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INTERIM REPORT
PART II
LIGHT SOURCE EVALUATION

February 1970

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1. FACTORS AFFECTING THE PERFORMANCE OF PYROTECHNIC MIXTURES

The object of this study is to investigate the feasibility of utilizing high intense light emitted from rapidly burning pyrotechnic mixtures for optical incapacitation. Several mixtures have been selected for initial study. The compositions of these mixtures were itemized in a previous progress report.[1]

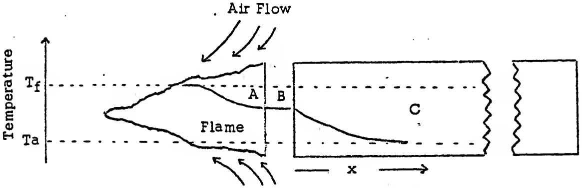
It is useful to review the mechanisms of pyrotechnic burning and the important factors, relevant to light emission, so as to fully understand the utility of this approach.

1.1 DESCRIPTION OF BURNING PROCESS

The basic ingredients of most pyrotechnic compositions consist of a fuel and an oxidizer. These ingredients should be stable under normal shelf conditions, yet they should be easy to ignite. Further, once ignition occurs, the heat released during burning should be sufficient to sustain the burning process.

It is useful to consider the following model to explain the burning behavior ~~of a pyrotechnic mixture.~~

Three thermal zones are established when an illuminating composition is ignited and burns propagatively (see Figure 1).



T_f = Flame Temperature
T_a = Ambient Temperature
x = Distance Below Burning Surface

Figure 1. Profile of Combustion Zone

Zone A is essentially the "burning surface". Both exothermic and endothermic reactions take place resulting in the formation of gaseous fuel and oxidizer intermediates. These intermediates react exothermically in the flame zone. Usually the pyrotechnic is designed to be fuel rich and the excess fuel reacts with oxygen from the atmosphere. In these cases the flame size and intensity are somewhat dependent upon the required environmental oxygen and its availability.

The energy required to form the reactive intermediates are generated by the exothermic reactions which occur in the flame zone and in Zone A. The dominant heat transport mechanisms are radiation feedback from the flame and conductive transport from condensed phase reactions which occur in Zone A. Energy from Zone A is also transferred to Zone B which may be considered the pre-ignition zone. Directly below Zone B is the remainder of the unreacted pyrotechnic composition, or Zone C.

The radiative heat transport from the flame to Zone A can be described mathematically by the Stefan-Boltzmann equation

$$I = \epsilon \sigma F (T_f^4 - T_o^4) \quad (1)$$

where I is in terms of energy per unit area per unit time (e.g., cals/ cm^2-sec), ϵ is the emissivity of the flame, σ is the Stefan-Boltzmann constant, F is a flame shape factor, T_f is the flame temperature and T_o is the temperature of the surface receiving the radiation.

The temperature in Zone A is further affected by the local endothermic and exothermic transitions which occur in forming the reactive intermediates. The important reactions which limit the burning rate of the pyrotechnic are the endothermic processes. Typically, these processes involve

a. phase changes, and

b. pyrolytic decomposition

to generate gaseous combustion reactants.

Under steady-state conditions the thin pre-ignition zone (i.e., Zone B) can be assumed to have a uniform temperature. For simple systems this zone has thicknesses in the molecular size range, and its temperature is governed almost completely by the endothermic processes taken place.

The temperature profile within the body of the pyrotechnic (i.e., Zone C) can be approximated by the Rosenthal equation[2]

$$T_x = T_a + (T_s - T_o) \exp(-vx/\alpha) \tag{2}$$

where T_x is the temperature at distance x below the reacting surface (Zone B), T_a is the ambient temperature, T_s is the temperature within Zone B, v is the burning rate, and α is the thermal diffusivity of the mixture: It should be noted that thermal diffusivity is related to more conventional thermal properties, i.e.,

$$\alpha = k/\rho c, \quad cm^2/sec \tag{3}$$

where k is the thermal conductivity, ρ is density and c is the specific heat.

1.2 FACTORS AFFECTING LIGHT OUTPUT

The distribution of radiation in any spectral region is determined by the chemical nature and physical state of the products which emit in that region, and the temperature reached by these emitting species. The rate at which a pyrotechnic mixture burns depends on the amount and rate at which heat is evolved. Sufficient heat must be produced to raise the temperature of the ingredients to a point at which an exothermic reaction will be initiated and the reaction rate must be sufficient to more than compensate for heat losses in order for the burning to be sustained. Mathematically, the burning rate, v, can be related to the energy fedback from the exothermic processes and the rate determining endothermic process which must occur to produce the reactive intermediates

$$v = \Sigma(I)/\rho\,(\Delta H + C\,\Delta T) \tag{4}$$

where $\Sigma(I)$ is the radiative, convective and conductive heat flux fedback to the pre-ignition zone, ΔH is the heat absorbed in the pre-ignition zone by the endothermic processes and $C\,\Delta T$ is the heat required to elevate the temperature of the pyrotechnic (i.e., at the boundary between Zones B and C) to the reaction temperature. The latter ($\rho C\,\Delta T$), can be best described as a heat loss term.

The rate of burning, the products formed, and the flame temperature are affected markedly by the composition of the mixture, as well as by the physical condition of the materials and the ambient conditions under which it is burned. Some of the more important factors which affect the performance of light producing pyrotechnics which were considered in our initial selection compositions are as follows,

1. heat of reaction

2. composition of emitters

3. particle size

4. consolidation

5. pyrotechnic diameter

6. container design

1.2.1 Heat of Reaction

The heat of a reaction is defined thermochemically as the difference between the thermodynamic heats of formation of the reactants and products of the reaction. For example, referring to the energy diagram shown in Figure 2, one selects a pyrotechnic mixture having substituents which have a higher heat of formation than the reaction products and one which requires a minimal amount of input energy, ΔH_a, to initiate burning.

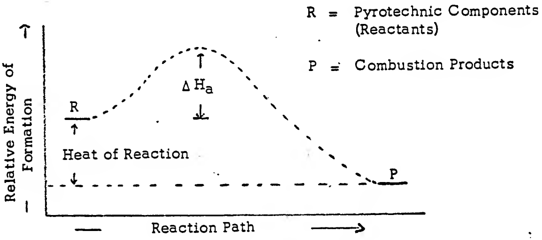


Figure 2. Reaction Energy Diagram

One of the important factors in determining the luminous intensity of a light-producing pyrotechnic device is the temperature reached by the emitting species in the flame and produced by the burning of the pyrotechnic mixture. The temperature reached depends, in turn, on the amount and rate at which energy is released by the reaction. Therefore, the energy released during combustion should be high and the products formed should be stable at the high temperatures necessary to produce the desired luminous intensity.

1.2.2 Desired Output Spectra

The ultimate pyrotechnic composition must emit intense light in regions most sensitive to the eye. It can be seen from the "standard observer curve", shown in Figure 3 that the eye is only sensitive to a very narrow region of electromagnetic radiation.

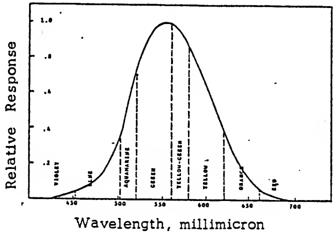


Figure 3. Standard Observer Curve

This region extends between approximately 400 to 700 mμ (or 4000 to 7000 Angstroms). In Figure 4, the visual response curve of the human eye is shown. In this figure the effective radiation, in terms of photometric units (lumens) as a function of wavelength is shown. The absolute photopic luminosity is defined as the ratio of the electromagnetic flux sensed by the eye (in units of lumens) to the total radiant flux (in terms of watts). The most sensitive region in this narrow spectrum lies between 500 and 560 mμ. Therefore, for effects related to visibility of the light source, the pyrotechnic mixtures should be designed to emit strongly in this wavelength region. A separate question arises as to whether optical incapacitation effects are similarly correlated over the visible range. This answer is not known at present but will be assumed to be positive for the present.

Special design features must be included in a pyrotechnic to insure that a significant fraction of the total radiation emitted by the flame is in the visible region. The emission from a pyrotechnic flame is composed of line spectra, band spectra and continuum. The latter is directly dependent on the temperature of the flame. The continuum is essentially blackbody or greybody radiation. The distribution of the radiant energy versus wavelength can be estimated from Planck's equation

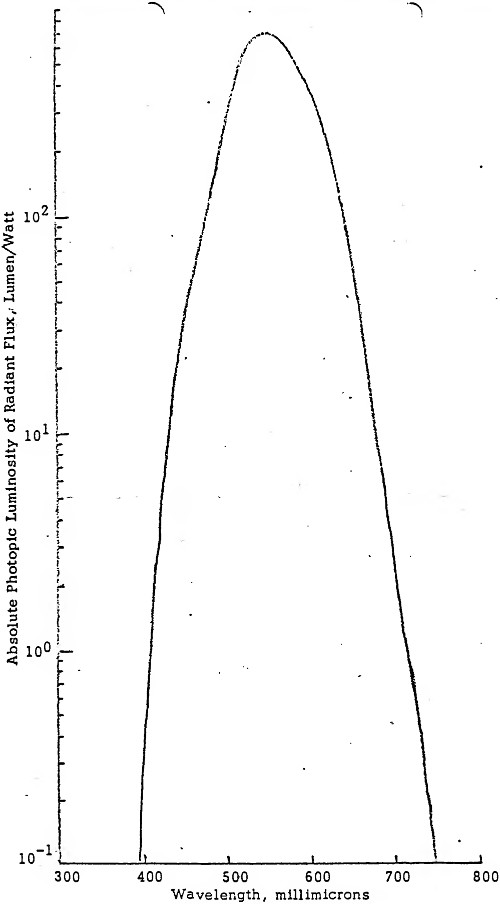


Figure 4. Visual Response Curve of the Human Eye, Spectral Dependence of Luminous Flux (Reference 3)

$$I_\lambda = \frac{2\pi c^2 h \epsilon}{\lambda^5 (\exp(hc/k\lambda T) - 1)} \qquad ((5)$$

where I_λ is the radiant flux, in terms of energy per unit area per unit time at wavelength λ, emitted by a hot source at temperature T, h is Planck's constant, c is the speed of light, k is Boltzmann's constant and ϵ is the emissivity of the flame. Typical flux-wavelength distributions calculated from this equation are shown in Figure 5.

