders cannot follow extremely rapid signal variations. The customary solution is to use an oscilloscope as the output device. An oscilloscope beam consists of electrons, which, because of their almost negligible mass, can be electrically or electromagnetically deflected with extreme rapidity. Ordinary oscilloscopes have phosphors that decay quite rapidly; that is, the image remains on the screen for a very brief period of time. In order to capture a permanent record of the trace on the oscilloscope screen corresponding to the pulse shape of a light flash, the face of the screen is usually photographed by a camera arranged so as to have its shutter open during a time interval that includes the very brief period during which the trace is on the screen.

10.5. Interrelationships of Basic Variables for Devices Employing Rotation

The most common type of rotational unit is that in which several outward-facing lamps are equally spaced around the periphery of a rotating turntable, all at the same distance from the center of rotation. The other type of rotational device, in which a vertically mounted stationary central lamp has mirrors or lenses rotating symmetrically around it, is optically equivalent to the rotating-lamp type, and can be replaced conceptually by a rotating-lamp unit with suitably designed angular intensity distributions for the lamps. The following analysis will be phrased in terms of a rotating-lamp device.

Table 10.5-1 below lists the four quantities characterizing the <u>device</u> as a whole, the symbols to be used here for those quantities, and the customary units for specifying the quantities. Table 10.5-2 lists the same information for the two quantities characterizing the individual rotating <u>lamps</u>, or the signal issuing from them.

Table 10.5-1. Quantities Characterizing Rotational Warning-Light Devices

Quantity	Symbol	Units[a]	Abbreviated Units
Flash rate	ϕ	flashes per minute	fl/min (fpm)
Number of lamps	n	[flashes per revolution]	fl/rev
Period of rotation	τ	seconds [per revolution]	sec/rev
Turntable speed	ω	revolutions per minute	rev/min (rpm)

[a] The units in brackets are usually regarded as dimensionless and are customarily omitted.

Table 10.5-2. Quantities Characterizing Individual Rotating Lamps

Quantity	Symbol	Units[a]	Abbreviated Units
Beamspread (Horizontal)	σ	degrees [per flash]	deg/fl
Flash Duration	t	seconds [per flash]	sec/fl

[a] The units in brackets are usually regarded as dimensionless and are customarily omitted.

With respect to the device variables of Table 10.5-1, three equations give their interrelations:

$$\tau\left(\frac{\text{sec}}{\text{rev}}\right) \cdot \omega\left(\frac{\text{rev}}{\text{min}}\right) = 60\left(\frac{\text{sec}}{\text{min}}\right) \qquad (10.5\text{-}1)$$

$$\phi\left(\frac{\text{fl}}{\text{min}}\right) = n\left(\frac{\text{fl}}{\text{rev}}\right) \cdot \omega\left(\frac{\text{rev}}{\text{min}}\right) \qquad (10.5\text{-}2)$$

$$\phi\left(\frac{\text{fl}}{\text{min}}\right) \cdot \tau\left(\frac{\text{sec}}{\text{rev}}\right) = 60\left(\frac{\text{sec}}{\text{min}}\right) \cdot n\left(\frac{\text{fl}}{\text{rev}}\right). \qquad (10.5\text{-}3)$$

The units of the quantities in these equations have been included above in order to (a) stress that the numerical constants in the equations apply only when the variables are measured in these particular units; and (b) to prove the dimensional balance of the equations. Note that $\underline{n}$, the number of lamps on the turntable, would normally be considered a dimensionless quantity, but this number is necessarily the same as the number of flashes that hit a fixed observer during one revolution of the device. The dimensional balance of the equations is clearly visible, as above, only if (a) $\underline{n}$ is given explicit units of fl/rev; and (b) the number 60 is identified as being a factor expressing the number of seconds in a minute.

The units of beamspread, $\underline{\sigma}$, are usually given simply as degrees, but again to make the dimensional balance of some equations evident, the units are given in Table 10.5-2 more precisely as degrees per flash.

Three equations that relate the quantities of Tables 10.5-1 and 10.5-2 to each other are:

$$\sigma\left(\frac{\text{deg}}{\text{fl}}\right) \cdot \tau\left(\frac{\text{sec}}{\text{rev}}\right) = 360\left(\frac{\text{deg}}{\text{rev}}\right) \cdot t\left(\frac{\text{sec}}{\text{fl}}\right) \qquad (10.5\text{-}4)$$

$$\sigma\left(\frac{\text{deg}}{\text{fl}}\right) = 6\left(\frac{\text{deg/rev}}{\text{sec/min}}\right) \cdot \omega\left(\frac{\text{rev}}{\text{min}}\right) \cdot t\left(\frac{\text{sec}}{\text{fl}}\right) \qquad (10.5\text{-}5)$$

$$\sigma\left(\frac{\text{deg}}{\text{fl}}\right) \cdot n\left(\frac{\text{fl}}{\text{rev}}\right) = 6\left(\frac{\text{deg/rev}}{\text{sec/min}}\right) \cdot t\left(\frac{\text{sec}}{\text{fl}}\right) \cdot \phi\left(\frac{\text{fl}}{\text{min}}\right). \qquad (10.5\text{-}6)$$

The number 360 in Eq. (10.5-4) is identified for dimensional purposes as representing the number of degrees in one complete revolution; and the number 6 in Eqs. (10.5-5) and (10.5-6) is the result of dividing the constant 360 of Eq. (10.5-4) by the constant 60 of Eqs. (10.5-1) and (10.5-3), with the corresponding dimensions preserved.

For convenient reference purposes, the six preceding equations, which appear cluttered with the dimensions attached, are rewritten without dimensions as follows:

$$\tau\,\omega = 60 \qquad (10.5\text{-}7)$$

$$\phi = n\omega \qquad (10.5\text{-}8)$$

$$\phi\,\tau = 60n \qquad (10.5\text{-}9)$$

$$\sigma\,\tau = 360t \qquad (10.5\text{-}10)$$

$$\sigma = 6\omega t \qquad (10.5\text{-}11)$$

$$\sigma\, n = 6t\phi\,. \qquad (10.5\text{-}12)$$

THE CONSTANTS IN THESE EQUATIONS ARE CORRECT ONLY IF THE UNITS USED ARE AS GIVEN IN TABLES 10.5-1 and 10.5-2, WHERE THE SYMBOLS ARE ALSO DEFINED.

These six equations permit convenient calculation of the values of whichever of the basic variables one needs to determine, from the values of whichever variables are known.

In order to demonstrate a little of the utility of Eqs. (10.5-7) to (10.5-12), let us suppose we are given a device containing lamps each having a beamspread σ equal to 6°. Then Eq. (10.5-11) tells us immediately that

$$t = \frac{1}{\omega} \quad (\sigma = 6°); \qquad (10.5\text{-}13)$$

that is, for the particular beamspread $\sigma = 6°$, the duration of each flash in seconds and the turntable speed in rpm are simply reciprocals of each other (regardless of how many lamps are on the turntable). Eq. (10.5-11) shows that for any beamspread, the relationship is always one of inverse proportionality, the constant of the proportionality being $\sigma/6$.

If we now assume further that the flash rate ϕ is 90 fpm, in addition to the beamspread σ being 6°, then Eq. (10.5-12) reveals that

$$t = 0.0111n \quad (\sigma=6°,\ \phi=90 \text{ fpm}); \qquad (10.5\text{-}14)$$

that is, with the flash rate kept fixed, the duration of each flash is proportional to the number of lamps on the turntable (always), and for these specific values of beamspread and flash rate, the duration is 0.0111 sec (=1/90 sec) multiplied by the number of lamps. Since the values assumed above are not far from typical for actual rotational warning-light devices, we see from Eq. (10.5-14) that the duration of the flashes produced by such devices is approximately equal to as many hundredths of a second as there are lamps in the device. (If ϕ=100 fpm instead of the more common 90, the relationship is exact, with $\sigma = 6°$.) The lamp most commonly used in rotating warning units (PAR-36, #4416) has a horizontal beamspread of 4.5°, rather than 6°, so at 90 fpm the most representative numerical version of Eq. (10.5-12) is

$$t = 0.008333n \quad (\sigma=4.5°,\ \phi=90\text{ fpm}). \qquad (10.5\text{-}15)$$

With a beamspread as narrow as 4.5°, the flash rate necessary for the relationship t=0.01n to hold exactly is 75 fpm, a value toward the lower end of the range covered by commercial units.

As another illustrative application of the equations of this section, we can now be more specific concerning the fact mentioned in the discussion of pulse shape (Section 10.4) that for rotating lights, the curves defining pulse shape and angular intensity distribution are the same, if the scales of time and angle are suitably adjusted. Eqs. (10.5-10) to (10.5-12) can be combined and rewritten in the form

$$\frac{\sigma}{t} = \frac{360}{T} = 6\omega = \frac{6\phi}{n} \,. \qquad (10.5\text{-}16)$$

The expressions in Eq. (10.5-16) give us the value of the equivalence factor we seek, expressed as degrees of beamspread per second of flash duration (σ/t). The equation expresses this factor in three different but equivalent ways: (a) as 360 divided by the rotation period in seconds; (b) as 6 times the rate of rotation in rpm; and (c) as 6 times the flash rate in fpm divided by the number of lamps on the turntable. If the last three expressions in Eq. (10.5-16) are indeed all equal to σ/t, then they must be equal to each other as well, as we have just asserted. That these three alleged equalities are really correct can be verified directly in Eq. (10.5-7), relating the first and second of the last three expressions (τ and ω); in Eq. (10.5-8), relating the second and third of these expressions (ϕ, n, and ω); and in Eq. (10.5-9), relating the first and third of these expressions (ϕ, n, and τ).

In establishing an equivalence between a beamspread and a flash duration, we are necessarily restricting the definition of flash duration. Just as "beamspread" usually does not mean the total angular width of the beam, but only -- according to one common definition -- the width out to the angles at which the intensity is 10 percent of the peak intensity, similarly we have to redefine "flash duration" not as the total duration of the flash, but as the length of time between the instants at which the intensity first rises above 10 percent of the peak, and first falls below 10 percent of the peak. Eq. (10.5-16) is also valid when interpreted as applying to total beamspread and total flash duration; it holds for any case in which the limits of beamspread and flash duration are defined in corresponding ways, and, of course, does not hold otherwise.

10.6. Effective Intensity

In the perception of emergency-vehicle warning lights, the problem is often separation of a fairly bright signal from all the other lights in the background. In most earlier signaling work, particularly in connection with marine aids to navigation, the background was totally black and the problem was catching sight of the faint signal light at the greatest possible distance. Thus the central interest in that situation -- and still in much sea and air signaling work today -- is in comparing the detectability of lights close to the absolute threshold. A convenient numerical specification of the visual effectiveness of a flashing light with respect to simple detection, when the light is seen foveally as a point source against a black background, is the intensity of a steady light that reaches threshold visibility at the same viewing distance (visual range) as the flashing light. A partially self-explanatory name for this quantity might be something like "steady-light equivalent intensity", but historically the name effective intensity has become standard. Because effective intensity is the only widely used measure of the visual impact of flashing lights, it will be discussed in considerable detail in this section. Comments will be included relating to the discrepancy between the viewing conditions listed above and those that apply to the noticing of emergency-vehicle warning lights.

Blondel and Rey, working in France in the early years of the twentieth century, proposed as a formula for effective intensity the equation

$$I_e = \frac{\int_{t_1}^{t_2} I(t)\,dt}{a + (t_2 - t_1)}, \qquad (10.6\text{-}1)$$

where I_e is the effective intensity of the flashing light; $I(t)$ is the instantaneous actual intensity of the light at the time $\underline{t}$ during the course of a single flash; t_1 and t_2 are the beginning and ending times of the useful, higher-intensity portion of the flash; and $\underline{a}$ is a constant (having the dimensions of time) that Blondel and Rey found to have a value of about 0.21 when t, t_1, and t_2 are measured in seconds. The integral in the numerator of Eq. (10.6-1) represents the total luminous energy content of the flash (per unit solid angle of the beam) between the times t_1 and t_2; that is, the area under the temporal pulse-shape curve between the limits t_1 and t_2. The calculation of areas under curves can be accomplished numerically in a computer program, but for practical purposes, the use of an area-measuring instrument called a <u>planimeter</u> on the pulse-shape graph is quick and reasonably accurate. Counting of graph-paper squares under the pulse-shape curve is another technique that is commonly used.

The major difficulty with the Blondel-Rey formula (10.6-1) is the vagueness of the definitions of t_1 and t_2. At least partly because of this uncertainty, not much attention was paid to the formula for many years. Blondel and Rey themselves worked mostly with pulse shapes that they treated as reasonable approximations to rectangles; that is, flashes having neglible rise and fall times and constant intensity throughout the duration of the flash. For such flashes, t_1 and t_2 are chosen unambiguously as the beginning and ending times of the total flash, and with the constant intensity denoted by I, formula (10.6-1) reduces to simply

$$I_e = \frac{I \cdot (t_2-t_1)}{a + (t_2-t_1)} . \qquad (10.6\text{-}2)$$

If t is used as an abbreviation for the total flash duration (= t_2-t_1), the equation (10.6-2) can be written in the form most commonly used in the technical literature:

$$I_e = \frac{It}{a+t} . \qquad (10.6\text{-}3)$$

Blondel and Rey empirically derived Eq. (10.6-3) on the basis of actual threshold experiments with flashing lights having virtually rectangular waveforms. The formula (10.6-1) was proposed by them as a generalization of Eq. (10.6-3) suitable for application to flashing lights with significantly long "tails" at the beginning and/or end of the flash, and non-constant intensity in between. As seen in Figs. (10.4-1) to (10.4-3), all of the common types of emergency warning lights have such non-rectangular pulse shapes.

The Blondel-Rey formula was given new life by Douglas (1957), who proposed defining t_1 and t_2 unequivocally as those times within the flash that made the effective intensity I_e of Eq. (10.6-1) as large as possible. Douglas showed mathematically that the values of t_1 and t_2 that yield the maximum I_e are, for t_1, the time during the brightening phase of the flash at which the instantaneous intensity I(t) rises to this maximum I_e value; and, for t_2, the time during the dimming phase of the flash at which I(t) drops back to the maximum I_e value. The use of this criterion may at first appear to be hopelessly circular, since the calculation of I_e depends upon the choice of t_1 and t_2, and the choice of t_1 and t_2 requires knowledge of the maximum value of I_e. Fortunately, by means of a simple iterative procedure (successive approximation) described by Douglas (1957), it is possible to converge simultaneously on the values of the maximum I_e and the corresponding t_1 and t_2. The method is also described in a guide put out by the Illuminating Engineering Society (1964).

Douglas' proposed definition and calculation procedure made the Blondel-Rey equation a practical tool at last, and the Blondel-Rey-Douglas formula has been widely accepted and used in the field of signal lights. Although the formula is still frequently written in the incomplete form (10.6-1), the actual current definition of effective intensity is

$$I_e = \max_{t_1,t_2} \left[\frac{\int_{t_1}^{t_2} I(t)dt}{0.2 + (t_2 - t_1)} \right] , \qquad (10.6\text{-}4)$$

where

$$\max_{t_1, t_2}$$

denotes the maximum value obtainable through variation of both t_1 and t_2; and the specific value 0.2 has been used for the constant a.

In a companion article to Douglas' 1957 paper, Projector (1957) points out that the constant 0.2 (approximately) applies to lights near conditions of absolute threshold only, and that the value of a becomes smaller -- and, correspondingly, the value of I_e becomes larger -- as the lights become significantly brighter than threshold. As a result, when a flashing light and the steady light that matches it for threshold detectability are approached by an observer, the flashing light becomes noticeably brighter than the steady light. A similar effect, again corresponding to a decrease in the applicable value of a, occurs if the background departs from total darkness, as it does for daylight signaling. Projector's (1957) paper is a helpful summary of the history, meaning, and implications of the Blondel-Rey-Douglas formula for effective intensity, and, together with the Douglas (1957) paper, should be consulted by anyone interested in the fine details of the subject.

Unfortunately, the term "effective intensity" is now used ambiguously with at least the three distinct meanings of: (a) steady-light equivalent intensity, for threshold foveal viewing of point sources against a dark background; (b) steady-light equivalent intensity for whatever viewing conditions are being considered; and (c) the I_e value calculated from the Blondel-Rey-Douglas (BRD) formula (10.6-4), which is intended to be a prediction of the intensity defined in meaning (a) above. Some signal-lighting scientists are now becoming interested in separating these meanings by the coining of new names, but at present a reader of the technical literature is expected to judge the intended meaning of 'effective intensity' from the context.

Because no alternative formula is currently available -- or, at least, none has found widespread acceptance -- the effective intensity of signal lights is commonly calculated by the BRD equation (10.6-4), even when the viewing conditions depart significantly from those for which the calculated I_e value is expected to be valid. It is important to note that the conditions under which emergency-vehicle warning lights are viewed frequently depart in <u>every</u> particular from those to which the BRD formula is thought to apply, and almost always differ from the latter in at least one respect. In the emergency-vehicle warning-light situations of greatest interest, viewing is peripheral rather than foveal; the background is usually spotted with other lights at night and in the daytime may be dazzlingly bright, rather than totally dark; noticing of the signal rarely occurs when it is anywhere near the dimness characterizing dark-background thresholds; and, because the increase of the brightness of an approaching emergency-vehicle warning signal is accompanied by an increase of the angle subtended by the light source at the target driver's eye, detection often takes place when the light is no longer a perceptual point source, but has a visible disk. Moreover, in the classical Blondel-Rey situation, the viewer knows the lights are out there and is looking for them, often in an at least approximately known direction; while, in contrast, a driver is rarely expecting the approach of an emergency vehicle, is usually concentrating on other matters, and is obliged to monitor a fairly wide cone of directions that may cover a full 180° at intersections. Some day, undoubtedly very far into the future, sufficient psychophysical data may have been collected to permit the "constant" a in the BRD formula to be replaced by a function of all the relevant viewing variables, so that realistic estimates of equivalent steady-light intensity can be made regardless of viewing conditions. At the present time, however, it is not even known whether the basic form of the BRD equation applies to viewing conditions departing as drastically from the Blondel-Rey situation as those associated with the detection of emergency-vehicle warning lights; the problem of calculating equivalent intensity for purposes of peripheral conspicuity may go beyond merely finding an appropriate value for a. In the meantime, there is no obvious practical alternative to BRD effective intensity as a quantitative specification of the luminous output of a flashing light, and Eq. (10.6-4) is commonly used -- because it is an agreed-upon formal measure -- even when it is known that the flashing light being described will be used under conditions to which the value of $a=0.2$ does not apply, and to which even the basic form of the equation may not apply.

Another basic assumption underlying all the various forms of the Blondel-Rey equation is that it is sufficient to deal with the temporal profile of a single flash; that is, it is assumed that the flash rate is slow enough that the visual effectiveness of each flash is not significantly influenced by earlier or later flashes. With brief flashes (under a hundredth of a second) and long dark intervals between flashes (several tenths of a second), the assumption is probably justified. When the flash duration becomes extended and the dark period shortened, significant interactions between flashes may arise and the BRD formula may give inaccurate predictions. Projector (1957) has discussed some of the earlier experimental work bearing on this problem. The approximate visual equivalence of inverse flash cycles -- in which the durations of the light and dark phases are interchanged (see Section 7.3) -- obviously is not predicted by a formula such as (10.6-4) that is influenced only by the profile of the light phase. Effects related to flash rate, such as brightness enhancement (see Section 7.2), similarly cannot be encompassed by any such formula. It would appear reasonable to expect that a more widely valid formula for effective intensity might be based on the temporal profile of a complete cycle, including both the light and dark phases. Unfortunately, no all-inclusive formula of that kind has yet been developed.