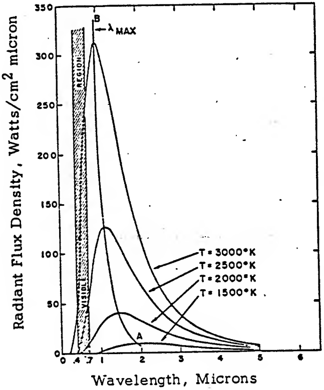


Figure 5. Planck's Law: Radiance as a Function of Wavelength for Various Temperatures

It can be seen from this figure that very little of the energy emitted by blackbody radiation is distributed in the wavelength band most sensitive to the eye. Further, in order to generate an intense source in the visible spectrum, a very high flame temperature will be required and even under these conditions the efficiency of the source in terms of the fraction of visible light energy generated out of the total radiation energy would be very low.

1.2.3 Desirable Pyrotechnic Ingredients

This observation leads one to recognize that pyrotechnics composed of organic fuels which have the highest heat of reaction cannot be considered since these mixtures produce flames having characteristics similar to blackbody emitters. This is particularly true for fuel rich compositions which have a tendency to generate significant amounts of carbon and aromatic soot particles.

The radiant emission in the visible can be improved by including chemicals in the pyrotechnic mixtures that will form thermally excited reaction products capable of emitting radiation at desired wavelengths. This process can be described by the following equation,

$$\underbrace{A + B}_{\text{Pyrotechnic Components}} \rightarrow \underbrace{[C + \text{heat}]}_{\text{Reaction Product in Flame}} \rightarrow \underbrace{[C^*]}_{\text{Thermally Excited Product Species}} \rightarrow \underbrace{C + h\nu}_{\text{Light Emission}} \qquad (6)$$

Many inorganic salts exhibit this phenomena. Several elements which react in pyrotechnic flames forming oxides, hydroxides and chlorides have been used to "color" flames. These include, strontium which produces a red color, barium (green), sodium (yellow), calcium (yellow-green and orange) and copper (blue to green). Lithium (red), boron (green), thallium (green), rubidium (red) and cesium (blue) are also strong color producers but their use is not as practical because of cost, toxicity or the nature of their compounds.

The actual emitting species of these metals are known to be the di- and tri-atomic species which can exist at high temperatures in the flame. For example,

a. the red light produced by flares containing strontium and a source of chlorine is a result of SrCl emission (strong emission near 640 mμ). In the absence of chlorine, emission has been attributed to SrO.

b. $BaCl_2$ emits in the 505-535 mμ region (green).

c. BaO emits over a broad spectrum, 400 to 800 mμ.

d. The hydroxides of these metals also emit in the respective wavelength bands.

e. MgO emits at approximately 500 mμ.[4]

1.2.4 Color Intensifiers

Where possible, chlorides are added to the pyrotechnix mixtures to enhance the color of the flame. Perchlorate oxidizers contribute the minimal requirements without reducing the efficiency of the energy output. In some cases it has been found that the addition of chloro-organics significantly increase the color intensity. Substances such as hexachlorethane, hexachlorobenzene, polyvinylchloride are sometimes employed for this purpose.

2. CRITERIA USED TO SELECT CANDIDATE PYROTECHNIC MIXTURES

The following considerations were made in selecting candidate pyrotechnic formulations[1] for the initial experimental investigations. Based on the premised desirability of producing flames which emit radiation in the visible wavelength region, primary consideration has been given to inorganic compositions.

2.1 OXIDIZER

Comprehensive literature surveys by Shock Hydrodynamics and other investigators have shown that perchlorates are the most desirable oxidizers. They contain a relatively high ratio of oxygen to total molecular weight, their heats or reaction with metals such as aluminum and magnesium are significantly better than other oxidizers and they generate only oxygen as a gaseous product. Perchlorates are generally stable, yet they are easily ignited, unlike oxidizers such as nitrates and metallic oxides. Nitrates suffer additional disadvantages in that they are not as exothermic and thus tend to have a slower burning rate with fuels such as aluminum and magnesium (see Equation 4), and they generate a non-reactive gaseous product, nitrogen.

Of the alkali perchlorates, lithium and sodium perchlorates have the highest rates of oxygen to total molecular weight, viz., 64/106.4 and 64/127.45, respectively. However, these compounds are extremely hygroscopic. This characteristic decreases the storage life of a pyrotechnic system. The absorption of water by these oxidizers is an exothermic process. Because of this factor one must also be concerned with the design of special safety precautions.

Potassium perchlorate was selected as a primary oxidizer for the initial candidate mixtures. This oxidizer has an oxygen-total weight ratio of 64/138.55, which is somewhat lower than $LiClO_4$ and $NaClO_4$, however, it is a stable compound and its heat of reaction with aluminum, for example, is slightly greater than the reactions between $LiClO_4$ or $NaClO_4$ and aluminum.

2.2 FUEL COMPONENTS

It has been found that aluminum and magnesium are the best fuels for use in photoflash mixtures. The heat of reaction and peak light intensities resulting from $Al/KClO_4$ are much higher than equivalent $Mg/KClO_4$ compositions. The radiation emitted follows generally what would be expected for continuum radiation. Peak light intensities for stoichiometric mixtures of $Al/KClO_4$ and $Mg/KClO_4$ have been measured to be approximately 40 and 18 million candles, respectively.

2.3 CONSOLIDATION OF MIXTURE

It has been shown, that the manner in which the fuel and oxidizer are incorporated in the pyrotechnic device will greatly influence its performance.[5] Consolidated compositions contain binders, usually organic polymers, which form a rigid or semi-rigid body. The consolidated composition however is a burning system which has a relatively large spatial separation between fuel and oxidizer. Thus, the burning rates are relatively slower than a comparative non-consolidated system. Non-consolidated systems under confinement usually have higher deflagration rates than consolidated systems and the intensity of the emitted light is greater. Most photoflash systems are thus non-consolidated, and this type of system was selected for these studies.

2.4 OUTPUT IMPROVEMENT (SELECTION OF STANDARD MIXTURE)

A standard photoflash composition, III-A, was selected as a reference. The composition of this mixture is shown in Table I. The addition of barium nitrate to this mixture increases the radiation output in the visible spectrum over that of the basic $Al/KClO_4$ mixture. As discussed in a previous section, the BaO and $BaCl_2$ formed in the burning processes emits strongly in the wavelength region most sensitive to the eye.

2.4.1 Mixture "D"

During the Korean conflict[5] an experimental photoflash mixture having a very high fuel to oxidant ratio was developed having a peak

TABLE I. CHARACTERISTICS OF TYPE III PHOTOFLASH COMPOSITION[6]

Ingredients	Specification	Microns	Percent
Aluminum, atomized	JAN-A-289	15	40
Potassium Perchlorate	PA-PD-254	24	30
Barium Nitrate	PA-PD-253	147	30

PHYSICO-CHEMICAL DATA:

Heat of Reaction, cal/g—2774 (calc)

Reaction Temperature, °C—approx. 3500

Gas Volume, cc/g—24 (calc)

Tapped—1.67

Vac. Stab, 120°C, cc gas/40 hrs—0.16

SENSITIVITY DATA:

Impact:	PA, inches—40 +
Friction Pend:	Steel—Crackles; Fiber—No Action
Ignition Temp, °C:	5 sec value—610; DTA—No Ignition
Hygroscopicity:	57% RH, room temp; Hrs 24; % Wt Gain < 0.1
Electrostatic Sensitivity:	Joule, Min 2.14; 50% Pt—3.5; 100% Pt—4.5; Temp—65°F; % RH—40: Unconfined—Yes

light output twice that of the Type III mixture. This mixture consisted of 70% Al/30% $KClO_4$. A further improvement in performance is anticipated by replacing a portion of the $KClO_4$ oxidizer with $Ba(NO_3)_2$ which will act as an oxidizer and color enhancer (see Table II for compositions of candidate pyrotechnic mixtures).

TABLE II

Pyro* Composition Designation	Arbitrary Type Designation			
	A	B	C	D
Ingredients	%	%	%	%
Al	40	50	25	70
$KClO_4$	30	40	30	20
$Ba(NO_3)_2$	30		10	10
Ca Si		10		
Mg			35	
TOTAL	100	100	100	100

*All mixtures prepared in accordance with PA-PD-267.

TYPE A Follows the formulation given in PA-PD-267 for Type III Class A (Fine Oxidizers).

TYPES B, C, & D follows the same guidelines including particle size given in PA-PD-267.

2.4.2 Mixture "B"

The addition of calcium silicide should have two effects on the basic $Al/KClO_4$ reaction:

1. Because of the exothermic nature of CaSi in an oxidizing environment, the heat of reaction of this mix should be greater than the selected reference (i.e., mixture A). This increase in the heat of reaction will raise the flame temperature and the radiation intensity of the flame.

2. The flame emission of calcium is at 550 and 620 mμ. This is in the yellow-green and orange areas of the spectrum and as can be seen from Figure 4 should improve the flame luminosity in the most sensitive wavelength regions.

A smaller percentage of calcium silicide than barium nitrate is required because of molecular weight differences. Calcium has an atomic weight of less than a third that of barium. Thus, on a weight basis calcium should be more efficient.

2.4.3 Mixture "C"

It has been observed that the use of magnesium-aluminum fuel mixtures results in flashes of longer duration. This fuel combination is also easier to ignite as compared with aluminum. Mixture "C" was therefore formulated for purposes of determining the differences in potential effectiveness with flash duration.

2.5 PARTICLE AND SHELL SIZE

The same guidelines of particle size suggested for the reference photoflash mixture (designation "A") are being used for the other mixtures. This control is necessary so as to minimize the number of unknown experimental parameters.

A representative array of shell sizes have been included in the experimental plan. These shells were described in Reference 1. All of the casings are composed of aluminum.

2.6 METHOD OF INITIATION

An additional variable which was included in the experimental plan was the method of initiation. Simple central burster initiation as well as an imploding initiation system are included in the test plan for comparison.

REFERENCES

1.

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3. R. L. Tischer and K. Scheller, "A Gaseous System of High Luminous Efficiency", (Presented at the Western States Combustion Institute Meeting, 1967), Report WSCI-67-12, Aerospace Research Labs.

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FINAL SUMMARY REPORT
PART 2
LIGHT SOURCE EVALUATION

June 1970

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TABLE OF CONTENTS

1. INTRODUCTION

The objective of this investigation of pyrotechnic light sources was confined primarily to the evaluation of output illumination levels, the factors controlling them and comparisons with the existing criteria for optical incapacitation, since these considerations determine the suitability of such a system to a variety of possible weapon applications.

The effort was directed primarily at comparisons of existing threshold energies for incapacitation and damage, pyrotechnic output energies, and the fabrication of test devices with controlled parameters, followed by estimation of their output energies by means of appropriate instrumentation. The approach permitted a comparison with existing data on energy levels corresponding to optical incapacitation and damage. This comparison was used to obtain first order estimates of the effective ranges at which these pyrotechnic illumination devices would either incapacitate or permanently damage exposed personnel.

The four pyrotechnic light mixtures shown in Table I were evaluated during this investigation. In the following sections there are presented the methods and techniques employed, results obtained, and the conclusions regarding the feasibility of this approach.

TABLE I. COMPOSITION OF EXPERIMENTAL MIXTURES

Composition Designation	A	B	C	D
Ingredients	%	%	%	%
Al	40	70	25	50
$KClO_3$	30	20	30	40
$Ba(NO_3)_2$	30	10	10	--
$Ca(Si)_2$	--	--	--	10
Mg	--	--	35	--

2. DESCRIPTION OF EXPERIMENTAL PHOTOFLASH DEVICES

A brief description of the charges was included in the Final Summary Report - Part I. Two basic photoflash cartridges were employed. Design drawings of these cartridges are presented in Figures 1 and 2. The performance of each of the four selected pyrotechnic mixtures was evaluated in each cartridge design. The specifications of each of the mixtures were previously described (see Reference 1).

2.1 PHOTOFLASH CARTRIDGE, TYPE S

The outer diameter of the Type S photoflash cartridge is 2.7 in. and the length is 6.6 in. The outer shell is made of aluminum. A scale drawing of the cartridge is shown in Figure 1. A linear charge of DuPont PETN primacord, .22 in. diameter and 5.25 in. long, was surrounded by the photoflash mix. This central bursting charge was used to break the casing, and to ignite and disperse the pyrotechnic mixture.

2.2 PHOTOFLASH CARTRIDGE, TYPE SDE

This cartridge was identical to the type S with the exception that DuPont Deta sheet explosive was wrapped around the exterior cylindrical wall of the Type S cartridge. These sheets were cut, as shown in Figure 1, to permit the complete coverage of the outer wall. The purpose of this design was to compact the photoflash mixture first before it was disseminated, in an attempt to improve the light output (i.e., as discussed in the last progress report, the rate of burning and light output should increase with the degree of charge compaction). The ignition train was designed so that the Deta sheet would be detonated before the central bursting charge.

2.3 PHOTOFLASH SHELL, TYPE SS

The Type SS shotgun shell has an O.D. of 0.853 and a length of 3.20 in. It is also made of aluminum. Except for dimensions, this photoflash shell design is similar to the 2.7 in. photoflash cartridge (see Figure 2).

2.4 PHOTOFLASH SHELL, TYPE SSDE

This shell is identical to the Type SS, with the exception that Dupont Deta sheet is wrapped around the cylindrical body in a similar manner as the SDE.

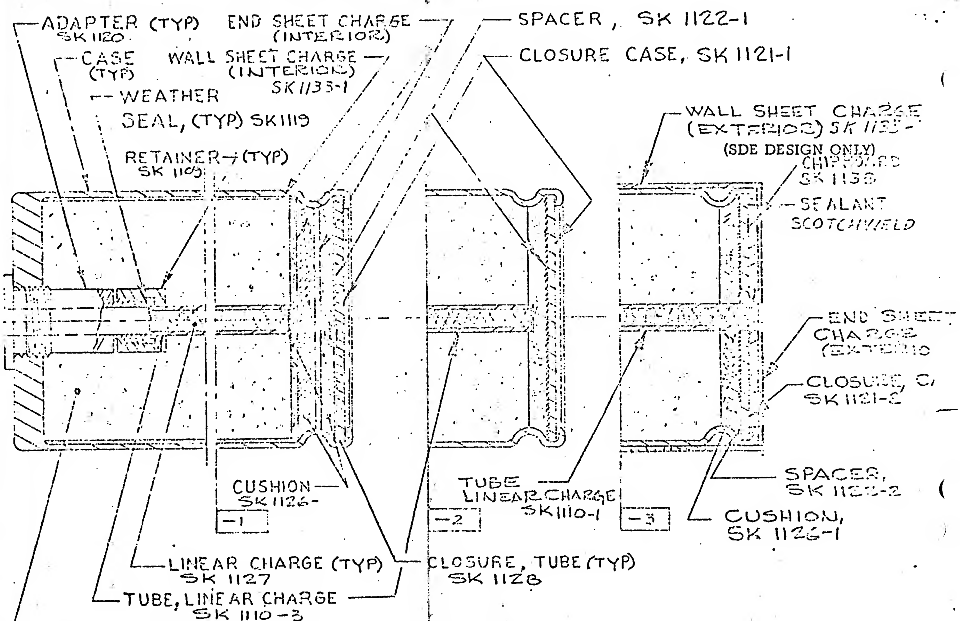


FIGURE 1. 2.7" PHOTOFLASH CARTRIDGE
SCALE 1/1

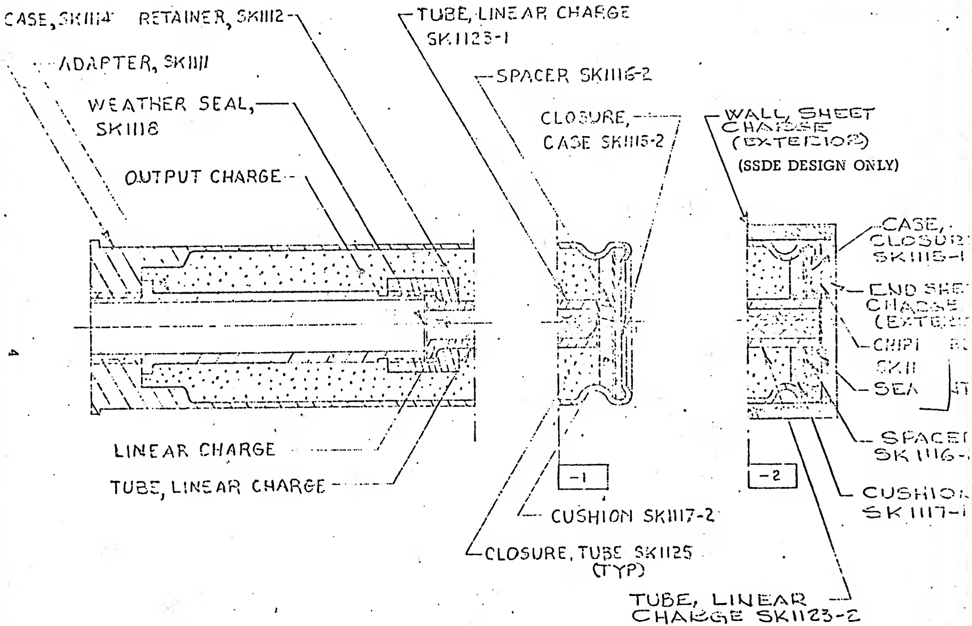


FIGURE 2. 0.83" PHOTOFLASH CARTRIDGE
SCALE 2/1

3. DESCRIPTION OF EXPERIMENTS

The experimental techniques employed and the specific experiments performed are outlined in this section.