When the light flash is extremely brief, as is, for example, the output of a gaseous discharge lamp (usually under 0.001 sec), the term t_2-t_1 in the denominator of formula (10.6-4) is, for practical purposes, negligibly small compared with the constant 0.2. Therefore, the expression being maximized becomes

$$\int_{t_1}^{t_2} I(t)dt/0.2,$$

or

$$5\int_{t_1}^{t_2} I(t)dt. \qquad (10.6\text{-}5).$$

With t gone from the denominator, the maximum value of the integral (area) in the expression (10.6-5) is obtained by choosing t_1 as small as possible and t_2 as large as possible; in other words, as the beginning and ending times of the total flash, respectively. Thus, for very brief flashes, the ambiguity associated with the time limits in the original Blondel-Rey formula (10.6-1) is eliminated and, to a practical degree of approximation,

$$I_e = 5\int_{\text{total}} I(t)dt. \qquad (10.6\text{-}6)$$

Since the integral in formula (10.6-6) represents the total luminous energy (per unit solid angle) contained in the entire brief flash, the possibility suggests itself of using a photoelectric device that responds to total energy rather than flux, in order to measure directly and instantly the effective intensity of gaseous discharge lights. Douglas (1958) worked out the design of equipment for achieving the same end by measuring average intensity over the complete flash cycle, rather than total energy in the flash, and such equipment is used in practice for the measurement of the effective intensities of lights with sufficiently brief flashes. When the flash duration increases beyond about a millisecond (0.001 sec), the duration term t_2-t_1 in the denominator of formula (10.6-4) becomes large enough to be no longer entirely negligible. Correspondingly, the times yielding the maximum I_e move in somewhat from the beginning and end of the flash. As indicated by Douglas (1958), the increasing error of formula (10.6-6) as flash duration increases can be approximately compensated for mathematically, for flashes up to about 0.01 sec in duration; but for still longer flashes, this convenient instrumental method breaks down and a much slower procedure such as the direct application of formula (10.6-4) to a graph of the temporal profile of the flash becomes necessary.

The process of measuring areas under a curve with a planimeter and carrying out Douglas' (1957) iterative procedure for obtaining effective intensity is fairly time-consuming, although the iteration converges to an adequate approximation of the true answer with only a few repetitions. When the curve representing I(t) -- the pulse shape of the flash -- can be closely approximated by an explicit mathematical function, then the maximization process included in the BRD formula (10.6-4) can be carried out directly by the methods of calculus, instead of by a successive approximation process. Since the pulses produced by rotating incandescent lamps often have a smooth, symmetrical time course approximating the bell-shaped curve known as the normal distribution curve, and because the areas under various portions of the normal distribution curve have been published widely in the form of tables (in almost any book on statistics or probability), Wohlers and Leupp (1959) worked out the necessary mathematics and published a graph permitting immediate approximate determination of effective intensity for rotating lights having bell-shaped temporal pulse profiles. (They actually worked in terms of the error function, which is closely related to the more widely familiar normal distribution curve.) The essentials of how to use the Wohlers-

Leupp (WL) method are also included in the Illuminating Engineering Society's (1964) "IES Guide for Calculating the Effective Intensity of Flashing Signal Lights", a useful general summary of practical information about effective intensity.

There are several slightly awkward aspects of the WL method, in the form in which it has been presented in the existing literature (Wohlers and Leupp, 1959; Illuminating Engineering Society, 1964). These can be classified as minor annoyances, except for one feature of the method: the fact that the quantity that must be known in order to apply the WL curve is the ratio of a rotation rate to a beamspread. Expressing the key quantity in these terms limits the application of the method to rotating lights. Although the pulse shape of a light rotating at uniform speed can typically be more closely approximated by a normal distribution curve than can the pulse shape of a flashing light (see Figs. 10.4-1 to 10.4-3), a flashing-light pulse shape can be symmetrical enough to warrant application of the WL method. Wohlers and Leupp (1959) showed by graphical examples that their curve gives acceptably accurate results even for moderately asymmetrical intensity profiles.

It can be seen from Eq. (10.5-11) that a rotation rate (ω, in the notation of Section 10.5 of this report) divided by a beamspread (σ) has the dimensions of the reciprocal of flash duration (1/t). If effective intensity can be given as a function of 1/t, it can more conveniently be presented as a direct function of the flash duration, *t*. This has been done in Fig. 10.6-1, which has not been previously published.

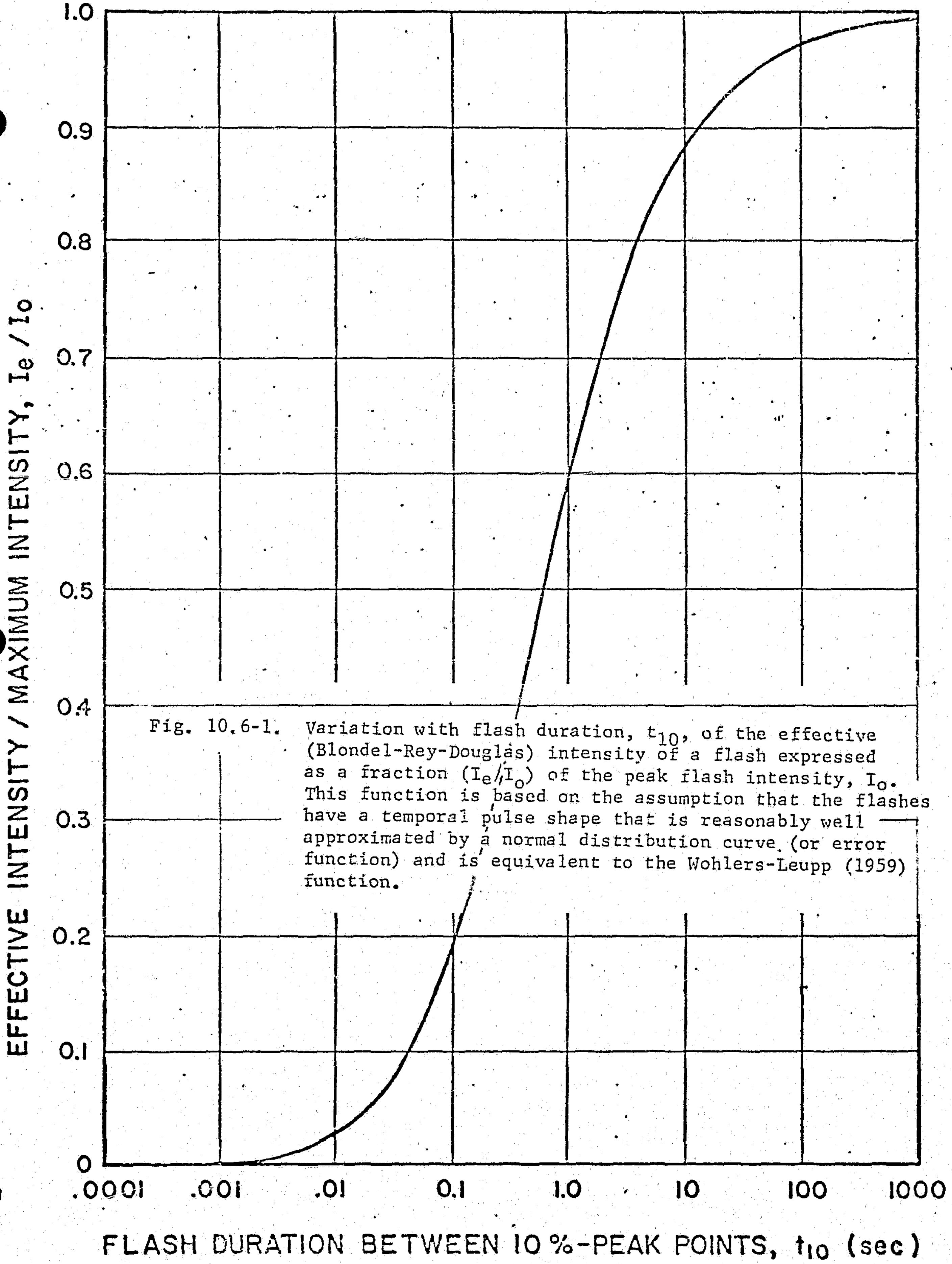


Fig. 10.6-1. Variation with flash duration, t_{10}, of the effective (Blondel-Rey-Douglas) intensity of a flash expressed as a fraction (I_e/I_o) of the peak flash intensity, I_o. This function is based on the assumption that the flashes have a temporal pulse shape that is reasonably well approximated by a normal distribution curve (or error function) and is equivalent to the Wohlers-Leupp (1959) function.

The curve shown is mathematically equivalent to the WL curve, as applied to an ideal normal distribution curve. The dependent variable (vertical scale or ordinate of the graph) is, as with the original WL curve, the ratio of the effective intensity I_e to the peak intensity I_o of the temporal pulse profile. The use of the ratio I_e/I_o instead of simply I_e allows a single curve to serve for lights of any absolute intensity level.

The independent variable (horizontal scale or abscissa of the graph) in Fig. 10.6-1 is t_{10}, the flash duration measured between 10%-peak points of the pulse-shape curve. This is the useful flash duration corresponding to the most common definition of the useful extent of the beamspread. (See Section 10.2 and the last paragraph of Section 10.5.) If we are not given direct information on the pulse shape or flash duration, we can calculate t_{10} from other quantities. Solving Eqs. (10.5-10) to (10.5-12) for t gives, respectively, the three formulas

$$t = \frac{\sigma T}{360} \qquad (10.6\text{-}7a)$$

$$t = \frac{\sigma}{6\omega} \qquad (10.6\text{-}7b)$$

$$t = \frac{\sigma n}{6\phi} \; . \qquad (10.6\text{-}7c)$$

Eqs. (10.6-7) furnish three alternate ways of calculating flash duration if t is not given directly. For flashing lights, the temporal information must necessarily be available, but for rotating lights, we see that the flash duration can be calculated as: (a) 1/360 of the product of the beamspread in degrees and the period of the turntable rotation in seconds; (b) the beamspread in degrees divided by 6 times the turntable speed in rpm; or (c) the product of the beamspread in degrees and the number of lamps on the turntable, divided by 6 times the flash rate in fpm. These equivalences, symbolized in Eqs. (10.6-7), are predicated on consistent definitions of the limits of useful beamspread and useful flash duration.

(a) Incandescent Lamps

As an illustration of how to find effective intensity using Fig. 10.6-1, consider a lamp having the angular intensity distribution shown in Fig. 10.6-2. The lamp is a PAR-36 sealed-beam unit of the type (designated #4416) most commonly used in rotating emergency-vehicle warning lights. The lamp, operated at its design voltage of 12.8, draws 30 watts and has a peak intensity, as seen in the graph, of 35 kcd (= 35 kilocandelas = 35,000 candelas). The beamspread is delimited by the angles at which the intensity is down to 10% of the peak, or 3.5 kcd in this case. As shown in Fig. 10.6-2, the angular intensity distribution is very nearly symmetrical, and the beamspread is about 4.5°.

If we now assume that the lamp is being used in a 2-lamp rotating unit that produces 90 flashes per minute, we can calculate from Eq. (10.6-7c) that

$$t_{10} = \frac{4.5 \times 2}{6 \times 90} = \frac{1}{60} = 0.01667 \text{ sec} = 16.7 \text{ msec.} \qquad (10.6\text{-}8)$$

(The subscript 10 on t, it should be recalled, simply indicates that the 10%-peak points are being used to define both the useful beamspread and the useful flash duration.)

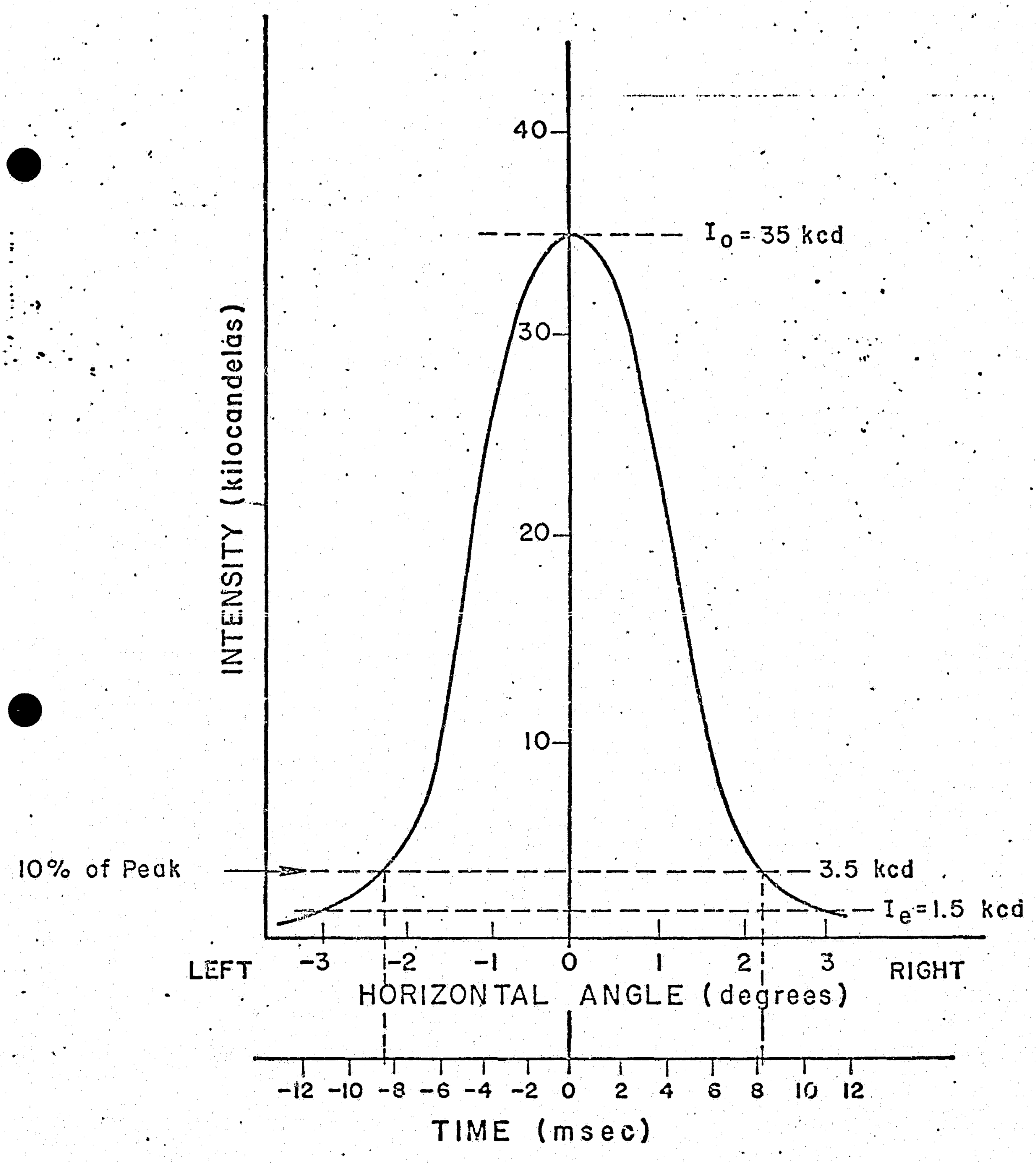


Fig. 10.6-2. Angular intensity distribution of a rotating #4416 PAR lamp, with a 4.5° beamspread. By using the lower abscissa scale, the same curve can be interpreted as a temporal pulse-shape curve.

As explained toward the end of Section 10.5, we can set up a general correspondence between angle and time, for rotating lights, and the lower abscissa scale in Fig. 10.6-2 can be read when the curve is to be interpreted as a temporal pulse profile. There is no need to do this extra work in calculating effective intensity, but for the present illustrative purposes it is helpful to see directly on the lower scale that the flash duration, t_{10}, is indeed 16.7 msec.

All that is necessary now is to find 0.0167 sec on the abscissa of Fig. 10.6-1 and read off an approximate I_e/I_o value of 0.044. In short, the effective intensity of the lamp is 4.4% of the peak intensity, or

$$I_e = 0.044\ I_o = 0.044 \times 35 \text{ kcd} = 1.54 \text{ kcd} = 1540 \text{ cd.}$$

This calculation indicates that a steady-burning lamp of only 1540-cd intensity would have the same visual range (in darkness) as the flashes from the lamp of our example, which has a peak intensity of 35,000 cd during its 16.7-msec flash.

If the same lamp is rotating on a 4-lamp turntable, with the unit still producing 90 flashes per minute, the value of <u>n</u> in Eq. (10.6-7c) is doubled, and the flash duration is correspondingly doubled to 33.3 msec. Looking in Fig. 10.6-1 at t_{10} = 0.0333 sec, we find that I_e/I_o is now about 0.081, so that

$$I_e = 0.081\ I_o = 0.081 \times 35 \text{ kcd} = 2.83 \text{ kcd} = 2830 \text{ cd,}$$

somewhat less than double what the effective intensity was with the same pulse profile compressed into half the time.

The fact that the curve of Fig. 10.6-1 is ever-increasing shows that for a fixed peak intensity I_o, the effective intensity I_e increases with increasing flash duration. This result is hardly surprising, since with a fixed peak, the shorter a flash is, the less energy it contains. However, a less obvious result can also be seen by inspection of Fig. 10.6-1: even at its steepest, namely for flash durations between 0.1 and 1.0 sec, the effective intensity does not increase by as great a factor as the flash duration does. For example, a 10-fold increase in flash duration from 0.1 to 1.0 sec produces an increase in I_e from 19% of I_o to 60% of I_o, only a little over 3-fold. In other words, what we found for the #4416 lamp is true in general: short flashes have an advantage over long flashes with respect to gaining visually effective light output for a given electrical power input to the lamp. The ratio of light output to electrical input is known technically as <u>luminous efficacy</u>.

(b) Luminous Efficacy

In the calculations above for the #4416 lamp, which has a rated electrical power consumption of 30 watts, we found that a two-lamp rotating unit, drawing 60 watts (since the lamps burn continuously), produces flashes with an effective intensity of 1540 candelas. In units of candelas per watt, therefore, the luminous efficacy of the two-lamp unit is 1540/60 = 25.67 cd/W. The four-lamp unit draws 120 W and produces flashes (at the same rate as the two-lamp unit) with an effective intensity of 2830 cd. The efficacy of the four-lamp unit is thus 2830/120 = 23.58 cd/W. In short, the efficacy of the two-lamp unit with its 16.7-msec flashes is 8.9% higher than that of the four-lamp unit with its 33.3-msec flashes.

This approximately 9% difference in efficacy could in some cases be canceled out by the extra power drain from the motor rotating the two-lamp turntable, which has to run twice as fast as the four-lamp turntable to produce the same flash rate. On the other hand, this increased power drain due to motor speed might be partly compensated by the decrease in the weight load on the two-lamp turntable (namely, the weight of two lamps). All in all, it does not appear that the question of efficacy has much importance in terms of selecting among warning units using rotating incandescent lamps; for example, in deciding between the use of a single four-lamp unit or a pair of two-lamp units. Spatial factors, such as those described in Section 7.7, probably should form the primary basis of such decisions.

In grosser comparisons between types of warning lights, as for example between gaseous-discharge lamps and incandescent-lamp units, the question of luminous efficacy may be of greater significance. It is generally claimed that gaseous-discharge lamps have twice the efficacy of incandescent lamps. In an emergency vehicle with a limited supply of current available for the warning lights, this efficacy difference could provide one argument -- not necessarily decisive -- in favor of using gaseous-discharge lamps. The matter of efficacy as such will not be pursued any further here, but some properties of the signals produced by gaseous-discharge lamps will now be discussed, with reference to Fig. 10.6-1.

(c) Gaseous Discharge Lamps

It should be noted that the shortest flash duration included in Fig. 10.6-1 is 0.0001 sec, or 100 μsec, the order of magnitude of the duration of the flashes from gaseous-discharge lamps. As shown on the graph, the effective intensity of any such flash is essentially zero compared to the peak intensity of the flash. The actual value of I_e/I_o at t_{10} = 0.0001 sec is 0.0003, or 3/100 of 1% (determined by computer). Therefore, as calculated by the Wohlers-Leupp approximation, a discharge lamp with a peak intensity of a million candelas in a 100-μsec flash could be seen no further away than a steady light of only 300 candelas. It is clear from these considerations that statements of peak candlepower for gaseous-discharge lamps are not very informative in themselves, and in particular must not be thought of as being in any way comparable to candlepowers of long-duration flashes or steady lights. The figure that permits an immediate intuitive appreciation of how "powerful" a flash lamp is, is the BRD effective intensity.

The computer calculations from which Fig. 10.6-1 was generated indicate that for short durations -- below a millisecond -- the value of I_e/I_o is very nearly simply proportional to the flash duration, with a proportionality constant of about 3 (actually, slightly more than 2.92). That is,

$$\frac{I_e}{I_o} = 3\ t_{10} \qquad (t_{10} < 0.001\ \text{sec}); \qquad (10.6\text{-}9)$$

or

$$I_e = 3 I_o t_{10} \qquad (t_{10} < 0.001\ \text{sec}). \qquad (10.6\text{-}10)$$

The approximate proportionality expressed by Eq. (10.6-10) is closely valid over the same range of brief flash durations for which Eq. (10.6-6) is accurate. It has been possible to derive the former equation from the latter algebraically (not published) and confirm the computer calculations. The actual proportionality constant, given roughly as 3 in Eq. (10.6-10), is an irrational number (namely, $2.5 \sqrt{\pi \log_{10} e}$), which, to six decimals, is equal to 2.920163. These proportionality relationships apply accurately to brief flashes with pulse shapes that are nearly symmetrical and can be closely approximated by a normal distribution curve. However, the pulses from a gaseous-discharge lamp typically have a rapid rise and a slower (exponential) fall-off (as shown in Fig. 10.4-2), so that the normal distribution curve is a fair but not very accurate approximation. The constant 3 (or 300) in Eqs. (10.6-9) to (10.6-12) is therefore subject to an unknown degree of error when applied to such lamps, but it can be presumed that the effective intensities predicted by those equations do give a rough, order-of-magnitude estimate, as applied to real discharge lamps.

If t_{10} for a gaseous-discharge lamp is assumed to be about 100 μsec (it is frequently less), then Eq. (10.6-10) yields the following simple rule of thumb for estimating effective intensity from peak intensity for such lamps:

$$I_e = I_o \times 3 \times 10^{-4} \quad \text{(discharge lamps).} \qquad (10.6\text{-}11)$$

If I_o is measured in millions of candelas (Mcd), then Eq. (10.6-11) becomes

$$I_e = 300 I_o \quad (I_e \text{ in cd; } I_o \text{ in Mcd; } t_{10} \approx 100\ \mu\text{sec}). \qquad (10.6\text{-}12)$$

The simple relationship (10.6-12) allows an immediate rough mental estimate of effective intensity for discharge lamps for which a peak intensity is known. Thus, such a lamp with an impressive peak intensity of 10,000,000 cd (10 Mcd) should be visible at night at about the same distance as a steady light of 3000-cd intensity. If the actual value of the flash duration t_{10} for the particular lamp is known, then Eq. (10.6-10) will supply a more accurate estimate of the effective intensity.

(d) Fixed-Energy Flashes

As a conclusion to the discussion of effective intensity, it will be useful to consider a type of comparison among light pulses that cannot be made directly by using Fig. 10.6-1. Suppose we have a certain fixed amount of luminous energy to put into a flash. Is it best to squeeze this energy into a very brief pulse, or to spread it out over a long time? Or is there some optimum intermediate duration for the flash?

The total luminous energy (per unit solid angle) in a flash is equal to the area under the entire temporal pulse profile (intensity versus time). Let this total area under the curve be A (in units of candela-seconds). For pulses of various durations, with the <u>same</u> total energy content A, how does the effective intensity vary with the flash duration? Projector (1957) has published graphs answering this question for rectangular light pulses. The curve of Fig. 10.6-3 (not previously published) gives the answer on the basis of the Wohlers-Leupp assumption that the pulse shapes can be well approximated by normal distribution curves. In analogy with Fig. 10.6-1, to permit one curve to serve for all possible values of the total energy A, we plot I_e/A on the ordinate instead of simply I_e. This curve shows that to get the greatest possible effective intensity from a given total luminous pulse energy, it is necessary to squeeze the

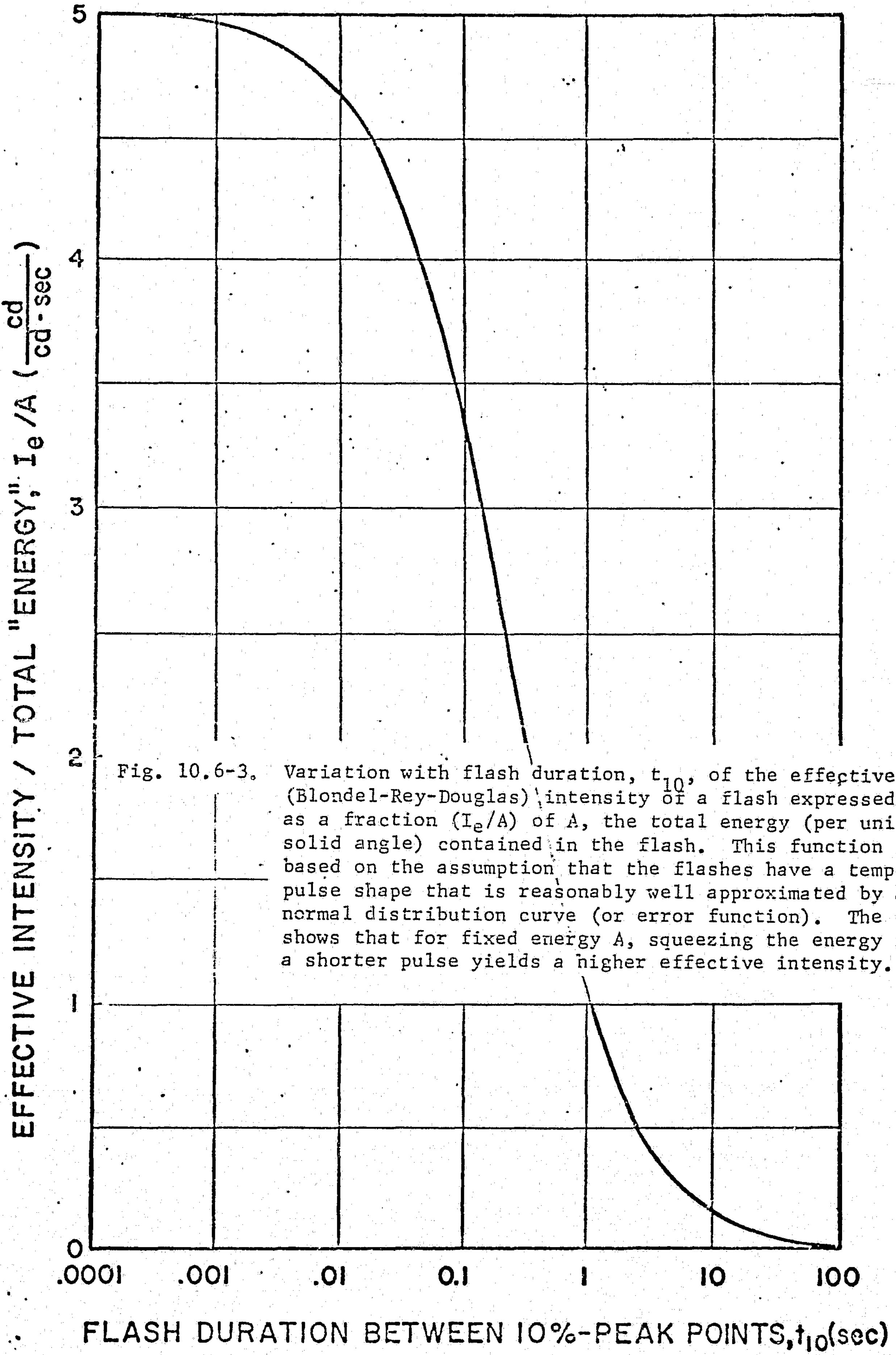


Fig. 10.6-3. Variation with flash duration, t_{10}, of the effective (Blondel-Rey-Douglas) intensity of a flash expressed as a fraction (I_e/A) of A, the total energy (per unit solid angle) contained in the flash. This function is based on the assumption that the flashes have a temporal pulse shape that is reasonably well approximated by a normal distribution curve (or error function). The curve shows that for fixed energy A, squeezing the energy into a shorter pulse yields a higher effective intensity.

energy into a brief pulse. However, nothing significant is gained by using flash durations below a tenth of a millisecond (100 microseconds), and nothing of much practical importance is gained by going below a millisecond (the loss of effective intensity at 1 millisecond being less than 1%). Extending the flash to a duration of a hundredth of a second causes an effective-intensity loss of 6.6%, and spreading the pulse over a full tenth of a second causes a drastic loss of 34.6% of the maximum possible I_e for the given amount of total luminous energy. For flash durations of 15 to 35 msec, the range that we have just seen (in Section 10.6a) includes typical cases of rotating incandescent lamps, the loss is from about 9% to 18%.

If gaseous-discharge and incandescent lamps were otherwise equal with respect to generating conspicuous signals, this intensity loss could be considered an argument in favor of the gaseous-discharge lamp. However, an intensity difference of 9% to 18% is not very significant visually, and could easily be outweighed by some other variable in which incandescent lamps might be superior to gaseous-discharge lamps. The problem of what type of emergency-vehicle warning-light unit is best is going to require perceptual experimentation to find a solution; the issue cannot be settled by effective-intensity computations alone.

10.7. Color

A statement that a light should be, for example, "red", is not a very precise specification. There is a considerable range of colors that would be called "red", in the sense that they are more red than anything else, but these colors may differ quite noticeably from each other. For example, a red light can have yellow added to it, to the point where the light appears to be somewhat orangish. At first, this slight yellow admixture might be of little concern, because the light is still predominantly red, and would not be thought of as any other color. With enough yellow added, however, the light may appear orange rather than red. Although red and yellow are widely used colors for emergency-vehicle warning lights, orange is not frequently assigned such a role. Consequently, a motorist seeing a pure orange warning light -- appearing equally yellow and red -- would be confused because he would not be able to decide whether a red or yellow was intended. It is accordingly necessary, in a signal system using both yellow and red, for reds to be kept from having too much yellow in them, and yellows to be kept from having too much red in them.

It is not sufficient to choose an intermediate orange color and specify that any color redder than the orange is to be regarded as red, and any color yellower than the orange is to be regarded as yellow. Warning lights are sometimes seen when they are rather faint and subtend a very small angle at the eye. The ability to tell colors apart is considerably reduced under such unfavorable viewing conditions, and then an observer could not be sure if he were viewing a very yellowish red or a very reddish yellow. There may be additional problems in color discrimination caused by color-distorting hazes or fogs, or by a non-neutral state of visual adaptation of the observer, as when he is driving on a road illuminated by yellow sodium vapor lights. The requirement, therefore, necessary to permit easy discrimination of red from yellow under most circumstances is that reds be permitted to have no more than a small amount of yellow in them, and yellows be permitted to have no more than a small amount of red in them.

The quantitative specification of color -- in the sense that excludes the intensity aspect -- is commonly expressed in terms of the chromaticity coordinates x,y based on the 1931 CIE standard color-matching functions (see Section 6.3). The usual procedure in indicating the allowable deviation away from a particular standard color is to box off the point corresponding to the standard color on the CIE x,y chromaticity diagram, by a set of limit lines. Each of the limit lines indicates how far off from the standard it is permissible to go in some particular color direction. With a red standard, for example, there would be a yellow limit (keeping the red from being too orangish); a blue limit (keeping the red from being too purplish); and a white (formerly, weak or pale) limit (keeping the red from being too whitish).

Some systems of color tolerances also include a strong limit, that keeps the color from being too saturated (pure, vivid, unwhite), but in many applications, including signal lights, the higher the saturation of the color, the better. There is, of course, a natural "strong limit", namely the saturation of the ultimately pure spectral colors such as come from a prism dispersing white light.

In actual practice, the limit on saturation is often indirectly imposed by the requirement for minimum intensity. Signal colors are normally produced by passing white light through a color filter that absorbs a considerable fraction of the white light, letting through mostly light within a restricted range of wavelengths that corresponds to the desired color. The purer (more saturated) the colored light coming through the filter is, the narrower the passed wavelength band must be. Thus, as the light getting through the filter is required to be progressively purer, more and more of the illuminating white light is being absorbed, so that the total amount of light coming through -- and therefore the intensity or luminance -- becomes lower and lower. Because blue light corresponds to a quite narrow band of wavelengths near the shortwave end of the spectrum, where the eye is relatively insensitive, a filter that passes saturated blue light has to absorb most of the luminous energy coming from the illuminating white light. In other words, a good blue filter has a low luminous transmittance. The same is true of saturated red filters, which pass only the longwave end of the spectrum, where the eye is also insensitive. On the other hand, green covers a fairly broad wavelength band in the part of the spectrum to which the eye is most sensitive, so a green filter that passes a fairly strong green can still have a rather high transmittance. It happens that a mixture of red and green light appears yellow to the eye, so a yellow filter can pass not only the yellow band of the spectrum, but considerable portions of the neighboring green and red bands as well. Therefore, saturated yellow filters can transmit a good portion of the white light that illuminates them.

The total luminous transmittance of a filter is partly determined by the spectral transmittances -- the fraction of light of each wavelength that the filter passes. However, it is also determined by the spectral power output of the source used to illuminate the filter. Ordinarily, the total transmittance of a filter is specified with respect to a light source that has a substantial amount of output at all wavelengths within the visible spectrum; that is, a "white" source. There is considerable variation, however, in the detailed spectrum of the many different types of sources that are thought of as providing "white" light. In modern emergency-vehicle warning lights, there are basically two types of white sources: incandescent (tungsten-filament) and gaseous-discharge (most commonly, xenon). In the range of temperatures at which the filaments of incandescent lamps are normally maintained by imposing the rated voltage, the light produced by these lamps is biased toward longwave output; that is, the light is relatively rich in red and relatively low in blue. On the other hand, xenon arc lamps and flashtubes produce a much "cooler" light, with considerably more blue content, relative to the red, than incandescent lamps provide. As a result, the transmittance of red filters is somewhat higher for incandescent-lamp light than for xenon-discharge light, while the reverse is true for blue filters. Table 10.7-1 shows typical transmittances, for both types of sources, of the colored domes and lamp faces commonly used in warning-light units.

Table 10.7-1. Transmittances of Typical
Colored Domes and Lamp Faces

Filter Color	Transmittance for Incandescent Lamp Light	Transmittance for Xenon Discharge Light
Red	0.20	0.17
Yellow	0.65	0.50
Green	0.27	0.33
Blue	0.03	0.06

As can be seen in Table 10.7-1, placing a blue dome or face coating over an incandescent lamp -- as is often done in jurisdictions that use blue lights -- results in a loss of something like 97% of the light supplied by the lamp. This loss of intensity is perceptually serious, and should be compensated for by increasing the output of the lamp. An extremely high-wattage incandescent lamp would be needed to bring the intensity passing through a blue filter up to a level comparable with the intensity passed through a white (clear) or yellow (amber) filter by a low-wattage lamp. Because the use of such high-wattage lamps introduces problems of power drain on the electrical system of the vehicle and heat accumulation in the lamp housing (which could melt the dome or other plastic elements of the unit), this method of compensation for intensity loss is not popular in practice. Instead, what has happened is that many of the manufacturers of domes and lamp-face filters have degraded the purity of the blue color of the filters by broadening the transmission band to include significant amounts of non-blue wavelengths. The result is blue signals that are either pale (whitish), or greenish, or both.

It can be seen in Table 10.7-1 that the use of a xenon flashlamp instead of an incandescent lamp, in a blue warning-light unit, is of some help in combatting the intensity-loss problem. Even with xenon flashers, however, the intensity through a blue filter is sharply lowered, so impure blue filters are commonly used with flashlamps, too.

The Society of Automotive Engineers (SAE), which publishes voluntary standards concerning most aspects of automotive equipment and materials, has a standard that sets limits on the colors of lights used on automobiles. SAE Standard J578a - Color Specification for Electric Signal Lighting Devices - sets chromaticity limits of the sort described earlier in this section, for red, yellow, and white lights only. This selection of colors in the standard is explained historically by the limitation of lights used on ordinary passenger vehicles to those three colors, as well as by the limitation of emergency-vehicle warning lights to the same three colors until the relatively recent proliferation of blue warning lights in the U.S.A. The SAE, which revises all of its many standards from time to time as changing practice and advancing technology require, is currently considering adding limits on the colors of blue and green lights to their Color Standard. At present, green is rarely, if ever, used in signal lights carried by emergency vehicles, so there is no need to consider the question of green boundaries here. However, in the absence of a current SAE blue standard, the boundaries for blue set by the CIE (International Commission on Illumination) will be presented as a general guide to what a good signal blue would be.

It should be noted that although the SAE standards have no legal force, manufacturers of automotive products are at a competitive disadvantage in the marketplace if they cannot certify that their products do meet the widely accepted SAE specifications. However, it is important to note that at the time of completion of this report (summer 1973), the National Highway Traffic Safety Administration is preparing the final version of a regulation (Motor Vehicle Safety Standard -- with the force of law) that covers vehicle lighting and that is now expected to conflict with the SAE color specifications. In the face of such a conflict, the SAE Color Standard will presumably have to be revised, and will probably then reference the NHTSA Standard.

Figure 10.7-1 shows, on the CIE 1931 x,y chromaticity diagram, the boundaries for red, yellow, and white prescribed by SAE Standard J578a, and the boundaries for blue recommended by the CIE.

In this diagram, roughly speaking, $\underline{x}$ represents the fractional red content in each color, and $\underline{y}$ the fractional green content. The assumption underlying the diagram is, in intuitive terms, that any light can be matched in color by some mixture of three fixed ("primary") lights, usually chosen as a red, a green, and a blue. Thus, the fractional blue content, denoted by $\underline{z}$, is whatever is left in a color other than the fractional red or green content; that is, by definition,

$$x + y + z = 1. \qquad (10.7\text{-}1)$$

Thus, because the value of $\underline{z}$ is fully determined by the values of $\underline{x}$ and $\underline{y}$, it is possible to represent any color on a two-dimensional plot of $\underline{y}$ against $\underline{x}$. The point at the upper tip of the horseshoe-shaped region in Fig. 10.7-1 has a high $\underline{y}$ (green) value and a low $\underline{x}$ (red) value, and therefore represents a strong green color. The right-hand corner is the

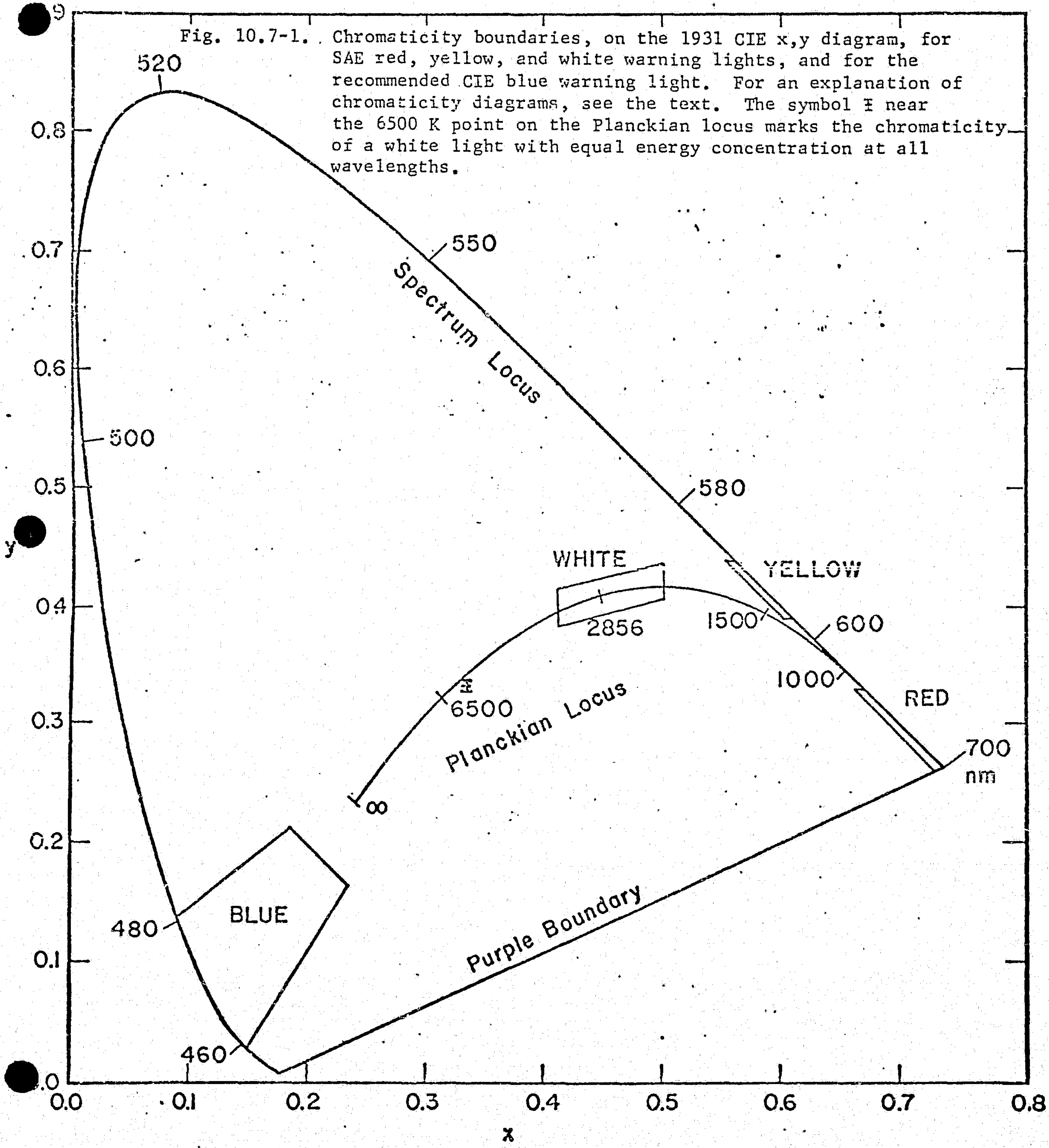


Fig. 10.7-1. Chromaticity boundaries, on the 1931 CIE x,y diagram, for SAE red, yellow, and white warning lights, and for the recommended CIE blue warning light. For an explanation of chromaticity diagrams, see the text. The symbol Ɪ near the 6500 K point on the Planckian locus marks the chromaticity of a white light with equal energy concentration at all wavelengths.

reverse: high in red (x) and low in green (y), and therefore represents a strong red. The lower left-hand corner is low in both red and green, and therefore is a strong blue (high z). Points near the center of the diagram represent colors containing substantial amounts of all three primary colors, and such colors are near-whites. It should be noted, finally, that chromaticity diagrams are completely independent of the dimension of intensity.