3.1 EXPERIMENTAL ARRANGEMENT

The intensity of the light output as a function of time was measured and recorded using a silicon photodiode (United Detector Technology Inc., PIN-10) and a Tektronix 535 oscilloscope with a Polaroid film attachment. The PIN-10 photodiode has a half-value response between 3800 and 10500 Å. The photodiode, PIN-10, was protected from fragments generated from the explosive dissemination by a metal shield. The light from the flash was indirectly focused onto the PIN-10 sensor using a mirror.

A Corning 1-56 filter was placed in front of the PIN-10. This filter has transmission characteristics similar to the eye response. It has a near gaussian transmission curve between 3600 and 7000 Å with a peak transmission at 5200 Å. The ultraviolet is cut-off at 3600 Å and less than 10% of the I-R radiation (i.e., between 1 and 4.5 microns) can be transmitted through this filter. Depending on the expected output of each test device, neutral density filters were also used so that the PIN-10 would operate within its linear response regime (i.e., so that light intensity versus output voltage would remain linear).

The output signal from the sensor was fed into a Tektronix 535 oscilloscope with a 50 ohm termination. The signals were permanently recorded using a Polaroid camera attachment. The oscilloscope and event were triggered using a 5 KV firing panel.

The events were also monitored photographically. A speed graphic single exposure camera and a Beckman & Whitley Dynafax motion picture camera were used with Polaroid filters. The Dynafax camera was operated at a framing rate of 3000 frames per second. Both cameras were protected from the blast. The Dynafax camera was located behind a barricade and received the light from the photoflash via a front surface mirror. The speed graphic camera was located behind thick glass.

3.2 DETECTOR CALIBRATION

The PIN-10 photodetector was calibrated using a National Bureau of Standards certified light source. The response of the detector was measured as a function of distance away from the standard source using the following equation

$$I = K \cdot F \cdot V \cdot D^2 \qquad (1)$$

where

- I is the intensity of the light source in candle-power,
- K is the calibration factor, 2640 foot-candles per 38.07 millivolts response,
- F is the factor which compensates for the transmission of the neutral density filters,
- V is the output signal, volts, generated by the photo-detector, and
- D is the optical distance between the PIN-10 photo-detector and the light source.

The spectral response characteristics of the photodetector are shown in Figure 3. The relative spectral sensitivity of the PIN-10 with the Corning 1-56 filter was calculated. These results are presented in Figure 4.

The optical distance between the light sources and the photo-detector was 23.5 feet in each experiment. The intensity of the source expressed in candle-power was calculated using Eq. (1). The values of candle-power estimated can be interpreted directly in terms of the luminous flux traveling through a normal plane which intersects the light path 1 foot away from the source (i.e., the density of luminous flux incident on a normal surface one foot away from a 1 candle-power source is 1 lumen/ft^2).

3.3 EXPERIMENTAL ERRORS

An experiment was performed to determine the amount of light received by the photo-detectors via wall reflection. A General Electric No. 22 photoflash bulb was placed 23.5 ft. away from the photo-detector in a similar manner as were the photoflash pyrotechnic test devices. Black paper was placed directly in front of the flash bulb to prevent direct light transmission to the photo-detector. When compared with a control test in which the light barrier was not used, it was calculated that less than 5% of the light received by the photo-detector was due to light reflections from the walls of the test chamber. As a precaution, in subsequent tests, all light colored objects were removed from the test chamber before each experiment. The walls of the chamber were washed down after each test, also, to remove any debris which might increase the light reflection.

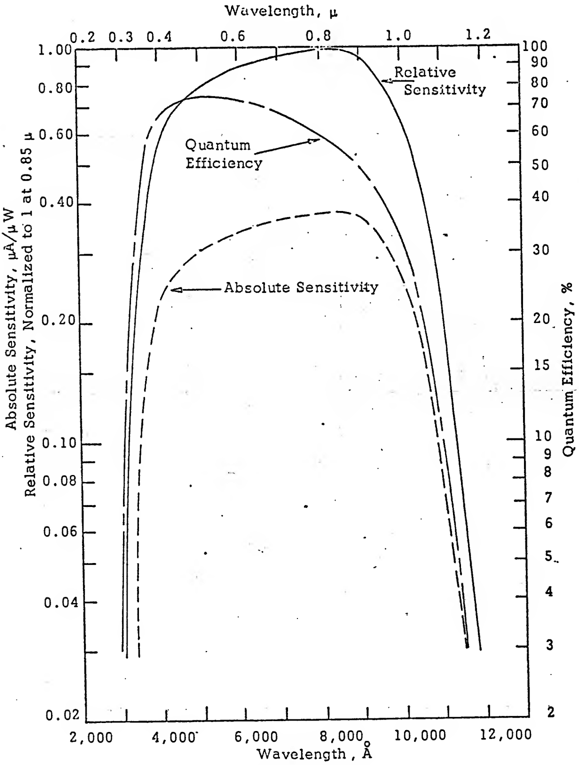


Figure 3. Spectral Characteristics of the United Technology PIN-10 Photodiode

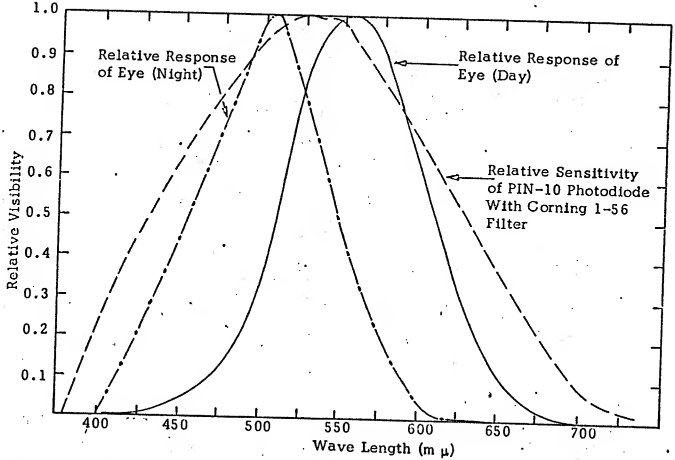


Figure 4. Comparison of Eye and Photodetector Sensitivity Curve

4. EXPERIMENTAL RESULTS

The measured outputs versus time for each of the experimental photoflash devices are shown in Figures 5 through 8. These figures were drawn from the oscilloscope traces obtained in each experiment. The results of each photoflash cartridge design were combined so that a ready comparison could be made regarding the relative performance of the light output from each of the four pyrotechnic mixtures. The peak light intensities, the half width of intensity-time and the total integrated area under each curve (i.e., total light output in candle-power-seconds) are reported in Table II. The maximum cloud size generated by each device is also included in this table. The latter data was obtained from the film records taken.

4.1 COMPARISON BETWEEN REPORTED AND MEASURED OUTPUT OF TYPE III MIXTURE

Mixture A has a composition identical to the standard Type III (i.e., mixture A) photoflash mix. This Type III photoflash mixture has previously been used in a variety of standard photoflash cartridges. Light output data was obtained for this mixture,[2] from other sources, and is summarized in Figure 9. The peak intensities and integrated candle-power-seconds total output are plotted as a function of charge size in pounds. Approximations of best-fit curves were drawn through each set of data as shown. The arrow on the abscissa represents the charge weight of the pyrotechnic mixtures in the Type S cartridge, 1.4 lbs.

The predicted peak intensity and total output for this charge are, respectively, 2.3×10^8 c. p. and 4.4×10^6 c.p.s. The experimental values obtained during the tests on this program were 1.96×10^8 c.p. and 2.0×10^6 c.p.s. (see Table II). These data are considered to be in reasonable agreement and provide an additional check on the accuracy of the measuring techniques and the charge preparations.