The "horseshoe" curve in the figure is the spectrum locus, the track of the chromaticities associated with spectrally pure (single-wavelength, monochromatic) light of all visible wavelengths. Some wavelengths, in nanometers, are marked along the locus. The straight line across the bottom of the horseshoe is known as the purple boundary (sometimes called the line of purples or the locus of purples). This line is the track of colors (purples) that can be formed by various mixtures of two fixed wavelengths -- one a red at the longwave end of the spectrum, and the other a violet (reddish blue) at the shortwave end. No color can exist physically that has a chromaticity outside the region enclosed by the spectrum locus and purple boundary.

The curve in Fig. 10.7-1 labeled "Planckian locus" shows the range of chromaticities taken on by a certain kind of ideal glowing (incandescent) body (known as a "blackbody" or "full radiator") as it heats up from low temperatures to high temperatures. Tungsten filaments show color changes closely following this blackbody locus, although they are not perfect blackbodies. The numbers along the locus are absolute temperatures in kelvins (formerly known as "degrees Kelvin" or "degrees Absolute"). It will be seen that at comparatively low temperatures (1000 K), a glowing body is quite red. As it heats up, it becomes yellower and then whiter. Finally, at extremely high temperatures (designated ∞ in Fig. 10.7-1), the body becomes bluish white. (The colors of stars are correlated with their temperatures in the same fashion.)

An incandescent lamp burned at rated voltage usually gives off a yellowish light similar in color to the light emitted by a blackbody in the temperature range of about 2800-3000 K. Such a lamp is said to have a color temperature of 2800-3000 K. As Fig. 10.7-1 shows, the unfiltered light from such a tungsten lamp (exemplified by the 2856 K blackbody point) lies within the area designated as "white" by the SAE. Unfortunately, xenon flashlamps have a color temperature in the neighborhood of 6500 K (about the same color as natural daylight), and, as the figure shows, such light is far too bluish to be considered white by the present SAE standard. Placing a suitable light yellowish filter over a xenon lamp would bring its color into the chromaticity region regarded as white by the SAE, without a serious loss of intensity, and some thought should possibly be given to adopting this practice when a flashtube is used as a white component of a warning-light configuration. Without such correction, the bluish white flash of an unfiltered xenon lamp can be confused -- particularly at night -- with the whitish blue flash that results when an unusually pale blue filter is used.

For reference purposes, the detailed specifications of the limit areas in Fig. 10.7-1 are given numerically in Table 10.7-2. Only the white area is fully delimited by four straight limit lines. The yellow and blue areas have the spectrum locus as the fourth limiting curve, and the red area is bounded by both the spectrum locus and the purple boundary.

Table 10.7-2. Limiting Regions on the 1931 CIE Chromaticity Diagram for Colors Used in Emergency-Vehicle Warning Lights

Color	Type of Limit	Limiting Line	Requirement	Corner Points of Limit Area	Wavelength[a] (nm)
Red	Yellow and white limit	$y = 0.33$	$y \leq 0.33$	(0.6620, 0.3300)	
(SAE)	Purple limit	$y = 0.992 - x$	$y \geq 0.992 - x$	(0.6698, 0.3300)[a]	611.31
		$(z = 0.008)$	$(z \leq 0.008)$	(0.7063, 0.2857)[b]	
				(0.7347, 0.2653)[a,b]	830.00
	Green limit	$y = 0.44$	$y \leq 0.44$	(0.5500, 0.4400)	
Yellow	Red limit	$y = 0.39$	$y \geq 0.39$	(0.5593, 0.4400)[a]	587.35
(SAE)	White limit	$y = 0.990 - x$	$y \geq 0.990 - x$	(0.6000, 0.3900)	
		$(z = 0.010)$	$(z \leq 0.10)$	(0.6094, 0.3900)[a]	596.29
	Yellow limit	$x = 0.50$	$x \leq 0.50$	(0.5000, 0.4050)	
White	Blue limit	$x = 0.41$	$x \geq 0.41$	(0.5000, 0.4350)	
(SAE)	Green limit	$y = 0.31 + 0.25x$	$y \leq 0.31 + 0.25x$	(0.4100, 0.3825)	
	Purple limit	$y = 0.28 + 0.25x$	$y \geq 0.28 + 0.25x$	(0.4100, 0.4125)	
	Green limit	$y = 0.065 + 0.805x$	$y \leq 0.065 + 0.805x$	(0.1856, 0.2144)	
Blue	Purple limit	$x = 0.133 + 0.600y$	$x \leq 0.133 + 0.600y$	(0.0897, 0.1372)[a]	480.39
(CIE)	White limit	$x = 0.400 - y$	$x \leq 0.400 - y$	(0.2331, 0.1669)	
				(0.1482, 0.0254)[a]	457.08

---

[a] Point lies on spectrum locus.

[b] Point lies on purple boundary.

In order to test whether the chromaticity of a given light does or does not fall within the areas shown in Fig. 10.7-1 (and characterized numerically in Table 10.7-2), it is necessary to measure the color of the light. The measurement of color can be accomplished in several different ways, of varying degrees of precision.

The crudest procedure is a visual method that determines only whether the light is inside or outside the acceptable area. In order to use this method, there must be available a set of <u>limit filters</u> having chromaticities that lie near the midpoints of the limiting line segments in Fig. 10.7-1. For example, a filter representing the green limit of the yellow area would appear to be a slightly greenish yellow when illuminated by an incandescent lamp having a color temperature of 2856 K. (An incandescent lamp burning at 2856 K is one standard for colorimetric work; it is referred to as CIE Source A.) The chromaticity of the light from the limit filter should have a <u>y</u> value of 0.44 (as shown in Table 10.7-2) and should have an <u>x</u> value lying somewhere between that of the corner (x = 0.5500) and that of the intersection of the line y = 0.44 with the spectrum locus (x = 0.5593). Any yellow light that is seen as no greener than this illuminated green limit filter is acceptable, as far as deviations in the green direction are concerned. For yellow lights, there would also be a red limit filter and a white (pale) limit filter. In addition to lying within the green limit, an acceptable yellow light would also have to appear no redder than the red limit and no whiter than the white limit. In order to maximize the sensitivity of the visual color judgments, the light from the unit under test should be collected by an optical instrument that also separately collects light from a limit filter transilluminated by Source A. The two beams of colored light are seen in the instrument as illuminating adjacent fields of comparable area, with as fine a dividing line between the fields as possible.

In Section 6.3, the tristimulus values X, Y, and Z were defined, and it was explained how they can be measured physically by using suitable combinations of photocells and filters. An instrument that operates on that principle is called a filter tristimulus colorimeter. The accuracies of the X,Y,Z readings depend on how closely the spectral responses of the filter-photocell combinations match the CIE $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$ color-matching functions (also described in Section 6.3). The relationship between the chromaticity coordinates x, y, and z, and the tristimulus values X, Y, and Z is quite simple, namely

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z}, \qquad z = \frac{Z}{X+Y+Z}. \tag{10.7-2}$$

The chromaticity coordinates are thus nothing more than tristimulus values expressed on a fractional basis. Because of the relationships expressed by Eqs. (10.7-2), which actually comprise the definitions of the chromaticity coordinates, it is clear why the latter sum to unity, as expressed in Eq. (10.7-1).

Most tristimulus colorimeters use a single photocell and a group of filters placed sequentially in front of the photocell. By simply mounting a set of the proper filters in a wheel that can be rotated in front of the entrance port of a photometer, any photometer can be used as a tristimulus colorimeter. Some of the better photometers today have a set of tristimulus filters available as an option. A photometer thus employed as a colorimeter is able to measure the color of an incoming light beam, as is required for checking warning lights. The prospective purchaser of equipment should be aware that many of the instruments that bear the name "tristimulus colorimeter" use an internal source of light and are capable of measuring the colors only of reflecting surfaces or transmitting filters, not of external light beams.

The most accurate -- and correspondingly most expensive -- method of measuring color is the spectral method. For directly measuring the color of an external light beam, such as the beam put out by a warning-light unit, the necessary instrument is called a <u>spectroradiometer</u>. The incoming light is split into its component wavelengths by a prism or diffraction grating inside the spectroradiometer, and the amount of energy at each wavelength is measured sequentially by an unfiltered photocell. The result is the spectral power distribution of the incoming light. From that information, the tristimulus values and chromaticity coordinates are obtained by computation, as described in Section 6.3. In the spectral method, the actual values of the color-matching functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, are used numerically, eliminating the error of approximating these functions by the spectral response of a filter-photocell combination.

A more indirect spectral method involves the use of a <u>spectrophotometer</u>, an instrument that splits the light from an internal light source into its component wavelengths, and uses the light of the various wavelengths in turn to measure the spectral reflectance of a surface or the spectral transmittance of a filter. A spectrophotometer could be used to measure the spectral transmittances of a set of warning-light domes of various colors. Then the colors obtained by using these domes over a particular white light source can be obtained by computation, provided the spectral power distribution of the white source is known. It is common to assume that the white source, if it is an incandescent tungsten lamp burned at rated voltage, has in the visible spectrum the relative spectral power distribution of a blackbody of the same color. Tables of the blackbody spectral distribution for different temperatures are available (see, for example, Wyszecki and Stiles, 1967, pp. 16-28), so the color of the light from the source-dome combination can be calculated without using a spectroradiometer on the white source. It is necessary only to determine the color temperature of the incandescent lamp. For rough calculations, a color temperature of 2856 K (Source A) can be assumed.

Unfortunately, the light from a real incandescent lamp does not actually match the relative spectral power distribution of a blackbody exactly. There is also usually some error in determining the color temperature of the lamp. Moreover, each "colorless" optical element that operates on the light -- such as the reflector of a PAR lamp, the glass in the front of the bulb, and any lenses in the unit -- changes the spectral distribution slightly because of the slight wavelength selectivity that almost all "colorless" objects possess. Another source of error in applying the spectrophotometric method arises from the fact that most of these instruments are designed to measure flat filters, but warning-light domes are usually curved. All of the preceding errors may be rather small, but the total final error may be significant. It is safer to use a spectroradiometer, where available, so that the light being measured in the instrument is the actual light sent out by the complete warning-light unit, with no assumptions being necessary.

PART IV. SUPPLEMENTARY MATERIAL

11. List of Manufacturers and Distributors

The following is a list of companies that either manufacturer or distribute emergency-vehicle warning-light equipment. We have received or requested catalog literature from these companies and have ordered representative samples of emergency-vehicle warning lights from a number of the included manufacturers. These sample units are being physically and perceptually evaluated in a phase of our overall program that will be separately reported at a later time.

It is believed that most major manufacturers are included in the list, as well as many of the largest distributors. It is frequently difficult to determine from a catalog alone whether a compnay produces its own lights, or distributes only the products of other firms that are manufacturers, so no attempt has been made here to distinguish the categories. A few of the listed companies produce or distribute lights that are only marginally classifiable as emergency-vehicle warning lights; for example, hand-held high-intensity spotlights, or truck lights that can be flashed as warning lights.

Since updated versions of this list may be included in later reports of this project, we would be grateful for any corrections, additions, withdrawals, or identifications as manufacturer or distributor. Communications should be directed to:

Sensory Environment Section (462.02)
Emergency-Vehicle Lighting Project
BR-A313
National Bureau of Standards
Washington, D.C. 20234

Abex Corp. - see Signal-Stat Co.

Aero Safety Device, Georgetown, Delaware.

Ed. Agramonte, Yonkers, New York.

Automotive Conversion Corp., Troy, Michigan.

Auto Safety, Inc., Cumming, Iowa.

Baader-Brown Mfg. Co., Springfield, Ohio.

Bangor Punta Co. - see Stephenson.

Blitzer - trademark of Northern Signal Co.

George F. Cake, California.

Cassell Company, Napa, California.

Cats-Eye Lamp Div. (Holophane Co. of Johns-Manville Corp.) Columbus, Ohio.

Cristie Electronics, Los Angeles, California.

W. S. Darley and Co., Melrose Park, Illinois.

Dazl-Ray Corp., Kansas City, Missouri.

Dictograph Security, Florham Park, New Jersey.

R. E. Dietz Co., Syracuse, New York. (See also NAPA.)

Dominion Traffic Sign and Signal (Division of Grote Manufacturing Co.), Richmond, Virginia.

Do-Ray Lamp Co., Chicago, Illinois.

Dunbar-Nunn Corp. - see Unitrol.

Dura Corp. - see Weaver.

Esco Light - trademark of Streeter Amet.

Fargo International, Chevy Chase, Maryland.

Federal Sign and Signal Corp., Blue Island, Illinois.

FEDTRO, Inc., Rockville Center, New York.

General Telephone and Electronics (GTE) - see Sylvania Inc.

Griffin Lamp Co., Shelby, Miss.

Grimes Manufacturing Co., Urbana, Ohio.

Grote Manufacturing Co., Madison, Ind. (See also Dominion Traffic Sign and Signal.)

Holophane Co. - See Cats-Eye Lamp Div.

Home Safety Equipment, New Albany, Indiana.

Hope-Tronics Ltd., Hempstead, New York.

Illinois Central Industries - see Signal-Stat Co.

International Luminite, Chicago, Illinois.

International Telephone & Telegraph Corp. (ITT) - see Portable Light Co. and Sireno.

Jabsco Products - see Portable Light Co. and Sireno.

Johns-Manville Corp. - see Cats-Eye Lamp Div.

K-D Lamp Co., Cincinnati, Ohio.

Kel-Lite Industries Inc., Covina, California.

Walter Kidde and Co. - see Weaver.

Kustom Signals, Chanute, Kansas.

Macchi Corp., San Francisco, California.

Mangood Corp. - see Streeter Amet.

Mars Signal Co., Chicago, Illinois.

Miro-Flex Co., Inc., Wichita, Kansas.

Motorola, Chicago, Illinois.

NAPA (supplied by Dietz), Syracuse, New York.

North American Signal Co., Chicago, Illinois.

Northern Signal Co., Saukville, Wisconsin. (See also Blitzer)

On-Guard Corp., Carlstadt, New Jersey.

Orion Industries - see Pathfinder Auto Lamp.

Paralta Equipment Co., Hammond, Indiana and Los Angeles, California.

Pathfinder Auto Lamp (Subsidiary of Orion Ind.), Miles, Illinois.

Peterson Manufacturing Co., Grand View, Mo.

Pichel Industries, Pasadena, California.

F. Morton Pitt, San Gabriel, California.

Portable Light Co. (Jabsco Products, ITT) Costa Mesa, California.

Rochester Safety Equipment, Rochester, New York.

Safety Guide Products, Scottsdale, Indiana.

Safety Products, Chicago, Illinois.

Signal-Stat Co. (Abex Corp., Division of Illinois Central Industries), New York, New York.

Sireno (Jabsco Products, ITT), Costa Mesa, California.

Smith and Wesson Electronics Co. - see Stephenson.

Soderberg Manufactures, Alhambra, California.

Spartan Manufacturing Co., Flora, Illinois.

J. W. Speaker Corp., Milwaukee, Wisconsin.

Stephenson (Smith & Wesson Electronics Co., A Bangor Punta Co.), Eatontown, New Jersey.

Sterling Siren Fire Alarm Co., Rochester, New York.

Streeter Amet (Division of Mangood Corp.) Grayslake, Illinois. (See also Esco Light.)

Sylvania Inc. (GTE), Mountain View, California.

Robert E. Thomas Co., Inc., Santa Ana, California.

Trippe Manufacturing Co. - see Tripp-Lite Co.

Tripp-Lite (Division of Trippe Manufacturing Co.), Chicago, Illinois.

Truck Lite Co., Jamestown, New York.

Unitrol (Dunbar-Nunn Corp.), Anaheim, California.

Unity Manufacturing Co., Chicago, Illinois.

Vehicle Safety Products Manufacturing Corp., Syracuse, New York.

Weaver (Division of Dura Corp., a Kidde Co.), Springfield, Illinois.

Werlin Safety Products, Folcroft, Pennsylvania.

Whelen Engineering Co., Inc., Deep River, Connecticut.

Yankee Metal Products Corp., Norwalk, Connecticut.

12. Appendix: NBS Photometry Facilities and Procedures

12.1. Introduction

An emergency warning light consists of a light source and an optical system which together produce a beam of light. In the photometry of these devices, the intensity of the device as a function of angle of viewing is measured. A variety of techniques and equipment have been developed for tests on various types of sources.

Photometric testing is carried out on a photometric range by comparison of device output with a standard lamp of known luminous intensity in a specified direction. These comparisons are made with photosensors which are color corrected by filters so that the spectral response is similar to the CIE luminous efficiency function. Considerable care is required to keep the experimental errors within the desired limits.

A common example of an emergency warning light source is the PAR-type lamp which is a sealed beam lamp consisting of a filament placed at the focus of a parabolic reflector with a glass cover. Another example is a light source placed at the focus of a Fresnel lens.

For measuring the luminous intensity of such a device, a photometer employing an electrical photosensor is used. The response of the photosensor is read or recorded on an electrical measuring device such as a self-balancing recording potentiometer. This response is a function of the illuminance on the face of the photosensor, and the illuminance is expressed by the inverse-square law as follows:

$$E = \frac{I}{d^2}\ , \tag{12.1-1}$$

where E is the illuminance at the photosensor,

I is the luminous intensity of the light source, and

d is the distance between the light source and the photosensor.

The photometer is calibrated against a standard lamp of known luminous intensity in a specified direction, oriented in that direction at a known distance from the photosensor.

The emergency warning lights are mounted at one end of a photometric range. There are two ranges for the photometric measurement of these devices at the National Bureau of Standards. On the shorter range, the distance between the source and the photosensor can be varied to a maximum of 100 meters. On the longer range, this distance is a fixed 363 meters.

NBS has made photometric measurements of various kinds of sources, particularly those units used in airfield and aircraft lighting. Since these sources have been of many sizes, shapes, beam characteristics and intensities, a variety of corresponding procedures, techniques and equipment have been developed for their measurement. When photometric measurements are to be made, each source must be considered individually, and it is not possible to put forth any one general method for testing them. The intent of this appendix, therefore, is first to describe the photometric equipment most commonly used, with emphasis on its application to particular types of sources. Next, the theory and practical considerations of the various calibration procedures are discussed. Finally, there is a general description of the procedures used in these measurements.

The information and data contained herein have been obtained from many photometric tests of sources at NBS. Although this appendix deals specifically with photometry of emergency warning lights, the techniques and equipment mentioned are also adaptable to the photometry of other kinds of light units.

12.2. Equipment

12.2.1. Ranges

100 Meter Range

The 100 meter range is located in the basement of the NBS Metrology Building. The photosensor and standard lamp for calibrating it are mounted on a movable "photometer bar", shown in Figs. 12.2.1-1 and 12.2.1-2. By moving the photometer bar, a maximum distance of 100 meters can be obtained between the unit under test and the photosensor. The standard lamp can be moved in and out of the calibration position by remote control.

Test units are mounted on a goniometer, a device which can rotate the unit through known angles about a horizontal and a vertical axis. The test unit can then be set at a given angle with respect to one axis, and when photometric measurements are made, a traverse can be taken at this angle by rotating the goniometer about the other axis, thus obtaining an intensity distribution.

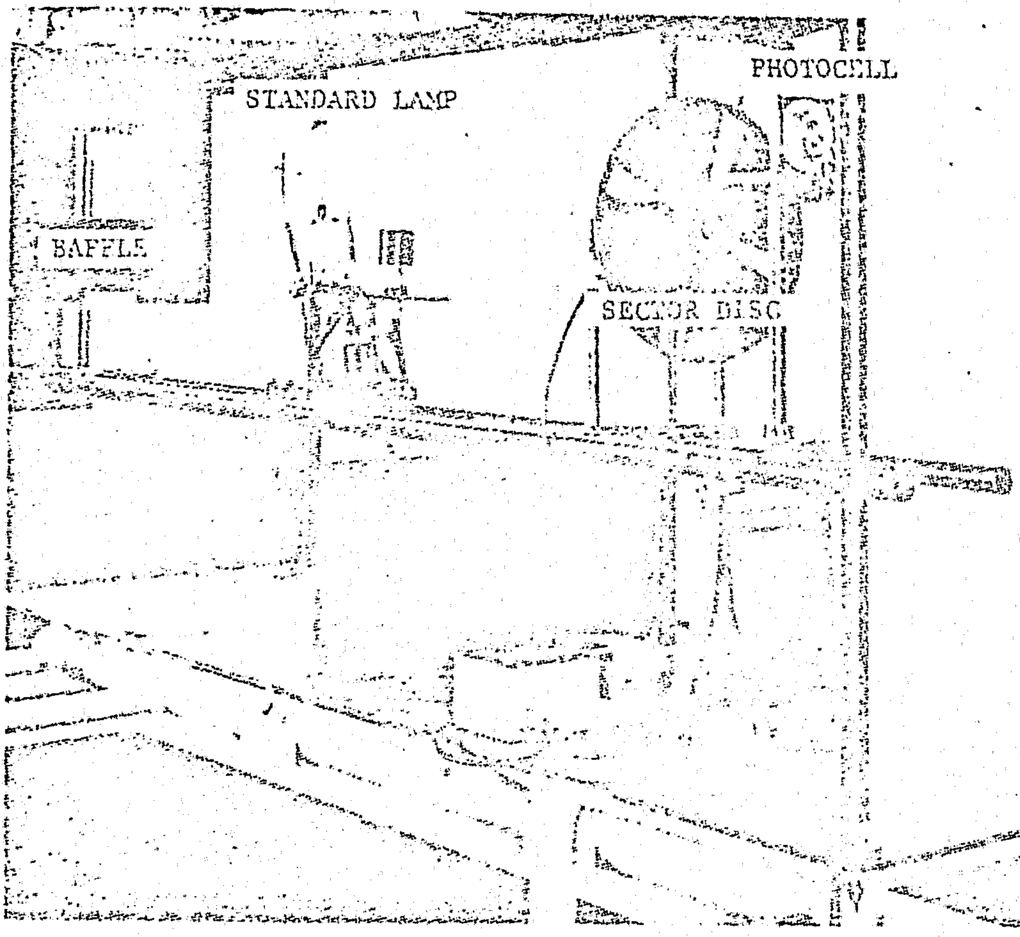


Figure 12.2.1-1. The Photometer Bar of the NBS 100-meter Range which can be utilized for photometric testing of emergency warning lights. Mounted on the bar is the equipment used in calibrating; however the shielding for stray light between the standard lamp and the photocell has been removed and a white background has been substituted for the normally black one.

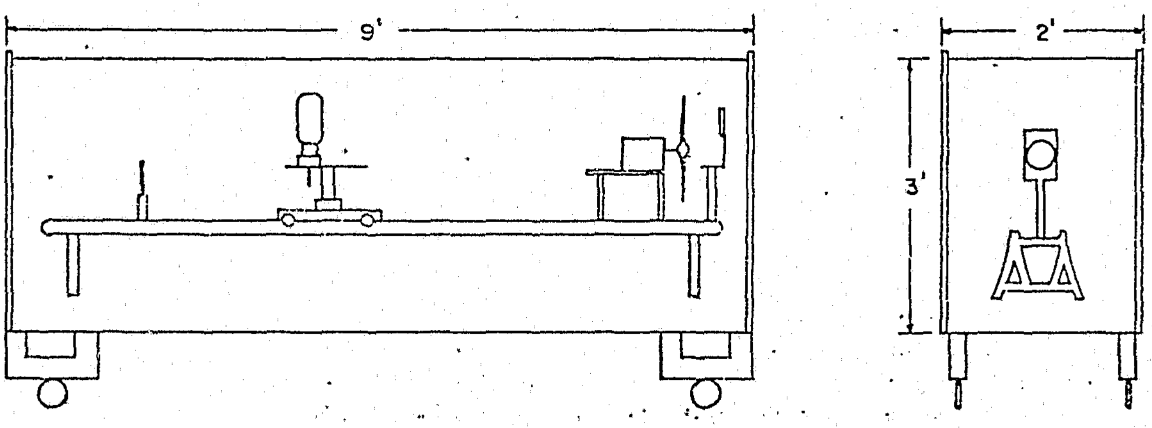


Figure 12.2.1-2. Dimensional diagram of the photometer bar in the NBS 100-meter Range. This bar supports the photosensor, and the standard lamp for calibrating it, which can be used to measure the output of emergency warning lights.

The goniometer which is located at one end of the 100-meter range is shown in Fig. 12.2.1-3. Units mounted on it can be rotated about a horizontal axis through two pivot points on the U-shaped inner frame. There are two rotary tables for horizontal traverses which permit the goniometer to be used as either a class A or class B goniometer as described by Projector (1953). The inner table on which the test unit is mounted is used almost exclusively, however. This table provides rotations about a secondary axis corresponding to the vertical, perpendicular to the horizontal axis which in this case is fixed. When the goniometer is operated in this manner, it is a class A goniometer.

Horizontal traverses obtained by rotating the larger table on which the outer frame is mounted result in rotations about a fixed vertical axis. When the goniometer is operated in this manner, it is a class B goniometer.

The goniometer is gear-driven in the horizontal and vertical directions and is usually turned by means of synchronous motors. When a self-balancing recording potentiometer is used to record the output of the photosensor, the recorder chart of the potentiometer is driven by another synchronous motor which is powered from the same source as is the goniometer motor. Gear ratios for the recorder and the goniometer can be varied to make available several choices of speed of rotation and chart speed, and hence provide a range of angular scales (degrees per division) on the chart.

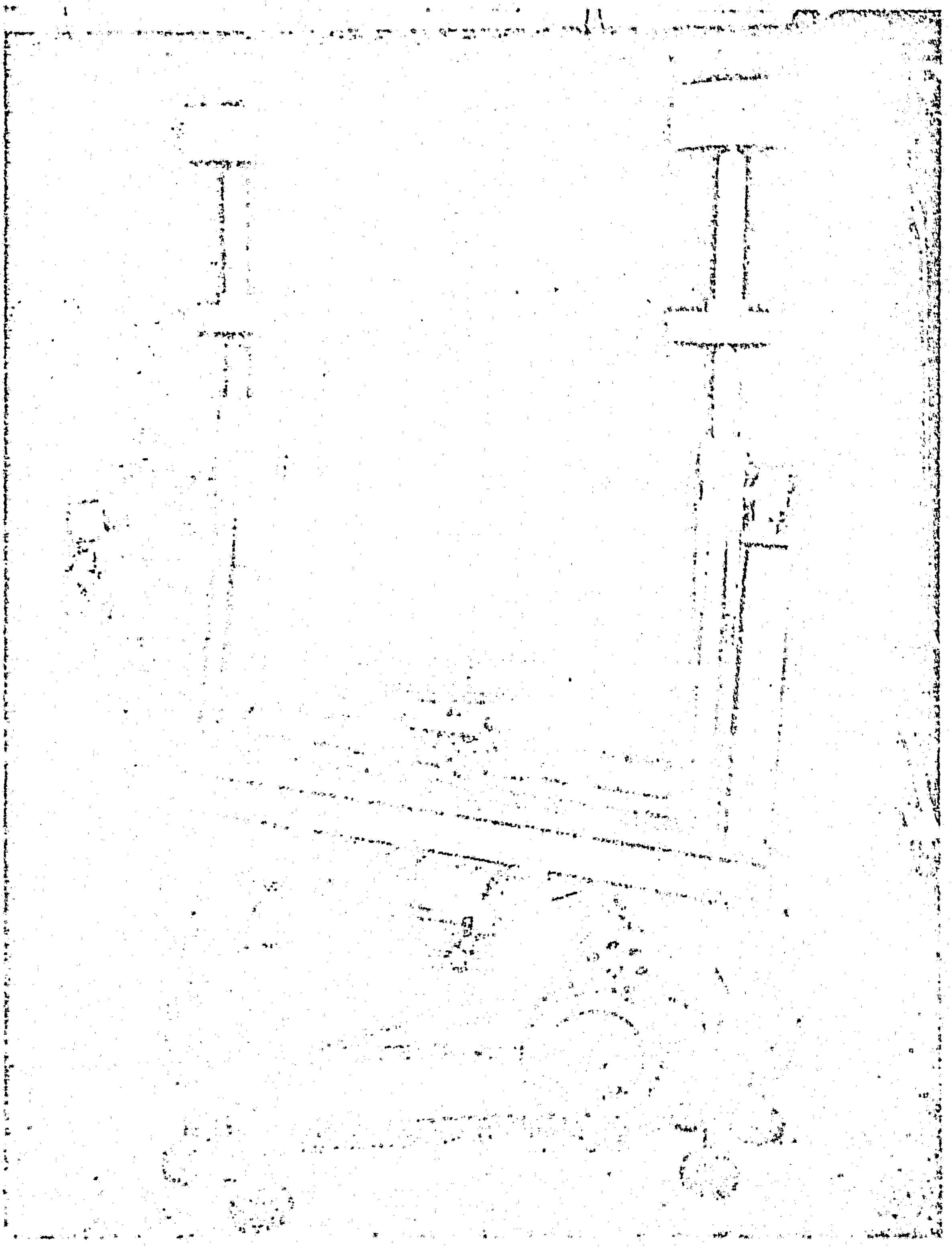


Figure 12.2.1-3. The Goniometer of the NBS 100-meter Photometry Range. This unit can be utilized to rotate an emergency warning light through known angles about a horizontal and vertical axis, to enable determination of the angular variation of light intensity.

One source of error in goniometry is the backlash of the driving gears. For horizontal traverses, the errors caused by backlash are minimized by running traverses in only one direction. In the vertical direction, backlash can result from inconstant torque and from the goniometer cradle passing through a balance position in the course of the traverse. To minimize these effects, with the test unit mounted on the goniometer the pinion gear on the vertical drive is disengaged, and the inner frame is balanced by means of the counterweights at the top of the goniometer. After this balancing, a constant torque is applied by means of a small weight at the end of a cable, which passes over a pulley connected to the vertical drive shaft (Projector, 1953). The pulley and weight are seen to the left of the goniometer (Fig. 12.2.1-3).

In order to minimize the errors caused by stray light from spurious reflections, the photometer bar is provided with a series of baffles. One of these baffles is seen in Fig. 12.2.1-1. In addition, there are adjustable baffles situated along the range between the goniometer and the photometer bar. The walls behind and around the goniometer and the background of the photometer bar are black. Additionally, there is a black curtain behind the goniometer that is pulled across when testing revolving or double-ended lamps.

The minimum test distance in photometry of these sources is called the "minimum inverse-square distance" (Illuminating Engineering Society, 1972, p. 4-23). The illumination from the light source, measured at distances greater than this minimum, obeys the inverse-square law which is a necessary criterion for the determination of luminous intensity. The photometric distance is made greater than this minimum distance. The minimum inverse-square distance is determined by the type and size of the light source, lens, reflector, etc., and must be considered individually for each unit. If this distance is more than 100 meters (approximately 328 feet), the 100-meter range cannot be used.

The photometry of a searchlight with a finite sized light source and emitting a collimated beam is illustrated schematically in Fig. 12.2.1-4. For this light source, the angle subtended by the optic (reflector) of the searchlight at the photosensor must be less than the angle subtended at the point on the reflector farthest from the light source by the smallest projected dimension of the light source. If the reflector is viewed through a telescope at the position of the photosensor, the reflector will then appear bright over all the aperture.

From these considerations, the minimum inverse-square distance, L_o, is given by

$$L_o = \frac{ad}{6s}, \qquad (12.2.1\text{-}1)$$

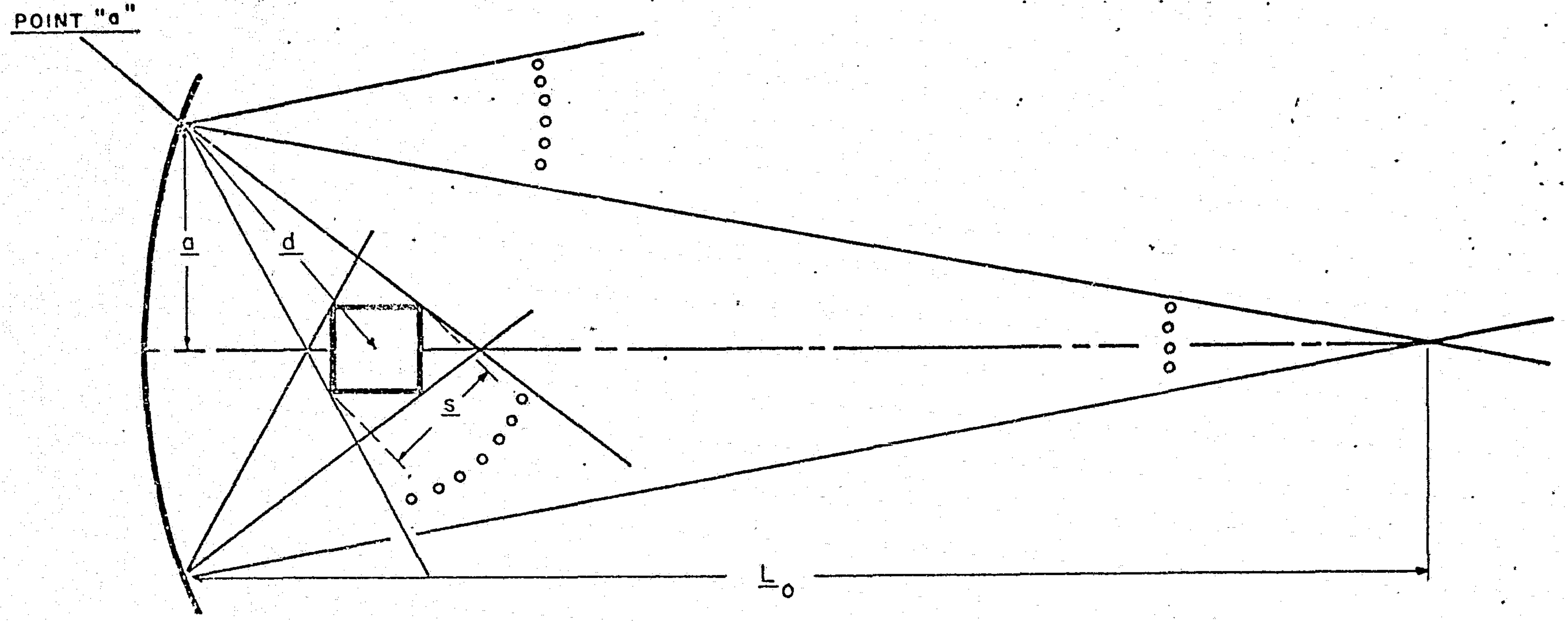


Figure 12.2.1-4. Diagram for the determination of the "Minimum inverse square distance"- The dotted lines subtend equal angles. This diagram assists in determining how far one must be from an emergency warning light in order to make measurements of light intensity which can confidently be extrapolated to still longer distances.

where $\underline{L_o}$ is the minimum inverse-square distance (in feet),

$\underline{a}$ is the distance from the point on the reflector that is farthest from the light source to the axis of the searchlight (in inches),

$\underline{d}$ is the distance from the light source to point "$\underline{a}$" (in inches),

and $\underline{s}$ is the smallest projected dimension of the light source as viewed from point "$\underline{a}$" (in inches).

If all lengths in the formula had been expressed in the same units, there would have been a factor of 2 in the numerator. The factor 6 in the denominator of Eq. (12.2.1-1) results from dividing 2 by 12, the number of inches in a foot.

To illustrate, these considerations may be applied to the photometry of two different sealed reflector lamps of the PAR-64 type, one with a 300 watt, 6.6 ampere (45 volt) filament, and the other with a 120 watt, 20 ampere (6 volt) filament. These lamps have the same overall dimensions and differ only in the size and construction of the filaments. Both lamps have clear covers and parabolic reflectors, and both emit collimated beams of light. For both lamps, the dimension $\underline{a}$ is 3.7 inches and the dimension $\underline{d}$ is 3.8 inches.

The filament of the 300 watt lamp is of the CC-6 type. That is, the filament wire is wound in a helix, and the helix is again wound into a larger helix. The axis of the larger helix is perpendicular to the axis of the reflector. The smaller helix is wound so tightly that its diameter can be considered the smallest dimension of the light source, and its projected dimension, dimension $\underline{s}$, is this diameter, 0.033 inch. $\underline{L_o}$ is therefore 70 feet, which permits the lamp to be photometrically measured on the 100 meter range.

The filament of the 120 watt lamp is the C-6 type. The filament wire is wound into a single helix. This helix is wound so loosely that the single turns of the coil can be discerned. Therefore, the diameter of the filament wire itself, 0.020 inch, is considered its smallest projected dimension. $\underline{L}_o$ is 120 feet, and on this basis this lamp also could be tested on the 100 meter range.

The above discussion for the determination of the minimum inverse square distance is exact only for axial measurements. For measurements off the axis, test distances of two or three times these computed minimum inverse square distance are sometimes required but are often impractical. Measurements near the axis are usually the most important in the testing of these sources; test distances only slightly greater than the computed minimum inverse square distances are necessary for most practical purposes (Walsh, 1953, Chapter XIV).

363 Meter Range

As discussed above, a longer range may be required where the device to be tested has a broad source. Larger lights are usually tested on the 363 meter range. The detector and standard lamp are located in the attic of the Polymers Building. The goniometer, recording potentiometer and all electrical controls are located in the attic of the Chemistry Building. The distance between the photocell and the goniometer is fixed at 363 meters (approximately 1191 feet).

12.2.2. PAR Lampholder

A special holder for PAR-type lamps is used to facilitate the mounting of lamps of this type. The holder has been designed to be mounted easily on the goniometer on the 100 meter range and is shown in Fig. 12.2.2-1. A set of removable mounting rings makes it possible to mount any of the several sizes of PAR lamps on the holder.

The holder contains a telescope which is used to align the holder with a mark at the other end of the range so that the axis of the PAR lamp reflector will coincide with the photometric axis. It is therefore possible to remove the holder from the goniometer and to replace it at some future time, aligned as before.

12.2.3. Photosensors

The photosensors used in the photometric measurements are constant current devices which produce currents proportional to the illuminance on their faces. All photosensors used are color corrected by means of optical filters in order to make their spectral response similar to the CIE spectral luminous efficiency function. Two different types of photosensors are in general use, the barrier layer photocell and the vacuum phototube. Although photomultiplier tubes have a higher signal-to-noise ratio at low illuminance levels and a fast photo-optical response, the present detectors are superior, on balance, within their limits of operation. This superiority is based on a combination of stability, simplicity of power supply circuitry, and relative ease of correcting their color response to correspond closely to the CIE luminous efficiency function.