4.2 COMPARISON BETWEEN CHARGES

Based on the peak intensity data, the overall performance of the Type A mixtures in the various shells was the best. In order of decreasing performance it was found that

$$A > C > B > D$$

The peak intensity of the output however is not the only criterion that should be used in evaluating the performance of a mixture for this application. The duration of the light pulse is of equal importance. From

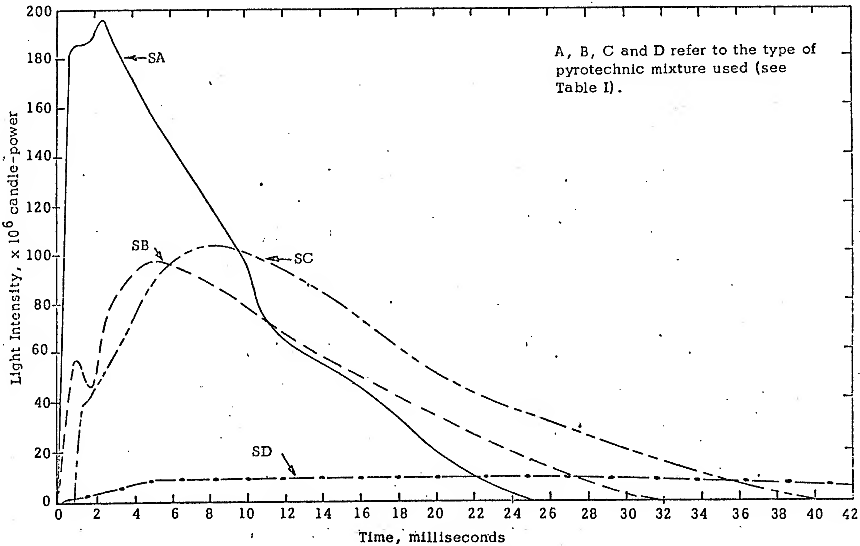


Figure 5. Light Output From Series S Photoflash Units

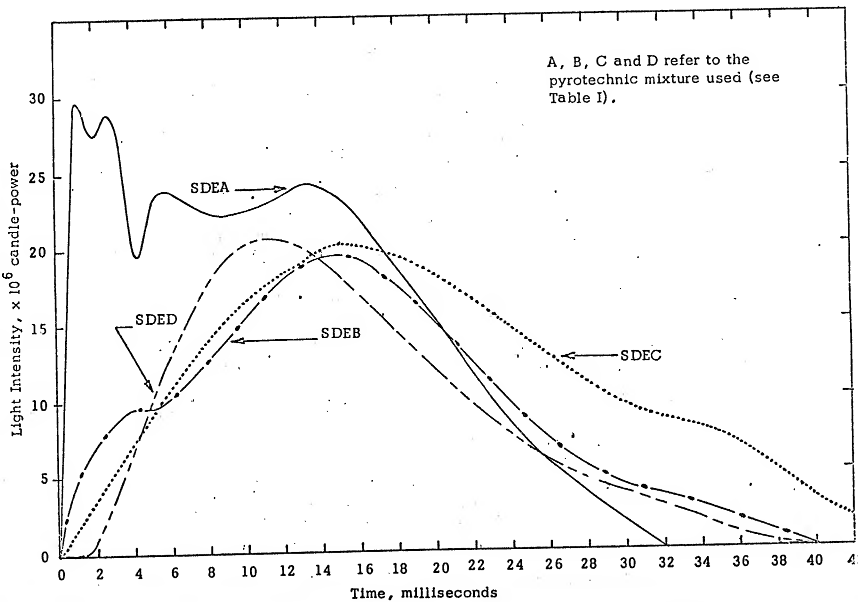


Figure 6 Light Output From Series SDE Photoflash Units

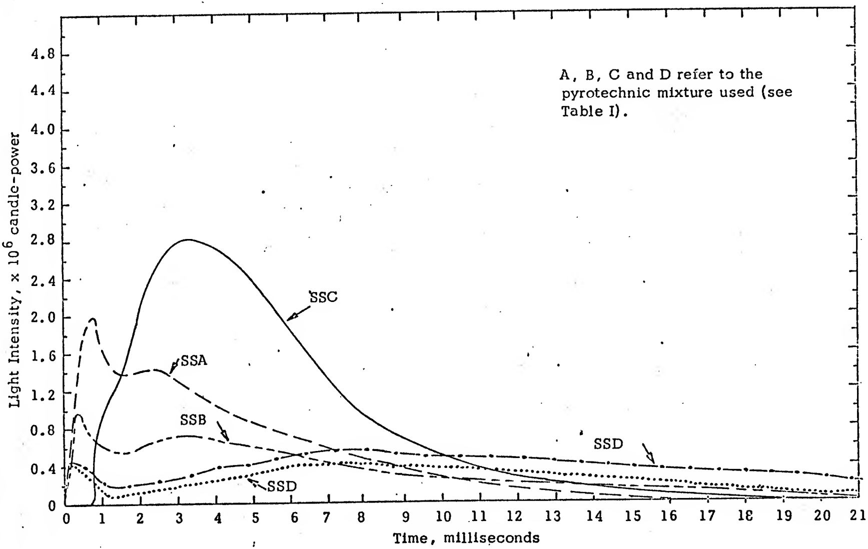


Figure 7. Light Output From Series SS Photoflash Units

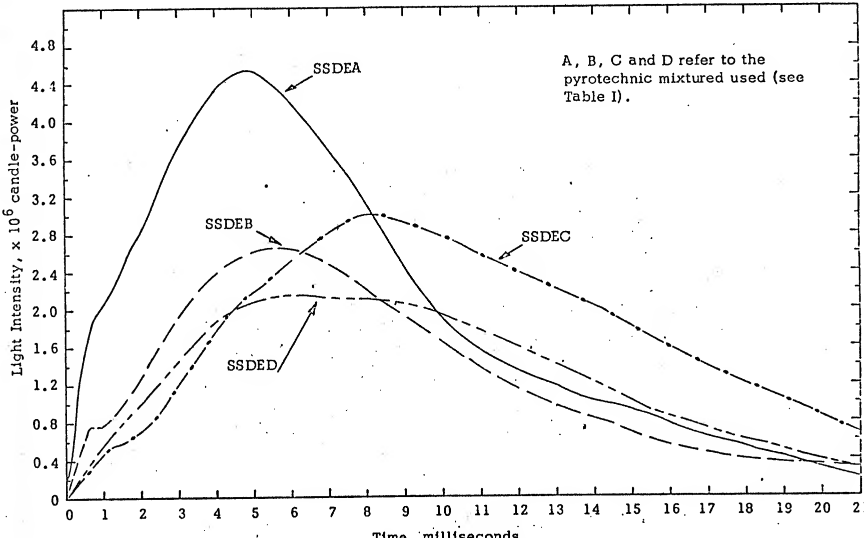


Figure 8. Light Output From Series SSDE Photoflash Units

TABLE II. SUMMARY OF TEST RESULTS

Sample* Type	Peak Candle-Power (10^6 cp)	Half-Width Duration (msec)	Total Output (10^3 cps)	Peak Cloud Size (ft.)
SA	195.7	9.8	2010	7.4
SB	97.8	15.5	1579	7.5
SC	103.6	17.8	2021	7.1
SD	9.5	40.4	371	3.5
SDEA	29.8	20.7	526	7.0
SDEB	19.5	20.1	375	7.0
SDEC	20.3	18.3	493	7.3
SDED	20.5	16.4	354	4.3
SSA	1.99	4.0	10.3	---
SSB	0.99	6.0	7.8	1.8
SSC	2.81	5.4	17.1	2.4
SSD	0.57	20.0	8.8	1.5
SSDEA	5.59	8.3	52.9	2.8
SSDEB	2.64	9.1	29.0	3.5
SSDEC	3.02	12.7	40.2	3.2
SSDED	2.14	13.0	28.6	2.7

*S and SDE refer to the type of photoflash cartridge used. A, B, C and D refer to the pyrotechnic mixture used (see Table I).

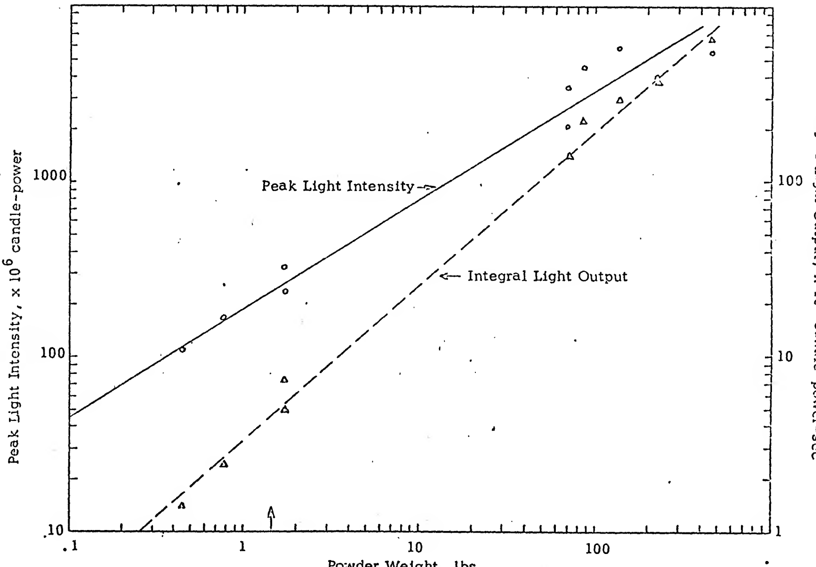


Figure 9. Peak Intensities Produced by Type III Photoflash Mixtures as a Function of Charge Weight[2].

the plots of intensity versus time it was shown that the light pulses from the "C" mixture were in most cases of longer duration. Based on the total integrated light output the "C" and "A" mixtures were equally effective.

i.e., $C \approx A > B > D$

It could be concluded that of the mixtures studied, the "A" and "C" mixtures provided the most intense and total light output. The "B" and "D" mixtures generated, significantly, less light in the visible spectrum.

5. DISCUSSION OF POTENTIAL FLASH BLINDNESS EFFECTS

Several important questions had to be answered before these data could be interpreted in terms of potential flash blindness effects:

1. What is the level of flash luminosity that will produce permanent eye injury?

2. What is the level of flash luminosity that will produce transient flash blindness?

3. If the measure of the transient flash blindness is expressed in terms of functional requirements calling for viewing and resolution of specific objects, how does the luminosity of the objects to be viewed by the observer affect recovery time from non-injurious flash blindness?

5.1 PERMANENT EYE DAMAGE

It has been reported that the threshold energy level for permanent eye damage is between 0.2 and 1.6 cals/cm^2.[3-6]

Zaret[3] expresses the requirements for permanent eye injury in terms of the fraction of the photopigments which are bleached by the light flash. This bleaching process involves the photochemical transformation of 11-monocis retinene to trans-retinene. The 11-monocis retinene complexes with the opsin enzymes to form the active photosensitive pigments. Upon light excitation the 11-monocis olefin is transformed to the more chemically stable trans isomer via an electronically or vibrationally excited state.[7-9] The trans-retinene, a yellow pigment, which is formed is not compatible with the opsin enzyme and, thus, does not form a photosensitive pigment. Recovery of the bleached pigment is dependent upon a chemical transformation back to the 11-monocis isomer catalysed by retinene isomerizase.

The concentration of visual pigment only begins to be significantly affected by light intensities of the order of 10^5 troland-seconds* and decreases rapidly with further increase in intensity. The concentration of bleached pigment as a function of light intensity can be expressed as follows[3]

---

*The troland is the unit of retinal illumination. It is equal to the product of the luminance of the object viewed in candles/(meter)^2 and the area of the pupil in mm^2.

$$C_b/C_o = 1 - \exp(-\alpha\gamma It) \qquad (2)$$

where

C_b is the concentration bleached at exposure It,

C_o is the original pigment concentration,

It is the retinal total irradiance in troland-seconds, and

$\alpha\gamma$ is the photosensitivity expressed in $(\text{td-sec})^{-1}$

In the case of the human pigments the value of $\alpha\gamma$ is approximately 10^{-7} $(\text{td-sec})^{-1}$. Zaret estimates that as the fraction of pigment bleaching approaches unity permanent retinal damage occurs. Within the time frame of the flashes which were produced in the experiments reported here, the threshold damage irradiances are approximately 0.4 cals/cm^2 (4×10^9 td-sec) and 1.6 cals/cm^2 (1.6×10^{10} td-sec)[10-12] for exposures of 1 and 100 msec, respectively. According to Brown,[4] these irradiance levels must be delivered at flux levels of at least 0.7 cals/cm^2-sec or the rate of heat dissipation in the eye tissue will be sufficient to prevent an elevation of temperature to the degree where thermal burn will occur.

At 5550 angstroms the wavelength of maximum sensitivity to the eye, one watt of radiant energy corresponds to 672.1 lumens. Assuming that all of the light emitted from the pyrotechnic flash devices tested during the program is at this wavelength, the light intensities required to affect thermal damage to the retina would be 1.75 and 6.99×10^4 lumen-sec/ft^2 for exposures of 1 and 100 msec, respectively. The above estimates take into account the fact that the light received at the cornea is intensified when it arrives at the retina (i.e., the image size is reduced): Ham[6] noted that an irradiance received at the cornea of a rabbit eye is intensified by a factor of 60 times when it reaches the retina.

With respect to the experiments performed in this investigation, these values are considered to be low. Assuming that the light emitted from the flash units have the same spectral characteristics as the sensor, than the luminous efficiency of the light output is only 28 percent that of 5550 angstrom light. The threshold light exposures would then be 6.26×10^4 and 2.48×10^5 lumen-sec/ft^2 for exposures between 1 and 100 msec, respectively.

Based on the luminous intensity data, shown in Table II, it can be seen that the small photoflash charges (i.e., the SS and SSDE series) are not capable of delivering damaging light flashes. The larger charges (i.e., the S and SDE series) can produce permanent eye damage. Further discussions regarding the possibility of permanent eye injury are presented elsewhere in this report (see Section 5.3.2).

5.2 RECOVERY TIME TO LIGHT FLASHES

Before one can estimate the recovery period after light exposure it is important that the important recovery measurement conditions be defined. Clearly, the intensity of the light which the observer is exposed to will determine recovery time. An additional consideration is the illuminance of the object which the observer needs to detect after exposure for functional reasons.

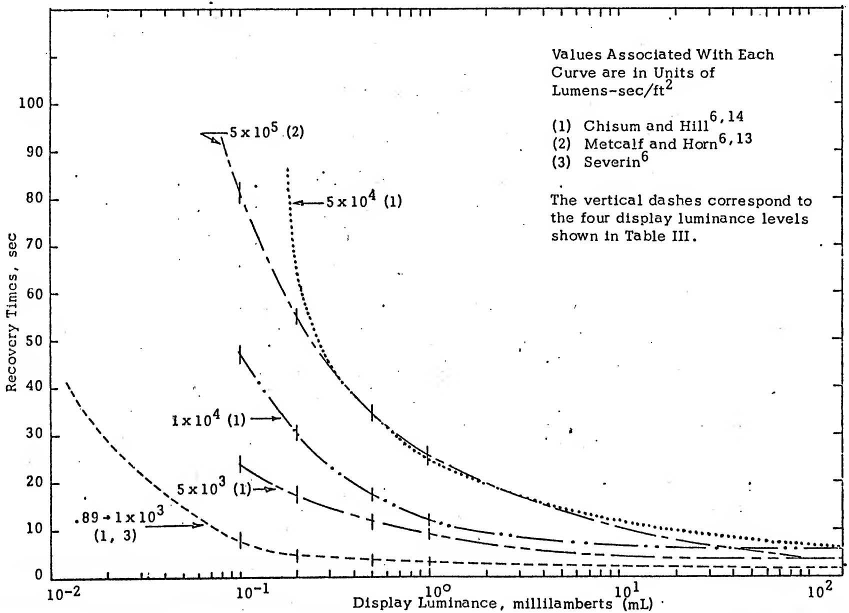
A review of the literature was made in order to define the dependence of recovery on the two factors noted above. The results of this search and the subsequent analyses are shown in Figure 10.

5.2.1 Review of Flash Blindness Experiments

Metcalf and Horn[6,13] conducted flash blindness experiments using the high intensity flashes from a carbon arc. The experiment was designed to determine the effect of light exposures likely to be encountered during nuclear operations. Each of the four subjects had their pupils dilated prior to exposure. A 6mm artificial pupil was used in order to maintain constant pupil size. The subjects were exposed for 100 msec to illumination ranging from 70 to 12,000 lumens per square foot. Following this exposure, the subjects were required to detect the flashing of a 17 minute visual angle circular patch. The luminance of the test patch was varied between .07 and 71 foot-Lamberts. A summary of a complete set of this data at a flash luminosity of 5×10^5 lumen-sec/ft^2 is shown in Figure 10.

The time required to recover visual sensitivity following exposure to high intensity, short duration adapting flashes also has been investigated by Chisum and Hill.[6,14] Adapting flashes of 33 to 165 μsec and 9.8 msec in duration with luminances from 1×10^4 to 5×10^8 lumens/ft^2 were used. Visual sensitivity was determined by the resolution of gratings requiring acuities* of 0.13 and 0.33 at display luminances between approximately .004 to 200 millilamberts. The 0.33 acuity level requires the function of cones while the 0.13 acuity level can be resolved by rod vision. The light pulses used by Chisum and Hill which best represent the flashes

*Acuity is defined as the relative ability of the visual organ to resolve detail. It is usually expressed as the reciprocal of the minimum angular separation in minutes of two lines just resolvable as separate.


Values Associated With Each Curve are in Units of Lumens-sec/ft^2
(1) Chisum and Hill[6,14]
(2) Metcalf and Horn[6,13]
(3) Severin[6]
The vertical dashes correspond to the four display luminance levels shown in Table III.
5×10^5 (2)
5×10^4 (1)
1×10^4 (1)
5×10^3 (1)
$.89 \rightarrow 1 \times 10^3$ (1, 3)
Recovery Times, sec
Display Luminance, millilamberts (mL)
0
10
20
30
40
50
60
70
80
90
100
10^{-2}
10^{-1}
10^0
10^1
10^2

from the pyrotechnic devices tested during this program were selected for the comparisons made in Figure 10. Also the data for the acuity level 0.33 was used, since the effects to cone vision are the most critical to this study. It should be noted that recovery from rod saturation is a much faster process than recovery from cone saturation. The latter also requires more energy for saturation.[3]

It was observed that the recovery times for the light illuminations of 5×10^5 lumens-sec/ft^2, reported by Metcalf and Horn, and 5×10^4 lumens-sec/ft^2, reported by Chisum and Hill were almost identical. This is not too surprising after one reviews the discussions by Brown[4] and Zaret.[3] Namely, both postulate that the relation between the energy of an adapting flash and recovery time for a specific visual task is similar in nature to that shown in Figure 11.

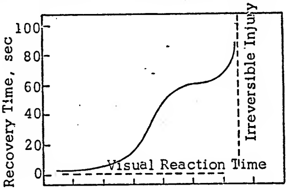


Figure 11. A hypothetical curve illustrating the relation between energy of a blinding flash and time required for detection of information in a visual display. The minimum detection time at low flash energy corresponds to visual reaction time. Detection time approaches infinity as flash energy approaches a value which will cause irreversible injury.