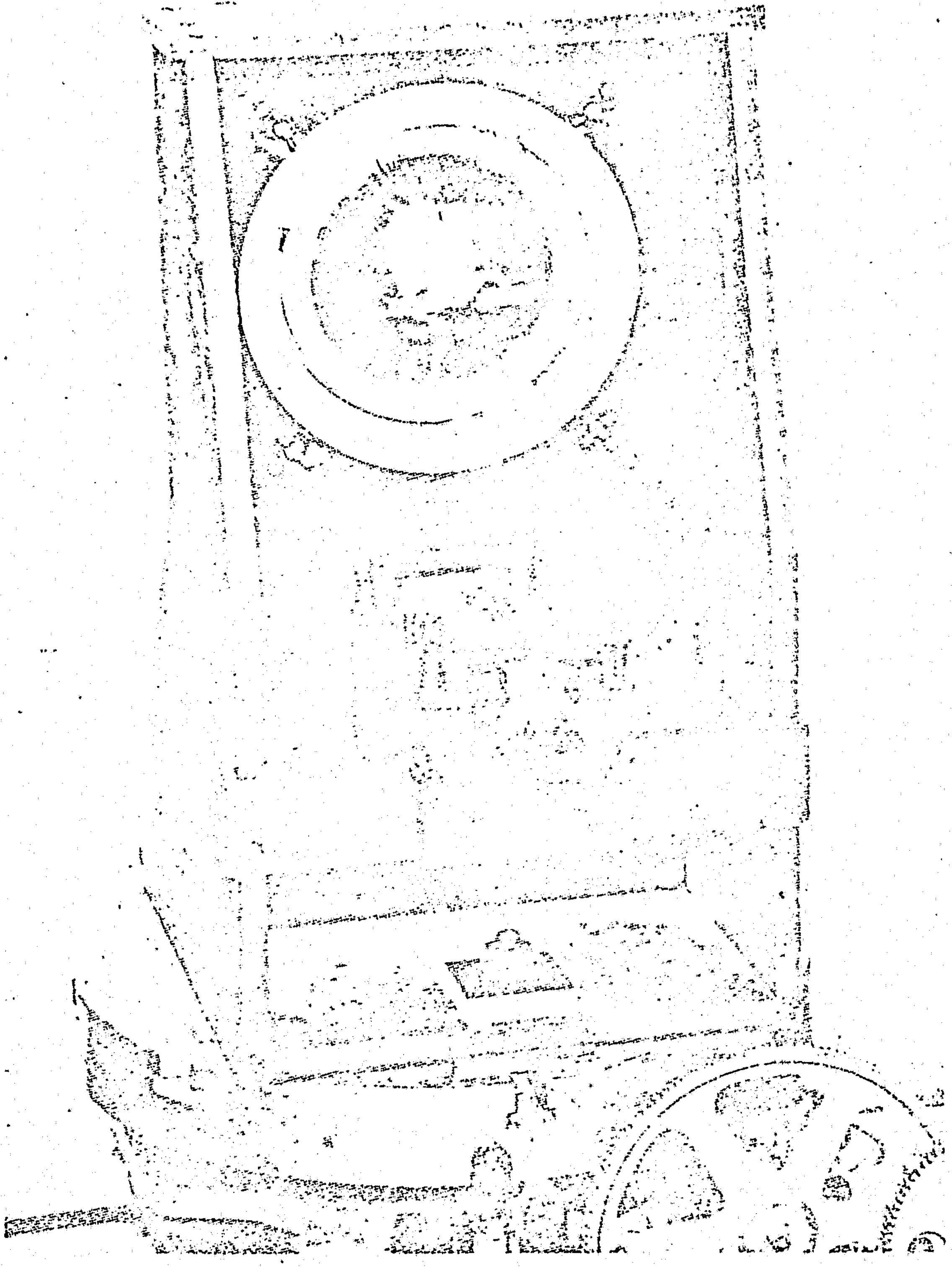


Figure 12.2.2-1. A rear view of the PAR Lamp Holder used to facilitate mounting of PAR-type lamps for testing in the NBS 100-meter Photometry Range. Seen are the telescope for aligning, the mounting ring, and the back of a PAR-56 lamp which has been mounted on the holder.

CONTINUED

3 OF 4

Barrier Layer Photocell

The barrier layer photocell, a solid state photoelectric device, is used in most of the photometric measurements. In the selection of a photocell for photometric testing, several cells which have been color corrected by means of color-correcting filters are checked for linearity and similarity of spectral response to the CIE luminous efficiency function. In order to check the adequacy of the color correction, the luminous transmittance of several colored filters for light of a specified color temperature is measured with these photocells. These measurements are compared with transmittances determined from spectrophotometric measurements. The results of one such series of measurements, using a lamp operating at Source A (color temperature 2854 K)* are given in Table 12.2.3-1.

The photocells with good color response are then tested for linearity, and the one most nearly linear in its response is selected for use. The response of the photocell being used at present, cell number 3 of Table 12.2.3-1 was found to be linear to better than 0.1% in the most useful range. This is sufficiently linear for photometric testing. The linearity was tested using several standard lamps of known horizontal intensity in turn at distances from 1 to 30 meters from the photocell. The results of the linearity measurements of this photocell are shown in Fig. 12.2.3-1.

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*Since these measurements were made, Source A has been redefined to have a color temperature closer to 2856 K.

Table 12.2.3-1. Color Response of a Group of Barrier-Layer Photocells with Filters

Color	Filter Characteristics for Source A			Transmittance Ratio #					
	x*	y**	T***	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Red	.725	.275	.0410	1.17	1.04	1.00	1.20	1.13	.98
"	.687	.313	.222	1.07	1.00	1.00	1.07	1.05	1.03
"	.648	.351	.324	.97	.95	.94	.94	.96	.94
Yellow	.630	.370	.427	1.02	1.00	.99	1.02	1.01	1.00
"	.578	.421	.612	1.02	1.01	1.01	1.02	1.01	1.01
"	.554	.444	.725	.97	.97	.97	.97	.96	.95
Green	.233	.679	.0370	.98	.98	1.01	.96	.94	.96
"	.310	.573	.201	.97	.97	1.00	.96	.94	.96
"	.350	.450	.409	1.00	1.01	1.02	1.00	.99	1.00
Blue	.160	.080	.020	1.01	.98	.99	.95	.96	1.00
"	.162	.293	.140	.90	.90	.92	.87	.88	.97
"	.320	.329	.250	.87	.88	.88	.88	.87	.87

Ratio of transmittance measured by photocell to transmittance determined from spectrophotometric measurements

* x-coordinate on the CIE chromaticity diagram

** y-coordinate on the CIE chromaticity diagram

*** Luminous transmittance of the filter as determined by spectrophotometric measurements

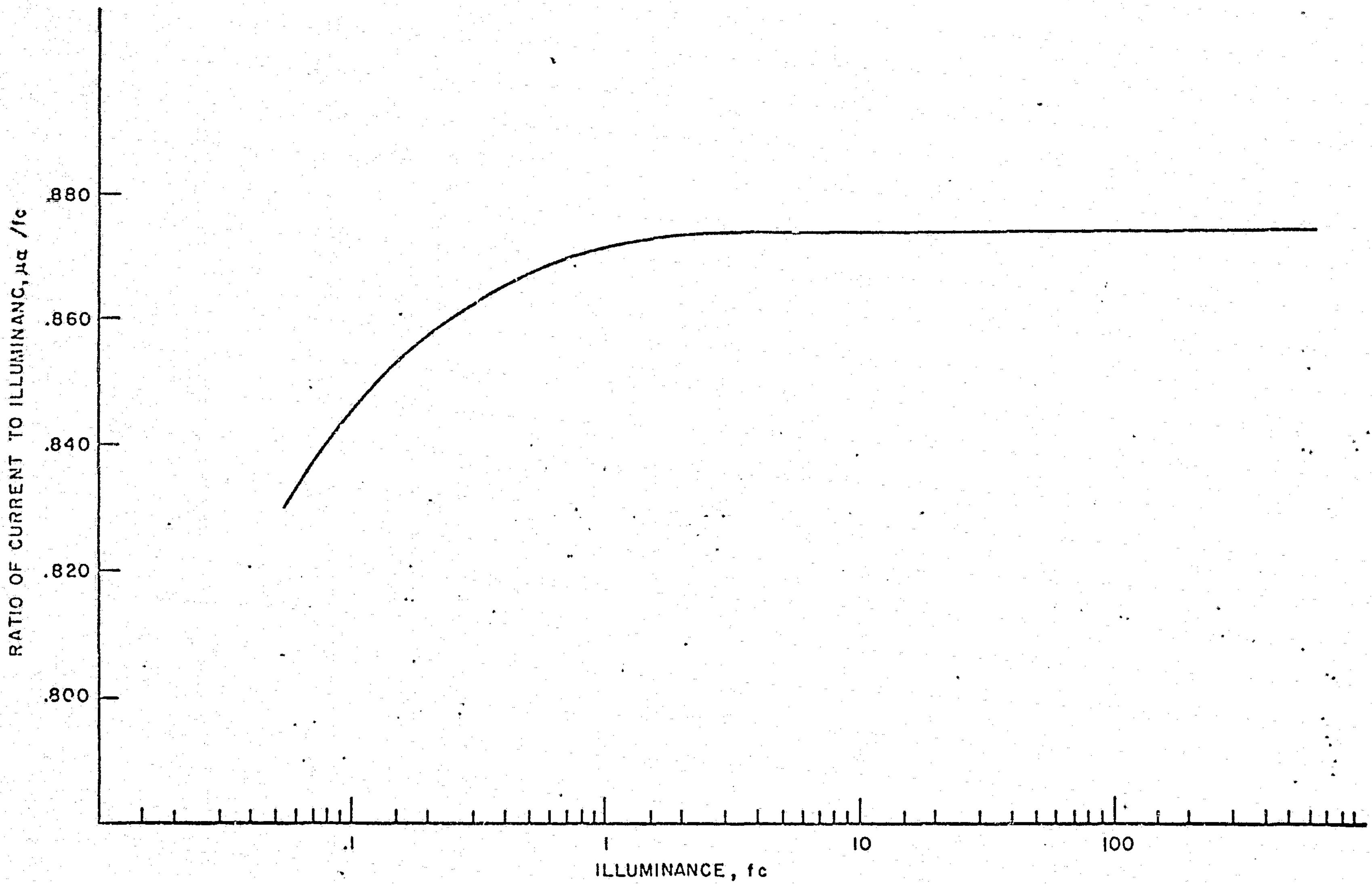

Figure 12.2.3-1. Linearity of response for a selected barrier-layer photocell of the type used as a detector in photometric testing of many types of lights. Note -- Voltage drop across photocell did not exceed 1 millivolt.

The barrier-layer photocell is used with two different circuits. For most photometric work with this type photocell, an external shunt is used. The voltage drop across the shunt is amplified by means of a linear amplifier, and the output of the amplifier is recorded on the recorder chart of a self-balancing potentiometer. This circuit is shown in Fig. 12.2.3-2. However, when greater precision is required in the measurements, or when the illumination of the face of the photocell is either very large or very small, a "zero resistance" circuit is employed, and intensity measurements are made using a Kohlrausch potentiometer (Barbrow, 1940; Projector, Laufer, and Douglas, 1944).

Vacuum Phototube

For flashing lights of short flash duration such as gaseous discharge lights, and for lights of very low intensity, a G.E. type PJ-14B vacuum phototube is used (Douglas, 1958). In the photometry of flashing lights, it is desirable to compute the effective intensity of the flash, which is determined from a measurement of the average intensity of the flash. The effective intensity of a flashing light is equal to the intensity of a steady-burning light of the same color which will produce the same visual effect under identical conditions of observation (Douglas and Freund, 1959).

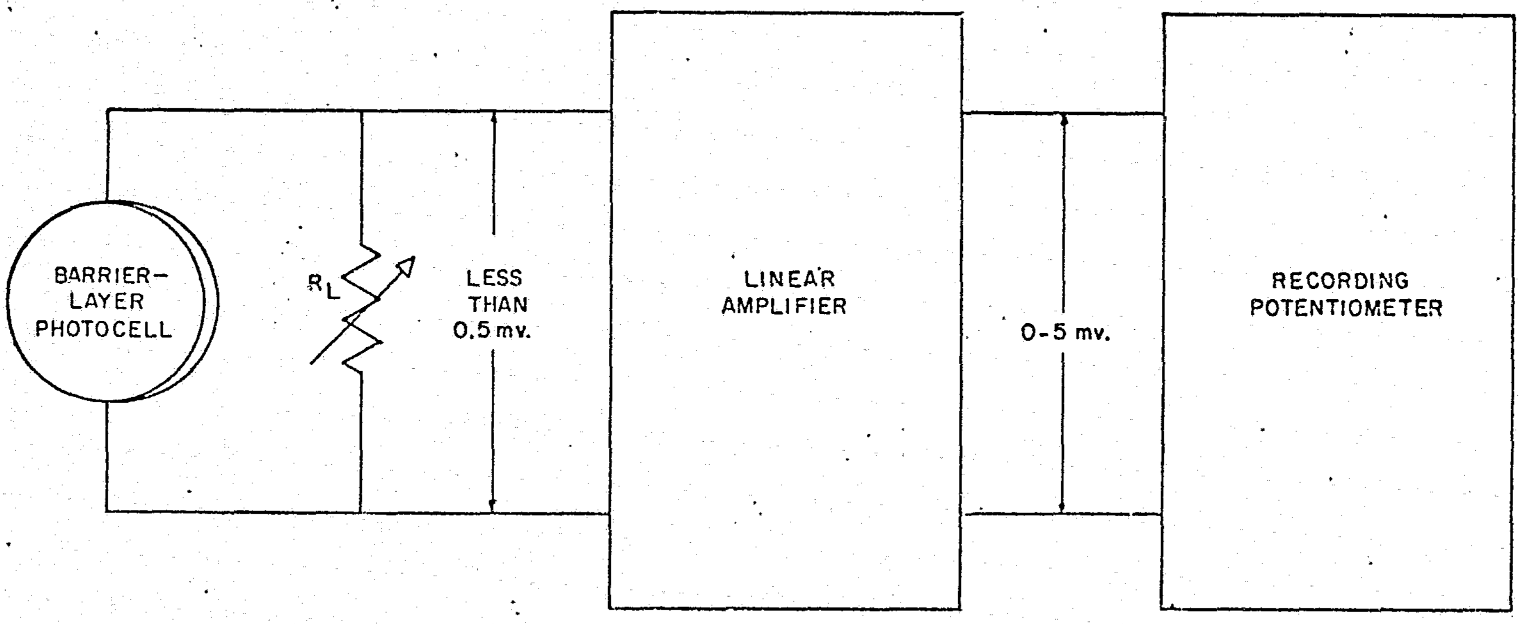

Figure 12.2.3-2. Block diagram of a barrier-layer photometer such as that used for measuring the output of many types of lights.

12.3. Calibration of the Photometric System

12.3.1. Introduction

Lamp standards of luminous intensity are used to calibrate the photometric testing equipment. A separate calibration is made before each test, and a record is kept of the photometer sensitivity in order to detect any irregularities. The illumination of the photosensor produced by the standard lamp is adjusted to some typical value of the illumination produced by the test light, usually in the range of 75% to 100% of the peak illumination produced by the test light. This procedure minimizes errors resulting from nonlinearity of the response of the photosensor. The adjustment of the illumination of the standard lamp on the photosensor is accomplished by varying the distance of the standard lamp from the photocell and by using optical attenuators. The photometer is usually calibrated so that it is direct reading in luminous intensity.

12.3.2. Standard Lamps

The standard lamps used are "working standards" whose luminous intensity in a given direction has been determined at a given voltage. Standard lamps are available ranging in intensity from about 8 to 900 candles. When a colored light is being tested, a filter is placed between the standard lamp and the photosensor, which results in a standard lamp-filter combination having approximately the same spectral characteristics as those of the light to be tested. This procedure minimizes errors resulting from inadequate spectral correction of the photosensor. In this procedure, a standard lamp of known color temperature as well as of known luminous intensity is needed.

12.3.3. Attenuators

Sector disks are almost always used for light attenuation, although neutral filters are also available. A sector disk is usually placed between the standard lamp and the photosensor to calibrate the photometer for the proper range of illumination. However, when the intensity of the light being photometrically measured is unusually high, the sector disk may be used to attenuate the illumination from the test light. The range of sector disks available is from 1% to 80% transmittance.

When a sector disk is used, it is placed within a few inches of the photocell in order to reduce error from stray light. The disk is rotated at a few hundred revolutions per minute, which is fast enough to minimize error from apparent flicker. When a high illumination is attenuated by a sector disk of low transmittance, there is an error which results from only one part of the photocell being illuminated at a time; this error is successfully eliminated by placing a condenser of about 4 mfd. across the output of the photocell. (In utilizing this technique, one must be careful to obtain a capacitor which does not itself generate an emf.)

12.3.4. Calibration Procedure

The calibration involves illuminating the photosensor with light from a standard lamp placed at a given distance from the photosensor, and then adjusting the sensitivity of the photometric system to some desired value.

If i is the photosensor current,

I is the intensity of the light illuminating the photosensor,

and D is the distance from the test unit to the photosensor,

then, since the photosensor produces a current proportional to the illuminance on its face,

$$i = kI/D^2 \qquad (12.3.4\text{-}1)$$

where k is the sensitivity of the photosensor.

It is usually convenient to calibrate the photometer to be direct reading, so that

$$I = N\delta, \qquad (12.3.4\text{-}2)$$

where δ is the reading of the potentiometer of the measuring circuit, and where N is an integral power of 10 or the product of an integer, usually 2 or 5, and an integral power of 10.

The photometer is then calibrated with a standard lamp of known horizontal luminous intensity. If

I_s is the luminous intensity of the standard lamp,

D_s is the distance of the standard lamp from the photosensor,

δ_s is the potentiometer reading,

and i_s is the photosensor current when the photosensor is illuminated by light from the standard lamp placed at the distance D_s from the photosensor, then

$$i_s = k\, I_s/{D_s}^2; \qquad (12.3.4\text{-}3)$$

and since the potentiometer reading is proportional to the photosensor current,

$$i_s/\delta_s = i/\delta. \qquad (12.3.4\text{-}4)$$

Combining Eqs. (12.3.4-1) through (12.3.4-4) yields

$$\delta_s = I_s D^2/ND_s^{\,2}. \qquad (12.3.4\text{-}5)$$

Calibration is accomplished by the following procedure: I_s and D_s are chosen so that $I_s/D_s^{\,2}$ will be approximately equal to I/D^2, where I is some typical value of the intensity of the light to be tested. A suitable value of N is then selected. Calibration to make the photometer direct reading is completed by one of the three following procedures, depending on the photometer circuit used.

a. External Shunt Circuit

A diagram of this circuit is shown in Fig. 12.2.3-2. In this circuit

$$\delta_s = \frac{R_L SKI_s}{D_s^{\,2}}, \qquad (12.3.4\text{-}6)$$

where S is the sensitivity of the photometer circuit and R_L is the resistance of the shunt.

Calibration, therefore, requires that, with the photocell illuminated by light from the standard lamp, the external shunt resistance is set so that the potentiometer indicates the values δ_s given in Eq. (12.3.4-5). The other parameters of the calibration are usually chosen so that the shunt resistance will be of the order of a few ohms. This order of resistance is used as it is large enough to be set accurately, and small enough so that the voltage developed across the photocell will not cause the photocell to respond nonlinearly. The practice is to maintain the sensitivity of the recorder at a fixed value of 5 millivolts for full-scale deflection. The sensitivity of the preamplifier is therefore set so that this recorder sensitivity and desired range of resistance may be used.

b. Phototube with Electrometer Amplifier Circuit

The procedure for calibration is the same as that for procedure a. The load resistor on the phototube and the controls of the amplifier are adjusted for the optimum performance range of the amplifier. Also, the output of the amplifier should not exceed 5 milliamperes. Hence, other parameters are adjusted so that $\underline{R}_L$ is greater than 1 ohm and is less than 5 ohms.

c. Zero-Resistance Circuit

In this circuit, if the photometer is balanced so that no current flows through the galvanometer, then

$$i = i_a a/r_x, \tag{12.3.4-7}$$

where

$\underline{i}$ is the photocell current,

$\underline{i}_a$ is the current through the slidewire between O and A,

$\underline{a}$ is the resistance of the slidewire between O and A,

and $\underline{r}_x$ is the resistance of the resistor, r_x.

Equation (12.3.4-7) is an approximation which depends on i_a being much greater than i. In practice, i_a is kept at about 10 milliamperes, and the range of i is from 1 to 20 microamperes. If i is 20 microamperes, the error resulting from the use of this approximation will be 0.3%. For larger values of i, a correction in the calibration can be made (Douglas, 1958).

Assuming the slidewire is graduated from 0 to 100, the reading of the indicator of the slidewire is graduated from 0 to 100, the reading of the indicator of the slidewire is

$$\delta = a/a_o, \qquad (12.3.4\text{-}8)$$

where a_o is the total resistance of the slidewire.

Then, combing Eqs. (12.3.4-1), (12.3.4-7), and (12.3.4-8) gives

$$\delta = \frac{r_x kI}{i_a a_o D^2} \qquad (12.3.4\text{-}9)$$

In the calibration of the zero-resistance circuit, i_a is usually kept constant and r_x is varied.

When the photocell is illuminated by light from the standard lamp, r_x is adjusted to obtain a zero reading of the galvanometer when the slidewire is set at the value δ_s of Eq. (12.3.4-5) for a given test distance, D. With the photometer thus calibrated, the intensity of the test light is given by Eq. (12.3.4-2).

d. Special Procedures

While photometric data are usually presented for a test light operating under a particular "design" (reference) condition, photometry of the test light under operating conditions other than the design condition is often desirable. Equation (12.3.4-5) can be generalized, taking into account this special condition as well as the transmittance of any filters or sector disks used in calibrating, so that

$$\delta_s = Y_c \, Y_s \, F I_s \, \frac{D^2}{N D_s^2} \,, \qquad (12.3.4\text{-}10)$$

where $\underline{Y}_c$ is the transmittance of the color filter at the color temperature of the standard lamp, $\underline{Y}_s$ is the transmittance of the sector disk, and $\underline{F}$ is the ratio of the output of the light under test when it is operated under the design condition to the output of the light when it is operated under test conditions. This ratio may be, for example, the ratio of the rated lumen output of the test lamp to the output of the lamp at the test voltage. It also may be the ratio of the intensity in a given direction at the operating voltage to the intensity in this direction at the test voltage.