For very low adapting flash energies* there is very little, if any, effect on the visual capability, and recovery time is minimal. As energy is increased, there is an increase in recovery time at an increasing rate. The form of this function depends on the nature of the visual task. As the energy of the adapting flash reaches a level which corresponds to a maximum possible bleaching of the photosensitive pigments of the retina, the rate of increase of recovery time may be expected to decrease. It is postulated as shown in Figure 11 that recovery time may actually assume a constant value over some range of adapting flash energies beyond that at which maximum bleaching occurs.

*Adapting flash energy usually refers to the total energy to which the subject is exposed and from which the subject must recover normal vision.

It appears that the data of Chisum and Hill at 5×10^4 lumens-sec/ft^2 and Metcalf and Horn at 5×10^5 lumens-sec/ft^2 can be explained by this qualitative argument. Although there are some differences between the individual experiments, the very close correlation in measured recovery times, together with the fact that the saturated bleach levels are being approached or perhaps exceeded in both, indicate that the intensity plateau is in the range of 10^4 to 10^6 lumen-sec/ft^2.

The data reported by Chisum and Hill at the illumination level of 1×10^3 lumen-sec/ft^2 was extended as shown in Figure 10 using data reported by Severin.[6] Severin reported results in which the display luminance of test patches were between 0.06 and 0.013 foot-Lamberts. The results obtained at an adapting flash intensity of 8.9×10^2 lumen-sec/ft^2, very close to 1×10^3 lumen-sec/ft^2, were used to extend the Chisum and Hill data. One reservation about Severin's data is that the duration of the adapting flashes was 150 msec. This is slightly greater than the normal blink time of 100 msec. Nonetheless, Severin's data does appear to agree with the general trend at high display luminances found by Chisum and Hill.

5.2.2 Additional Observations

An experiment was performed by Brown[4] to determine the dependence of recovery time from flash blindness on the luminance of objects viewed. The test subjects were exposed to light intensities of 3×10^{-2} to 3×10^2 ft-Lamberts for durations of 0.9 seconds. The display consisted of a grating pattern and observers were required to identify its orientation. A timer was started and the grating was illuminated with presentation of the flash. As soon as the grating orientation was detected, the observer depressed a switch that turned off the timer. Detection times were recorded only for correct identification of grating orientation.

The results of this study are reproduced in Figure 12. The families of curves in the upper part of the figure represent results with a grating, the individual lines of which subtended a visual angle of 3.8 min. According to Brown, the detection of the orientation of this target display depended on cone vision. The curves in the lower two graphs were obtained for a grating which represented a visual angle of 12.5 min. Rods may serve in detection of the orientation of this coarser grid.

It is clearly shown, again, that recovery times are dependent on the luminance of the object which the eye attempts to detect. There is one major uncertainty, regarding the quantitative nature of Brown's data, however. This experiment was performed by exposing the test subjects to a 0.9 sec light pulse duration. Since the blink time is of the order of 0.1 sec it is possible that the observers were not exposed to the full duration

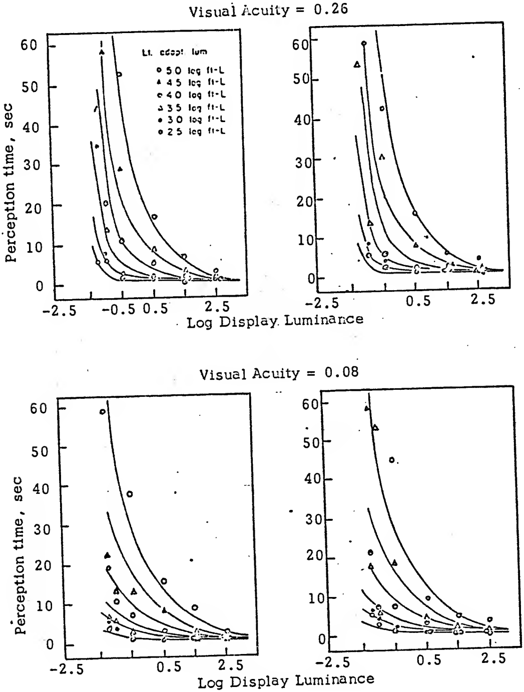


Figure 12. Relations of Perception Time to Log Display Luminance (ft-L) for Each of 6 Adapting Flash Luminances[4]

of the light pulse. Therefore there is an uncertainty in the total exposure duration of each subject to the light. Therefore these data were not used to correlate results obtained in the present study.

5.3 INTERPRETATION OF RESULTS

The measured light intensities and durations were interpreted in terms of possible irreversible and reversible eye effects.

5.3.1 Illumination of Photoflash

The experimentally measured illuminance of each pyrotechnic test device as reported in Table II was estimated as a function of distance from the flash origin using the inverse square law. These estimates are shown in Figures 13 and 14. The expected illuminance which observers would received from exposure to a G.E. No. 50 flash bulb are also shown in these figures. The value for the total output of this flash bulb, 1×10^5 lumen-sec/ft^2, was obtained from General Electric specifications.

5.3.2 Estimated Eye Effects

Some of the iso-illuminance curves shown in Figure 11 were extrapolated to a display illuminance level of 0.1 millilamberts (or 0.093 lumens/ft^2). The recovery time for each of the reported adapting flash energies shown in Figure 11 were estimated for each of four display luminances; 0.1, 0.2, 0.5 and 1.0 millilamberts. These estimates are tabulated in Table III.

TABLE III. ESTIMATED RECOVERY TIMES AS A FUNCTION OF ADAPTING LIGHT ENERGY AND TARGET DISPLAY LUMINANCE

Adapting Flash Energy (lumen-sec/ft^2)	Recovery Time (sec)			
	Target Luminance (millilamberts)			
	0.1	0.2	0.5	1.0
.5 → 5×10^5	82	55	35	26
1×10^4	47	31	18	12
5×10^3	24	17	12	9
.9 → 1×10^3	8	5	4	3

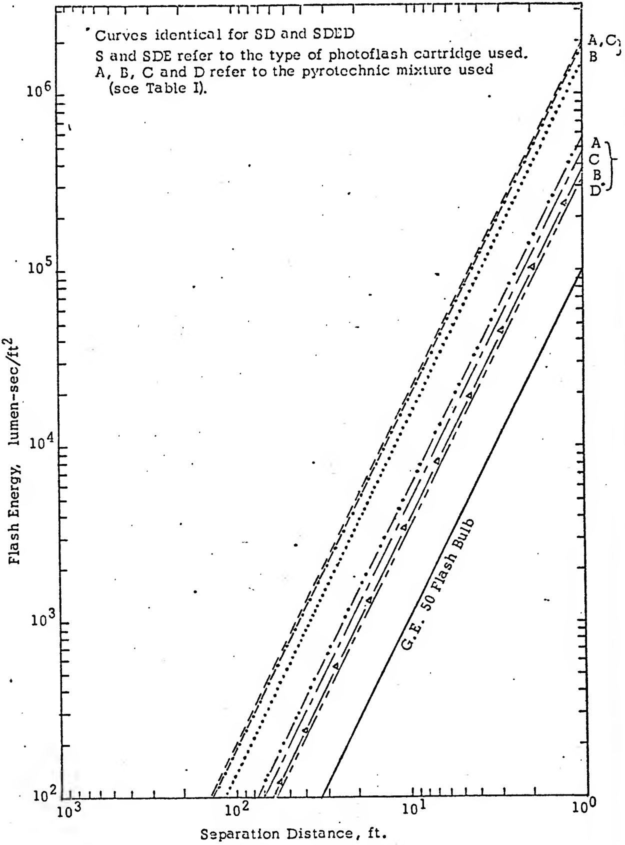
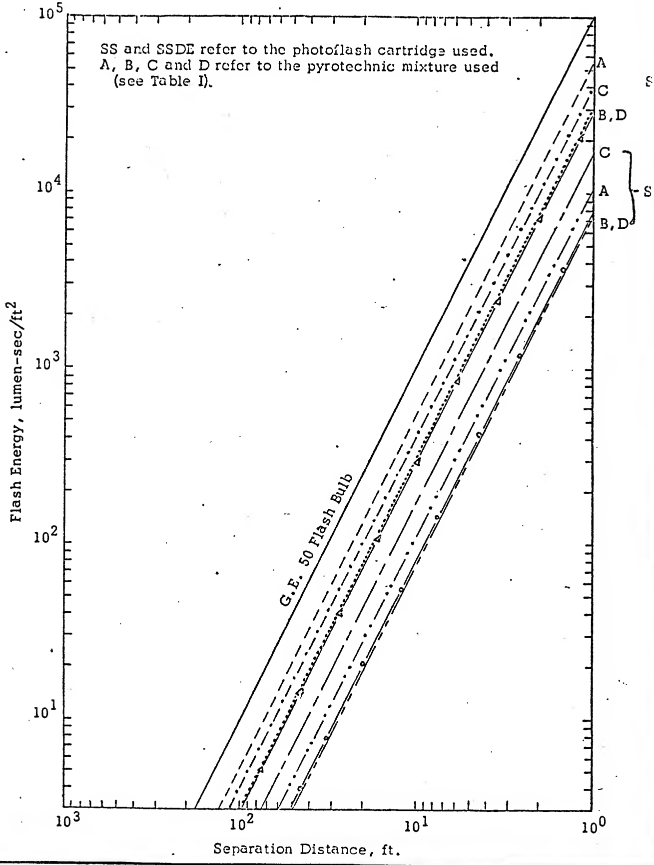