For lights which are flashed in service but on which photometric measurements are made with the light burning steadily at a selected voltage, the factor $\underline{F}$ is the ratio of the effective intensity of the flash in a given direction to the steady intensity at the selected voltage in this direction of view.

12.4. Testing Procedures

The photometer is calibrated as described above (Section 12.3.4, Calibration Procedure) to an illuminance range determined by the intensity of the light being tested, the test distance and the information desired. The test unit is mounted on the goniometer and is aligned. The angular settings of the goniometer are adjusted so that the origin of the goniometer settings will correspond to the desired axis. This axis usually is chosen with respect to either the seat plane of the unit or some characteristic of the beam such as its peak.

The baffling for stray light is put into place. The eye is placed in the position normally occupied by the photosensor. Examination can then be made to insure that the baffling is properly placed so that no obstructions exist between the light and the photosensor and that reflections from the walls, floor, and ceiling of the range are intercepted before they reach the photosensor.

If a sealed-reflector lamp is being measured photometrically, the lamp is usually operated at either rated voltage or rated current. Other lamps, such as those used in combination with an optical system, are usually operated at or corrected to rated lumen output. Power for the test and standard lamps is usually obtained from storage batteries, which are periodically recharged. Voltage and current are measured on a potentiometer, and photometric measurements are not made until the lamp has reached stability.

If the goniometer is to be motor driven, the gear ratios are chosen so that the traverse will be slow enough to insure the accurate recording of the characteristics of the light.

13. GLOSSARY

Note: a word enclosed in asterisks in these definitions, as *intensity*, is itself defined elsewhere within this glossary (or a different grammatical form, identical to the asterisked word except for the ending, is so defined). For unfamiliar words not defined within the glossary, see an ordinary dictionary.

<u>absolute threshold</u>: for any perceptual variable corresponding to the quantity of some stimulus variable, the smallest amount of the stimulus variable that can just barely be detected by an observer under optimum conditions, including no background. In signal-detection terms, the smallest signal that can just barely be distinguished from a background containing no signal and no external noise.

<u>adaptation</u>: the process whereby an observer's sensory system adjusts to a new pattern of stimulation, tending toward a new steady state.

<u>adaptation level</u>: the level of stimulation, in a particular sensory or perceptual dimension, to which an observer is currently *adapted*.

<u>adequate stimulus</u>: a stimulus or class of stimuli capable of generating a perception within a particular sensory system of an observer who is paying attention, under a specified set of conditions. Frequently used in the psychological literature in the misleading sense of the class of stimuli that are ordinarily thought of as adequate. For example, light is

referred to as "the adequate stimulus" for vision, even though electricity and pressure can also lead to visual perceptions under the proper conditions. In this usage, the term 'appropriate stimulus' would be better.

alpha rhythm: a component of the brain's electrical wave activity, having a frequency of 9-12 Hz. It is most prominent when the eyes are closed.

anomalous trichromat: a person whose color vision contains the normal three dimensions of variation, but whose detailed color sensitivity deviates significantly from normal.

attention-attracting power: synonym for *'conspicuity'*.

Bartley effect: *brightness enhancement*. The effect was not discovered by Bartley, but has been extensively investigated by him. The discovery is generally credited to Brücke, and the phenomenon is sometimes also known as the Brücke-Bartley effect or the Brücke effect.

Blondel-Rey-Douglas formula: a widely used formula for *effective intensity*, given in this report as Eq. (10.6-4).

brightness: attribute of visual sensation according to which an area appears to emit more or less light (*CIE* definition). Brightness is a subjective measure referring to the perceived amount of light. This concept is called *"luminosity"* in English-speaking countries other than the U.S.A. The "emission" of light may involve light generated directly by a self-luminous body, or light from another source being reflected from or transmitted through the surface in question. Not the same concept as *lightness*. Should also not be confused with "photometric brightness," an obsolete synonym for *"luminance"*.

brightness enhancement: the phenomenon of a flashing light, over a certain range of frequencies (2-20 Hz), appearing brighter than the same light shone steadily.

candela: the internationally recognized (*SI*) unit of *luminous* *intensity*. Formerly called the "candle" in the United States. Abbreviated cd.

CFF: abbreviation for *'critical flicker frequency'* or *'critical fusion frequency'*.

choice reaction time: synonym for *'disjunctive reaction time'*.

chromatic: "colored" (in the popular sense); having *hue*; non-neutral; having *saturation* greater than zero. Refers to the aspects of perceived *color* other than *brightness* (or *lightness*), namely *hue* and *saturation*. All colors not seen as white, gray, or black are chromatic.

CIE: abbreviation for 'Commission Internationale de L'Éclairage', the official name for the International Commission on Illumination, which sets international standards in the fields of light and color.

color: [This term has two different usages that should be carefully distinguished, as follows.]

color (perceived): those aspects of a visual perception not related to space (size, shape, position, texture) or time (motion, flicker, sparkle, changes in size or shape); *hue*, *saturation*, and *brightness* (or *lightness*) taken together; the perceptual response to a patch of light determined by the *spectral power distribution* of the light. In the popular application of the term 'color' in perception, the intensitive dimension (*brightness* or *lightness*) is not included; only *hue* and *saturation* are considered. The technical use of the term, however, includes all three dimensions, so that a change in only the brightness of a light is said to be a change in the (perceived) color. Note also that white, gray, and black are perceived colors ("neutral" or "achromatic" colors); whereas color perceptions involving *saturation* greater than zero (that is, perceptions having some *hue*) are designated *"chromatic"*. Where the context is clear, color perceptions may be referred to simply as "colors".

color (psychophysical): the aspect of a patch of light, determined by the *spectral power distribution*, that leads to a color perception. In technical usage, this is what is meant by the unmodified word 'color'. Two *spectral power distributions* that would be seen to match in perceived color by the "standard observer" (as represented by the *CIE* *color-matching functions*) are defined as having the same color; that is, color is measured by the *tristimulus values*. Note that color is a function only of the *spectral power distribution* associated with the light patch in question, but the color perception associated with that light depends also on the colors of all the other light patches present in the visual field at the time of viewing, and for some time before. (Example: two pieces of the same yellow paper have the same color, but if one is viewed against a vivid red background and the other against a vivid green background, the perceived colors will be different, the former piece appearing greenish yellow and the latter orangish yellow.) The technical usage of 'color' in the psychophysical sense, like the usage of 'color' in the perceptual sense, differs from ordinary usage in encompassing the third, intensitive dimension. Hence the *luminous* *intensity*, *luminance*, receiving-surface *illuminance*, *luminous* *reflectance*, or *luminous* *transmittance* (depending on the type of colored object) are part of the color.

color-blind: having some defect of color perception. Embraces *monochromats*, *dichromats*, and *anomalous trichromats*. The term 'blind' is not to be taken literally; a more accurate name is "color-defective".

color-matching functions: a set of three weighting functions, which, when applied to the *spectral power distribution* of a light, generate a numerical specification (*tristimulus values*) of the *color* of the light. Since objects of the same *color* generate the same color perceptions, provided they are viewed under fully equivalent conditions, these functions can be thought of as constituting a specification of which *spectral power distributions* are seen as matching by the observer for which the functions hold.

color-mixture functions: synonym for *'color-matching functions'*.

complex reaction time: *reaction time* measured in a complex situation involving different responses to a variety of different stimuli, the presence of distracting stimuli, and randomization of the place as well as the time of appearance of the stimuli. The phrase was used by Gerathewohl (1953, 1957), and is not a standard term in the literature of reaction time.

cones: one of two classes of light-sensitive receptor cells in the eye. The cone system mediates "day" vision, including color, and, in the central *fovea*, where there are only cones, vision for fine details is extremely good. (The other class of *photoreceptor* cell is the *rods*.)

conspicuity: the ability of a signal to attract attention or be noticed, relative to a specific background and a specific condition of the observer (*"set"*).

cortex: specifically, the cerebral cortex, the outer shell of the brain in which higher functions of thought, memory, perception, and motor patterning take place.

critical duration: with reference to seeing, the integration time of the visual system; the time interval within which no temporal changes in a visual stimulus can be distinguished. Below the critical duration, the total energy contained in a light flash determines its perceptibility; above the critical duration, longer exposure does not improve perceptibility, the controlling variable being the *intensity* (or *luminance*) alone.

critical flicker frequency: the flash rate at which a repetitively flashing light makes the transition from appearing to flicker to appearing to be steady. When distinguished from *'critical fusion frequency'*, the highest flash rate at which flicker can just barely be detected according to some criterion. If the criterion is detectability of flicker 50% of the time, and the same criterion is used for the *critical fusion frequency*, the concepts become synonymous.

critical fusion frequency: usually, a synonym for *'critical flicker frequency'*. When distinguished from *critical flicker frequency*, the lowest flash rate at which a flickering light is seen as steady, according to some criterion.

deuteranomalous: with respect to a person, afflicted with *deuteranomaly*; with respect to color perceptions or responses, characteristic of *deuteranomaly*.

deuteranomaly: a form of defective *trichromatic* color vision characterized by some tendency to confuse red, green, and yellow colors; partial *"green-blindness"*. The most common form of color defect.

deuteranope: a person affincted with *deuteranopia*.

deuteranopia: a form of *dichromatic* color vision characterized by an absence of red or green *hue* perceptions and a *luminous efficiency* function that is normal or slightly low in the green and blue wavelength range; *"green-blindness"*.

deuteranopic: with respect to a person, afflicted with *deuteranopia*; with respect to color perceptions or responses, characteristic of *deuteranopia*.

dichromat: a person affected with *dichromatism*.

dichromatic: with respect to a person, afflicted with *dichromatism*; with respect to color perceptions or responses, characteristic of *dichromatism*.

dichromatism: a form of defective color vision in which the normal three dimensions of color variation are reduced to two. As a consequence of the collapse of the third color dimension, there exist series of colors such that a color normal sees a continuous range of color variation from one end of the series to the other, but *dichromats* see all the colors in the series as being the same. There are at least three distinct types of dichromatism -- *protanopia*, *deuteranopia*, and *tritanopia* -- and each type is characterized by different series of colors that are abnormally perceived as the same.

differential threshold: the amount of change in stimulation, in any sensory or perceptual dimension, necessary for an observer to just barely notice a difference from the original stimulus.

discrimination: ability to distinguish between stimuli.

discriminative reaction time: frequently, a synonym for *'disjunctive reaction time'*. Sometimes used in the more restrictive sense of a *disjunctive reaction time* for which one of the responses is "no response". (Example: "press the button when the red light comes on; do not respond when the green light comes on.")

disjunctive reaction time: *reaction time* in a situation in which there is more than one category of stimulus, and different responses are required to stimuli in different categories. (Example: "press the left button when the red light comes on, and the right button when the green light comes on.")

distribution coefficients: obsolete synonym for *'color-matching functions'*.

duty cycle: a specification of the pattern of "on" or "high-level" periods and "off" or "low-level" periods in any repetitive process in which some device is operated intermittently or is repetitively changed from a "higher" to a "lower" condition and back. With respect to cyclically flashing lights, the term is frequently used as a synonym for *'light-dark ratio'* or *'light-time fraction'*.

effective color: the apparent *color* of a flashing light, as measured by a *color* match with a steady light. A generalization (introduced in this report) of the concept of *"effective intensity"*.

effective intensity: the apparent *luminous* *intensity* of a flashing light, as measured by the *intensity* of a steady white light seen as equally bright when viewed at the same distance, or having the same "visual range" (distance of view at which the *brightness* of the light reaches *threshold*). Sometimes used in the more restricted sense of effective intensity as calculated by some particular formula, usually the *Blondel-Rey-Douglas formula* [Eq. (10.6-4) of this report]. Although viewing distance and viewing conditions (background, atmospheric clarity, knowledge of the direction in which faint lights are located) enter into the operational measurement of effective intensity, it should be noted that *intensity*, whether effective or actual, is a property of the light source and is not a function of how the source is being viewed or where it is located.

effective luminous power: the apparent *luminous* power (*flux*) delivered by a flashing light within the area of a specified surface or within the *solid angle* of a specified conical beam, as measured by the *luminous* *flux* similarly delivered by a steady white light at the same location that is seen as equally bright or that has the same "visual range" (distance of view at which the *brightness* of the light reaches *threshold*). Sometimes used in the more restricted sense of effective luminous power as calculated through the use of some particular formula, usually the *Blondel-Rey-Douglas formula* for *effective intensity* [Eq. (10.6-4) of this report] or its analog stated directly in terms of *flux* rather than *intensity*. One may be concerned with the *luminous* power (effective or actual) emitted by a source, in which case it is a property of the source and independent of viewing distance; or with the power from the source passing through a specific external surface or *solid angle*, in which case it is a property of a light beam and, in general, depends both on the source and on the distance from the source to the receiving surface. There are theoretically (but not actually) some special situations, such as a beam with its rays precisely parallel ("collimated"), in which the distance variable does not affect the delivered *flux*.

<u>effective retinal illuminance</u>: the apparent *illuminance* of an observer's *retina* produced by a flashing light, as measured by the *retinal* *illuminance* produced by a steady white light at the same location seen as equally bright or having the same "visual range" (distance of view at which the *brightness* of the light reaches *threshold*). Sometimes used in the more restricted sense of effective retinal illuminance as calculated through the use of some particular formula, usually the *Blondel-Rey-Douglas formula* for *effective intensity* [Eq. (10.6-4) of this report] or its analog stated directly in terms of *illuminance* rather than *intensity*. The *illuminance* (effective or actual) of a given observer's *retina* produced by a source is not a property of the source, but of the beam of light by means of which the observer sees the source. The *illuminance* depends both on the source and, in general, on the distance from the source to the observer (although distance may not be a factor for special kinds of beams). For viewing

against a fixed background, *retinal* *illuminance* (effective or actual) is the variable largely determining how bright a light appears. Therefore, when effective retinal illuminance is measured by means of a *brightness* match to a steady white light, the distance of the steady light from the observer is, to a first approximation, irrelevant. However, the *retinal* *illuminance* supplied by the steady light would normally be calculated from its *intensity* (it being very difficult to directly measure light inside the eye), so the distance of the light from the observer, whatever it is, must be known. In order to allow for secondary effects such as the influence of *visual angle* on perceived *brightness* (for fixed *retinal* *illuminance*), it is simplest to place the fixed light at the same distance from the observer as the flashing light.

<u>effective tristimulus values</u>: the *tristimulus values* of the steady light determining the *effective color* of a flashing light. Can be used in the more restricted sense of the effective tristimulus values as calculated by some particular formulas, such as the tristimulus-value generalizations of the *Blondel-Rey-Douglas formula* for *effective intensity* [Eq. (10.6-4) of this report]. The concept and formulas [Eqs. (6.3-1)] were introduced in this report.

effectiveness: in the context of this report, the degree to which a signal achieves its desired purpose, such as alerting a driver that an emergency vehicle is approaching. Note that the adjective 'effective' in the five preceding definitions does not connote effectiveness in this sense, but in the sense of equivalence with respect to simple visibility.

efficacy: see *'luminous efficacy'*.

extended source: a source of light large enough to appear, at a specified viewing distance, as an area rather than a point. Sometimes used in the sense of a source of light large enough so that the *illuminance* of a receiving surface, moved toward and away from the source from a reference position located at a specified distance from the source, departs significantly (by some specified percentage) from the *illuminance* that would be predicted by treating the source as a *point source* and applying the *inverse square law*.

feedback: information regarding the effect on any ongoing process of an action ("input") taken with the intent of affecting the course of the process. The desired effect is frequently to maintain the final step ("output") of the process within specified bounds of acceptability.

feedback loop: the chain of steps involved in using the *feedback* from an input action to affect the nature of future inputs. The loop is continuous if both the generation of the feedback information and the process by which the feedback is used to modify the input are continuous in time (either can be discrete).

filter: with respect to the control of light, a light-transmitting object (such as a sheet of glass or plastic) used to modify the *color* of a light, either the *intensity* alone (in which case the filter is called "neutral"), or the *chromatic* aspect and the *intensity* together. (The *chromatic* quality of a light cannot be modified without some reduction in *intensity* by passing the light through a filter, unless the filter is fluorescent.)

fixate: to gaze at as steadily as possible.

flux: synonym for 'power'; energy per unit time. Used in the context of this report specifically in reference to power in the form of light. Flux may be either *radiant* or *luminous*. The *CIE* symbol for flux is $\underline{\Phi}$. The *SI* unit of *radiant* flux is the watt (abbreviated W) and of *luminous* flux is the *lumen* (abbreviated lm).

fovea: the central area of the *retina*; the portion of the *retina* on which the image of an object is focused when the observer is looking directly at the object. The fovea is located in a depression or pit in the surface of the *retina*, and its diameter subtends approximately the central 5° of the visual field. The most central 1° or 2° of the fovea contains only *cones*.

fusion: the disappearance of the sensation of flicker as a flashing light is flashed at faster and faster rates; the condition of the appearance of a flashing light as steady.

green-blind: an inexact and obsolete synonym for *'deuteranopic'*.

hertz (Hz): a synonym for 'cycle per second'; the internationally accepted (*SI*) unit of frequency.

hue: the perceptual dimension of *color* that varies most obviously with changes in the wavelength of spectrally pure (single-wavelength) lights; that aspect of *color* that is described by terms such as 'red', 'yellow', 'green', 'blue', etc.

illuminance: a measure of the visually effective amount of light falling on a surface; more strictly, the *luminous* *flux* (power) striking the surface per unit area. The *CIE* symbol for illuminance is E. The *SI* unit of illuminance is the *lux* (abbreviated lx).

inadequate stimulus: a stimulus or class of stimuli not capable of generating a perception within a particular sensory system of an observer who is paying attention, under a specified set of conditions. Frequently used in the psychological literature in the highly misleading sense of the class of stimuli that are in fact *adequate*, but which are not ordinarily thought of as *adequate*. For example, a blow on the eyeball is referred to as "an inadequate stimulus" for vision when it causes "stars" to be seen. In this usage, the term 'inappropriate stimulus' would be better.

intensity: a measure of the light output from an object that is being treated as a *point source*. Strictly, the amount of light *flux* (power) being emitted per unit *solid angle* within an infinitesimal conical beam with its apex at the source and its axis in a specified direction; the solid-angular density of light *flux* in a given direction. Reference may be made to either *radiant* or *luminous* intensity. The *SI* unit of radiant intensity is watt per *steradian*, and of luminous intensity is the *candela*. The *CIE* symbol for intensity is I.

inverse square law: the law that the *illuminance* of a surface produced by a *point source* of light decreases as the square of the distance between the source and the surface; that is, the *illuminance* is inversely proportional to the second power (square) of the distance.

lamp: as used by specialists in illumination, a bulb containing a source of light. This usage contradicts the nontechnical meaning, which uses 'bulb' for this purpose and reserves 'lamp' for the fixture containing the bulb.

light-dark ratio: for a cyclically repeating flashing light, the ratio of the amount of time during one cycle that the light is on, to the amount of time it is off. Symbolized in this report by a. The light-dark ratio ranges from 0 for a light that is always off, through 1 for a light that is on as much of the time as it is off, up to "infinity" (arbitrarily large values) for a light that is always on.

light-dark symmetry: for a cyclically repeating flashing light, a measure (defined in this report) indicating the degree of approach to equality, within one cycle, of the time on and the time off. Symbolized in this report by c, and defined as 4b(1-b), where b is the *light-time fraction*. The value of the light-dark symmetry ranges from 0 for a light that is either always on or always off, up to a maximum of 1 for a light that is on half the time and off half the time.

lightness: a perceptual variable correlating with the apparent *reflectance* of an object reflecting light, or the apparent *transmittance* of an object transmitting light. Lightness involves a perception of the prevailing illumination and of the degree to which the surface in question seems to be reflecting or transmitting that illumination. It is a property of the surface or body. *Brightness*, on the other hand, is a perception of the amount of light leaving the surface, without consideration of the original source of the light. The surface of a brilliantly illuminated piece of coal can be perceived as being simultaneously of low lightness and high brightness.

light-time fraction: for a cyclically repeating flashing light, the fraction of the time in a single cycle during which the light is on. Symbolized in this report as b. The light-time fraction ranges from 0 for a light that is always off, through 1/2 for a light that is on as much time as it is off, up to a maximum of 1 for a light that is always on.

lumen: the *SI* unit of *luminous* *flux*. Abbreviated lm. It is formally defined as the *luminous* *flux* emitted by a uniform *point source* of 1 *candela* into a *solid angle* of 1 *steradian*.

luminance: the measure of visually effective light output most commonly appropriate for an *extended source*. It specifies the output at a given point of the source surface in a given direction of view, and includes light reflected from, transmitted through, and emitted by, the surface.

Formally, it is defined as the *luminous* *flux* per unit *solid angle* per unit projected area of the source, the projection being onto a plane perpendicular to the given direction. The *CIE* symbol for luminance is L, and the *SI* unit is the *candela* per square meter (abbreviated cd/m^2), also known as the nit (abbreviated nt).

The fact that luminance has units equivalent to *luminous* *intensity* per unit area suggests an intuitively understandable operational meaning of the term: the luminance, in a given direction, of a uniform extended surface is measured by backing off in the given direction until the surface is far enough away to be effectively a *point source*; measuring the *luminous* *intensity* of this *point source*; and dividing the *intensity* by the area of the source as seen from along the given direction line (that is, the area projected onto a plane perpendicular to the direction line). The luminance of an *extended source* is thus the equivalent *luminous* *intensity* of the source when it is seen as a point, divided by the actual extended area of the source, corrected for the direction of view. For a non-uniform extended source, the luminance at a given point in a given direction is defined as the limiting value of the luminance (as just defined) of a small element of area surrounding the point, as the area of the element approaches zero.

luminosity: an obsolete synonym for *'luminous efficiency'*. The word is also used in Britain to mean the same thing as the American term *'brightness'*.

luminous: weighted by the *luminous efficiency* function; referring to the visual, as opposed to physical, effect. Contrasts with *'radiant'*. The word can modify names of quantities related to light emission, such as *'intensity'*. The symbol used by the *CIE* to distinguish the luminous quantity from the corresponding radiant or generic quantity is a subscript v. Thus *luminous* *intensity* is denoted I_v, although simply I may be used where the context is clear.

luminous efficacy: with respect to any light-producing device, the ratio of the amount of *luminous* *flux* (power) emitted to the amount of electrical power fed in. It is a measure of the efficiency with which the electrical energy is converted into visually effective (*luminous*) light energy, and was formerly known as "luminous efficiency", a term that now has another meaning. The *SI* unit of luminous efficacy is the *lumen* per watt (lm/W). The term 'luminous efficacy' also has another, related meaning (not used in this report), applying to a beam of light. In that case, it refers to the ratio of the *luminous* *flux* in the beam to the *radiant* *flux* in the beam, and is a measure of the efficiency of the radiant energy in the light beam in producing a visual (*luminous*) effect. The units of this kind of luminous efficacy are also lumens per watt. In general, the term 'efficiency' is now restricted to dimensionless quantities derived by taking the ratio of a dimensioned quantity to its maximum possible value, or the ratio of a dimensioned quantity representing the output of a conversion process to the similarly dimensioned quantity representing the input. 'Efficacy', on the other hand, is applied to the ratio of quantities representing in <u>different</u> units the output and input of a conversion process. Thus it is proper to refer to the efficiency with which a light source converts electrical power into radiant (light) power (both measured in watts); but the conversion of electrical power measured in watts into *luminous* *flux* (power) measured in *lumens* is a matter of efficacy. The value of efficiency is independent of the (common) unit of measurement, but the value of efficacy varies with the particular units used both for the input and the output.

<u>luminous efficiency</u>: the sensitivity of the eye to light of a given wavelength, relative to the maximum sensitivity at any wavelength (taken as unity). It is a dimensionless quantity. The luminous efficiency function is the weighting function used for converting *radiant* quantities specified *spectrally* to the corresponding *luminous* quantities. (Multiplication of the final sum by a constant is usually necessary.) Two luminous efficiency functions are standardized (by the *CIE*): the *photopic* function, having its peak at 555 *nm* and representing sensitivity under conditions of "day" vision; and the *scotopic* function, having its peak at 507 *nm* and representing sensitivity under conditions of "night" vision.

<u>lux</u>: the *SI* unit of *illuminance*. It is equal to one *lumen* per square meter (lm/m^2). Abbreviated lx.

<u>mesopic</u>: intermediate between *photopic* and *scotopic*. The mesopic *luminance* range is approximately 0.001 cd/m^2 to 10 cd/m^2.

<u>micrometer</u>: a millionth of a meter. Formerly known as a "micron". Not to be confused with the name of the tool used for precise length measurements. The names are spelled the same, but the word for the length unit is accented on the first syllable and pronounced with the <u>o</u> and first <u>e</u> long, whereas the word for the tool is accented on the second syllable and pronounced with the <u>o</u> and first <u>e</u> short. Abbreviated µm, the Greek letter µ (mu) denoting "micro" and having the meaning "one millionth". One µm is approximately equal to 39.37 millionths of an inch (the exact number being 100/2.54).

<u>micron</u>: obsolete synonym for *'micrometer'*. The old abbreviation was µ, a symbol now used only as a prefix attached to the name of other units.

<u>millisecond</u>: one thousandth of a second. The *SI* abbreviation is ms (m denoting "milli" and having the meaning "one thousandth"), but msec is still frequently seen.

monochromat: a person having color vision with only one dimension of variation, as opposed to the normal three. Monochromats can perceive only light-dark differences ("shades of gray") and are insensitive to both *hue* and *saturation*. They can match any two lights, regardless of *spectral* composition, by an intensity adjustment only. The vision of a monochromat can be thought of as bearing the same relationship to normal vision as a black and white television image bears to a color television image.

monochromatic: characteristic of the perceptions or responses of a *monochromat*. With respect to a person, possessing such vision. A person with monochromatic vision is sometimes inexactly referred to as being "totally color-blind".

nanometer: a billionth of a meter (10^{-9} m). Abbreviated nm. Formerly known as a "millimicron" ($m\mu$). One nm is approximately equal to 39.37 billionths of an inch (the exact number being 100/2.54).

negative flashes: brief darkenings of a light that is otherwise steadily on. The dark phases of an *occulting* light.

noticeability: a synonym for *'conspicuity'*. The ease with which a signal can be noticed.

occulting: characterized by momentary darkenings of an otherwise steadily burning light; *negatively flashing*.

on-off ratio: synonym for *'light-dark ratio'*.

perceptual insistence: a less widely used synonym for *'conspicuity'*.

period: with respect to a repetitive (cyclical) process, the interval of time between corresponding moments of two successive cycles of the process. When the process consists of repeated occurrences of a discrete, almost instantaneous event (such as a brief light flash), the period is the time elapsing between successive occurrences of the event. The period is frequently ascribed to the physical object generating the cyclical process (as for example, a flashing light or a rotating motor), instead of (or in addition to) the process itself. Thus it is acceptable to speak of the period of a rotating beacon, as well as the period of the rotation. The period is the reciprocal of the frequency, so that the product of a period in seconds and the corresponding frequency in *hertz* is unity.

periphery: outer regions; areas outside the central region. Applies to the *retina* or to the perceived visual field.

phase: point within a repetitive cycle. _In phase_: at corresponding points of the respective cycles. _Out of phase (completely)_: at opposite points of the respective cycles. _Out of phase (partially)_: not in phase.

photic driving: enhancement of the *alpha rhythm* of an observer's brain by stimulating him with a light flashing at the characteristic alpha frequency. The result of photic driving is frequently unpleasant, the effects ranging from mild dizziness, nausea, or nervousness, to grand mal seizures in epileptics.

photopic: pertaining to levels of illumination high enough to activate the *cone* receptors of the *retina*. Photopic vision is sometimes known as "day vision". It is distinguished by the perception of color and of fine detail. Contrasts with *'scotopic'*. The *luminance* above which vision is fully photopic is approximately 10 cd/m^2.

photoreceptors: the light-sensitive cells in the eye that permit vision. The photoreceptors are part of a complex network of cells, the *retina*, that lines the back of the inside of the eye. There are two basic types of photoreceptors, *rods* and *cones*.

point source: a source of light having a maximum diameter that is small compared with the distance of the source from the receiving surface. The minimum ratio of distance to diameter necessary to characterize the source as a point source is not sharply defined, but depends on the specific application. A common criterion is for the ratio to be large enough so that the *inverse square law* holds, within some specified percentage tolerance. Visually, the criterion is often that the source should have no visible disc, but should appear as a point. Constrasts with *'extended source'*.

protanopia: a form of *dichromatic* color vision characterized by an absence of red or green *hue* perceptions and a *luminous efficiency* function that is abnormally low in the long (red) wavelength range; *"red-blindness"*.

protanopic: with respect to a person, afflicted with *protanopia*; with respect to color perceptions or responses, characteristic of *protanopia*.

protanomaly: a form of defective *trichromatic* color vision characterized by some tendency to confuse red, green, and yellow colors; partial *"red-blindness"*. In this condition, red colors appear abnormally dark. This loss of *luminous efficiency* (sensitivity) in the long-wavelength range is the characteristic that most sharply differentiates this defect from *deuteranomaly*.

protanope: a person afflicted with *protanopia*.

pulse-to-cycle fraction: synonym for *'light-time fraction'*. Usually abbreviated as PCF.

Purkinje shift: the shift in the *luminous efficiency* function of the human eye toward shorter wavelengths when the illumination drops from *photopic* to *scotopic* levels. The effect is to make the sensitivity of the eye to red light worse, in comparison to its sensitivity to blue and green light, as the illumination grows dim. The eye's peak sensitivity at *photopic* levels is at 555 *nm*, a yellowish green wavelength. At *scotopic* levels, the peak sensitivity is at 507 *nm*, a wavelength that is seen at *photopic* levels as green, with perhaps a slight touch of blue. At *scotopic* levels, of course, all wavelengths look approximately gray, since the *rods* mediate *monochromatic* ("totally color blind") perception. The shift effect was first described in 1823 by the Czech physiologist Purkinje.

radiant: referring to the physical energy of a light, unweighted by any function related to visual response. Contrasts with *'luminous'*. The word can modify names of quantities related to light emission, such as *'intensity'*. The symbol used by the *CIE* to distinguish the radiant quantity from the corresponding luminous or generic quantity is a subscript $\underline{e}$. Thus *radiant* *intensity* is denoted $\underline{I}_e$, although simply $\underline{I}$ may be used when the context is clear.

reaction time: the time elapsing between the occurrence of a signal and the completion of the appropriate response by an observer of the signal.

red-blind: an inexact synonym for *'protanopic'*.

reflectance: the ratio of light *flux* reflected from a surface to the *flux* incident on the surface; the fraction of the light returned by the surface. May be *radiant* or *luminous*, and also *spectral* or total. The range of reflectance is from zero (absolute black) to unity (total reflection).

relative luminous efficiency: an obsolete synonym for *'luminous efficiency'*.

retina: an extremely complex network of chiefly nerve cells that lines the inside of the back of the eye. The retina contains the *photoreceptor* cells, and is thus the actual sense organ for vision. The adjectival form is 'retinal'.

<u>rods</u>: one of two classes of light-sensitive receptor cells in the eye. (The other class of *photoreceptor* cell is the *cones*.) The rod system mediates "night" vision and can respond to lower levels of light than the *cone* system. The rods do not generate *chromatic* perceptions, and the ability of the rod system to pick up fine details in the visual scene is poor.

<u>saturation</u>: perceived purity or strength of a color; the perceived degree of difference between the color and the neutral color (white, gray, or black) of the same *brightness* or *lightness*. Saturated colors are referred to as "strong", "deep", "vivid", or "brilliant". Colors of low saturation ("unsaturated" colors) are called "pale", "pastel", "weak", or "whitish", "grayish", or "blackish". Colors with zero saturation are called "neutral", "achromatic", or "white", "gray", or "black". They are also sometimes referred to as "hueless", since a color is perceived as having a definite *hue* if, and only if, it is perceived as having saturation greater than zero.

scotopic: pertaining to levels of illumination not high enough to activate the *cone* receptors of the *retina*, but high enough to activate the *rods*. Scotopic vision is often known as "night vision". It is distinguished by no perception of color and poor perception of fine detail. Contrasts with *photopic*. The *luminance* below which vision is strictly scotopic is approximately 0.001 cd/m^2.

set: (psychology) -- the state of an observer at a given moment with respect to attitudes, expectations, readiness, attention, and other such internal factors that partly determine the nature and speed of the response to a stimulus. For example, in a *reaction time* experiment in which a button must be pushed when a light comes on, the experimental subject can take the "motor set", in which he concentrates on readiness to push the button, or the "sensory set", in which he concentrates on readiness to see the appearance of the light. The motor set usually leads to shorter reaction times.

SI: abbreviation for "Système International", the official name for the International System of Units. This system of units is the internationally approved system for use in science and technology. It is based on the old MKS (meter-kilogram-second) system.

simple reaction time: *reaction time* in which there is a single, specified stimulus, and a single, specified response, both known to the experimental subject in advance. In this case, reaction time is a minimum since the need for higher mental processes is minimal.

small-field tritanopia: the degradation of normal color vision toward the *dichromatic* form known as *tritanopia* when the field of view is small and located in the central *fovea*. The question of whether small-field tritanopia also exists in the *periphery* is still open. Low intensity or brief flashing of the stimulus also seems to cause normal vision to tend toward *tritanopia*, so small-field tritanopia may be only one aspect of a phenomenon associated with delivery of low total energy to the *retina*.

solid angle: the analog in three dimensions of the concept of angle in two dimensions. The solid angle *subtended* by an object at a point is measured by the fraction of the total area of a sphere, centered at the point, that is included within the projection, from the point onto the sphere, of the outline of the object. The solid angle is independent of the radius of the sphere. The *SI* unit of solid angle is the *steradian*. In plane geometry, the word 'angle' refers both to a geometrical figure (formed by two intersecting lines) and also to a measure of the degree of separation between the lines in such a figure. In solid geometry, it is rare to refer to "a solid angle" -- the geometrical figure -- and the concept defined above is the measure. The geometrical figure constituting "a solid angle" would be a conical surface with a cross-section of arbitrary shape. In the context of an object *subtending* a solid angle at a point, the conical surface is that traced out by the projection line with one end anchored at the reference point, and the other end sweeping around the space-curve forming the outline (border) of the given object as viewed from the reference point. The intersection of this conical surface with any sphere centered at the reference point constitutes the projection of the outline of the object onto the sphere.

<u>spectral</u>: defined for each wavelength within a specified wavelength range. The word is used to modify the name of either *radiant* or *luminous* quantities. In the latter case, the wavelength range referred to would be the visible spectrum, which extends from approximately 360 *nm* to 830 *nm*. (The range can be broader or narrower, depending on the purpose and the accuracy desired.)

<u>spectral power distribution</u>: a wavelength-by-wavelength specification of the output of a source in terms of any appropriate *radiant* measure, not necessarily simply the *radiant* *flux*. Also called "spectral energy distribution". The word "power" or "energy" in these phrases serves only to indicate that a *radiant*, as opposed to *luminous*, specification is meant (as for example, *radiant* *intensity*). Note that no power at all can be emitted in an infinitesimally narrow (zero-width) wavelength band, so that the quantity actually specified must be some radiant measure <u>per unit wavelength</u> (usually per *nm*)

of the emission band. Such specification is known as "spectral concentration" and actually constitutes a measure of the derivative of the "power" with respect to wavelength. The "spectral power distribution" of a*point-source*signal light may therefore be actually a specification of the spectral concentration of radiant intensity, measured in $W \cdot sr^{-1} \cdot nm^{-1}$.

spectral transmittance: fraction of the incident light *flux* transmitted by a body, specified on a wavelength-by-wavelength basis. Although total *transmittance* (integrated over a specified wavelength range) may be either *radiant* or *luminous*, there is no distinction between *radiant* and *luminous* spectral transmittance (since any weighting constant for a given wavelength would be applied both to the incident and transmitted flux, and would divide out when the ratio was taken).

steradian: the standard (*SI*) unit for specifying *solid angle*. One steradian is defined as the *solid angle* *subtended* at the center of a sphere of unit radius by a portion of the sphere having unit area (that is, an area of one square unit). Since the total area of a sphere of radius R is $4\pi R^2$, the total area of a sphere of unit radius is 4π square units. Hence a complete sphere contains 4π steradians and a hemisphere contains 2π steradians. Abbreviated sr.

subtend: (geometry) -- to cut off or intercept, said of one geometric figure with respect to another. A surface is said to subtend a *solid angle* at a point when there is consideration of the *solid angle* formed by sweeping the other end of a straight line, starting at the point, around the boundary of the surface. A line segment is said to subtend an ordinary planar angle at a point when there is consideration of the angle formed by joining the point to the ends of the segment by straight lines.

threshold: (psychology) -- the least perceptible amount of any physical, psychophysical, or psychological quantity, or of the change in any such quantity. These two concepts are referred to as *absolute* and *differential* thresholds, respectively. An example of an absolute threshold is the lowest *luminance* that can just barely be seen in an otherwise totally dark field. An example of a differential threshold is the amount of difference in wavelength that can just barely be seen in the comparison of two spectrally pure lights viewed side by side. There is some vagueness in the notion of "just barely perceptible", and the threshold point is usually defined statistically. A common definition is the amount of the quantity or change in quantity that will be perceived on 50% of the presentations in a long sequence of repeated presentations.

transmittance: the ratio of light *flux* transmitted through a body to the *flux* incident on the body; the fraction of the light that gets through the body. May be *radiant* or *luminous*, and also *spectral* or total. The range of transmittance is from zero (complete opacity) to unity (total transmission).

trichromat: a person whose vision is *trichromatic*. All color-normal people are trichromats, but not all trichromats are color-normal (since *anomalous trichromats* exist).

trichromatic: three-dimensional with respect to *color*. Normal color vision is trichromatic; that is, there are three independent aspects in which *color* perceptions can vary. One of the infinitely many possible specifications of these three dimensions is: *hue*, *saturation*, and *brightness* (or *lightness*); another is: amount of redness, amount of greenness, and amount of blueness. Some people (*anomalous trichromats*) have vision that is trichromatic but not normal.

trichromatism: *trichromatic* vision or the condition of possessing such vision.

<u>tristimulus values</u>: a set of three numbers that constitute a full specification of the *color* of an object or patch of light. The tristimulus values for a light are calculated by weighting the *spectral power distribution* of the light by each one of a set of three *color-matching functions*, and, for each function, totaling the products across the entire visible spectrum. The sums are (except for a possible constant factor) the tristimulus values. For most of the standard sets of *color-matching functions*, the tristimulus values can be interpreted approximately as amount of redness, amount of greenness, and amount of blueness. The tristimulus values associated with the 1931 *CIE* *color-matching functions* -- the most widely used standard -- are denoted <u>X</u>, <u>Y</u>, and <u>Z</u>. The <u>Y</u> tristimulus value, although an approximate indication of greenness in relation to the magnitudes of <u>X</u> (redness) and <u>Z</u> (blueness), is precisely equal to the *luminance* or *luminous* *intensity* of a light, or the *luminous* *reflectance* or *luminous* *transmittance* of an object. The tristimulus values are a good guide to the color a light or object will appear to have when seen alone against a dark background by a normal observer adapted to darkness, but in general the color perceived to belong to a patch of light or to an object is a function not only of its own color (tristimulus values), but also of the colors (tristimulus values) of other light patches or objects simultaneously present in the background or viewed in the very recent past by the observer.

tristimulus values of the spectrum: synonym for *'color-matching functions'*. When two or more lights are mixed together, the *tristimulus values* of the combination must be equal to the sum of the *tristimulus values* of the component lights, because of the way *tristimulus values* are calculated. Since any light can be thought of as composed of a mixture of single-wavelength lights, it follows that the values of the three *color-mixture functions* at any one wavelength can be interpreted as the tristimulus values of a pure light of that wavelength. The *radiant* intensities of the single-wavelength lights, which determine the absolute sizes of the *tristimulus values* at each wavelength, are taken equal all across the spectrum, in the standard *CIE* functions. (This is called an "equal-energy" spectrum.)

tritanomaly: a rare form of defective *trichromatic* color vision characterized by some tendency to confuse white and yellow, and also by some tendency to confuse certain shades of blue and green. Sometimes referred to as "partial blue-blindness".

tritanopia: a form of *dichromatic* color vision characterized by an absence of blue or yellow *hue* perceptions and a *luminous efficiency* function that may be slightly below normal in the shortwave (blue) region of the spectrum.

visibility: an obsolete synonym for *'luminous efficiency'*.

visual angle: the angle *subtended* by any object at the eye of an observer. Visual angle may be specified in terms of the *solid angle* *subtended* by the entire surface of the object, or, more commonly, by the planar (ordinary) angle *subtended* by the largest linear dimension of the object.

14. References

NOTE: Following each reference, in brackets, are the page numbers in this report on which the reference is cited. Pages on which the reference are cited twice are denoted by a prime (apostrophe) following the page number.

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