Figure 13. Light Illumination From Type S and SDE Photoflash



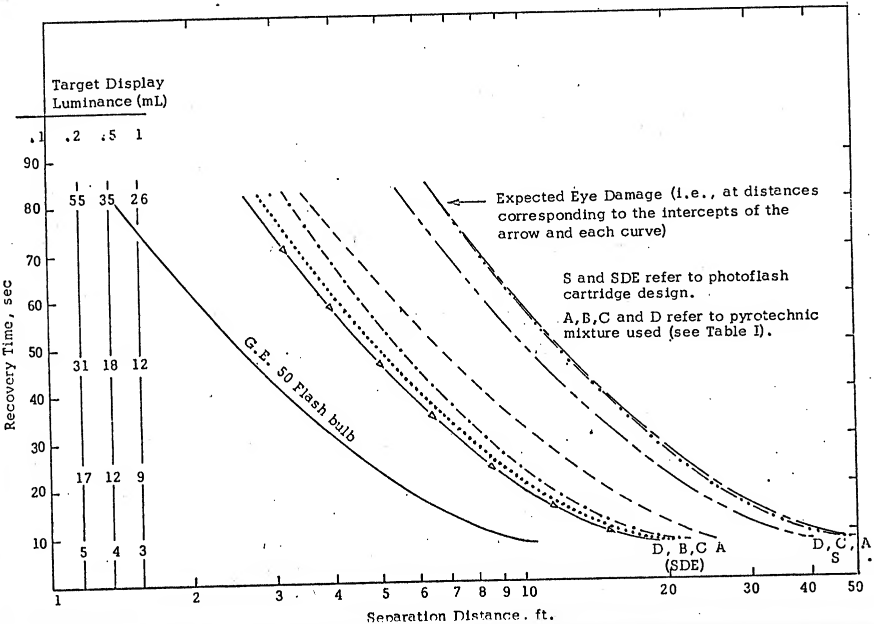
SS and SSDE refer to the photoflash cartridge used.
A, B, C and D refer to the pyrotechnic mixture used (see Table I).
G.E. 50 Flash Bulb
A
C
B,D
C
A
B,D
S
10^5
10^4
10^3
10^2
10^1
10^3
10^2
10^1
10^0
Flash Energy, lumen-sec/ft^2
Separation Distance, ft.

These estimates are also indicated by the vertical dashes crossing each of the curves in Figure 11.

For each pyrotechnic device tested, the recovery times for a subject exposed to the light flash were estimated using the data in Figures 11, 13, and 14 and Table III. These estimates were made as a function of distance away from the flash and the luminance levels of objects which the observer might attempt to detect after exposure. These estimates are reported in Figures 15 and 16.

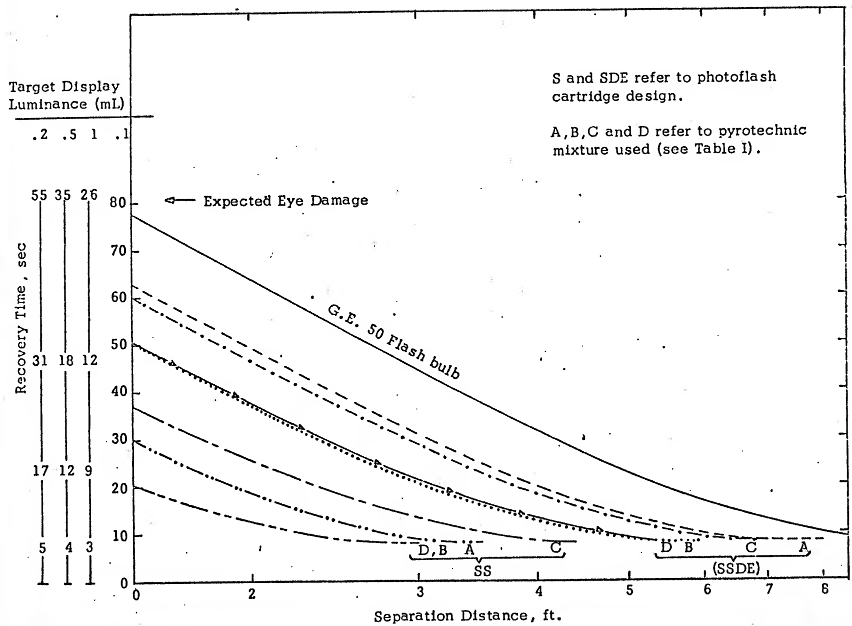
As expected the large photoflash devices (i.e., the S and SDE series) should be the most effective as far as separation distance is concerned. An observer separated from the flash by 50 feet can be affected if an SA charge is employed. At separation distances less than 7 feet there would be the possibility that irreversible eye damage could be affected using the SA charge. Significant flash blindness effects are expected within this distance range for all of the charges. Recovery times of as long as 60 seconds are predicted for the detection of objects which are very dimly illuminated.

The effects of exposure to a G.E. 50 flash bulb were also predicted. It can be seen that the estimated effects are not as great as for the S and SDE series photoflash units. By further comparison with a recent report by Tiller et al.[15] (ARPA Contract DAAK02-69-C-0338) the estimates made for the G.E. 50 flash bulb appear to be reasonable. Tiller et al. evaluated the effects of exposure to this flash bulb to subjects performing military tasks. The subjects were exposed to a flash at distances between 6 and 19 feet. After exposure the subjects were required to detect ground emplaced mines or detect and fire upon a test target. All of these tests were performed under various night time conditions to which the subjects had adapted before being exposed to the light flash. It was found that the subjects, all trained Marines, were able to resume their assigned task with the same efficiency after an average recovery time of 5 to 20 seconds. No indication of reflected luminances of the objects detected were made. It is felt, however, that the predictions of recovery times for dimly lit displays (viz., 0.1 and 0.2 millilamberts) agree with the results obtained by Tiller et al. Between 6 and 10 feet it is predicted that exposure to the G.E. 50 flash should take approximately 8 to 18 seconds. No predictions beyond 10 feet for the G.E. 50 were made because of lack of data. However there is much indication to suggest that at longer distances (i.e., lower flash energies) the recovery times versus distance decreases at a very small rate.



Target Display Luminance (mL)
.1 .2 .5 1
55 35 26
31 18 12
17 12 9
5 4 3
Expected Eye Damage (i.e., at distances corresponding to the intercepts of the arrow and each curve)
S and SDE refer to photoflash cartridge design.
A, B, C and D refer to pyrotechnic mixture used (see Table I).
G.E. 50 Flash bulb
D, B, C A (SDE)
D, C, A S
Recovery Time, sec
Separation Distance, ft.

The estimated recovery times after exposure to the smaller photoflash sources are shown in Figure 16. It is not anticipated that eye damage could be affected by these charges even at short separation distances. Again the "A" and "C" mixtures are expected to be the most efficient.



Target Display Luminance (mL)
.2 .5 1 .1
55 35 26
31 18 12
17 12 9
5 4 3
Recovery Time, sec
80
70
60
50
40
30
20
10
0
Expected Eye Damage
G.E. 50 Flash bulb
S and SDE refer to photoflash cartridge design.
A, B, C and D refer to pyrotechnic mixture used (see Table I).
D, B A C
SS
D B C A
(SSDE)
0
2
3
4
5
6
7
8
Separation Distance, ft.

6. CONCLUSIONS

Sixteen pyrotechnic flash mixtures - fragmenting container combinations were tested. It was shown that significant flash blindness effects can be expected to result from the exposure to these flashes, all of which occur within 50 msec. These effects can result by exposure to these charges at distances within a range of 50 feet depending on the pyrotechnic mixture and quantity, container design, and method of initiation.

6.1 CARTRIDGE DESIGN

The series S and SDE charges (i.e., the 2.7 in. photoflash cartridge) produced the most intense light and are expected to be effective at distances as far as 50 feet. The external explosive burster attached to the outside of the "S" cartridge was expected to increase the light intensity by compacting the mix before ignition.. However, for the larger cartridge this does not appear to have been successful. For the smaller 0.83 in. photoflash cartridge the expected trend resulted. The effective compaction by this imploding mechanism probably increases with decreasing cross-sectional area.

6.2 PHOTOFLASH MIXTURE

The type "A" and "C" mixtures in all cases generated the most light output. In some cases the "C" mixture produced light pulses of longer duration as previously anticipated. The "B" and "D" mixtures were not as effective. In fact the performance of the "D" mixture was relatively poor.

6.3 DATA INTERPRETATIONS

In order to estimate the flash blindness effects, correlations between reported data had to be made. The results of the analyses appear to be consistent with expectation, namely that recovery time is dependent not only on the flash energy but also on the luminance of objects which are visually sought during the recovery period. Also the relatively insensitive change of recovery time at flash energies which produce 90 to 100 percent pigment bleach was shown in this analysis.

It is useful to note that the large light sources used in our experiments (i.e., the S and SDE series), produced more intense illumination than the source employed by the Vertex Corporation. Correspondingly, longer incapacitation times are predicted for the S and SDE photoflash units as compared with the G.E. 50 photoflash used in the Vertex studies. In addition, on the basis of our independent experimental data, we could predict the shorter incapacitation times reported by Vertex for their weaker light source.

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APPENDIX I

In order to clarify the question of potential applications of bright light sources, a series of simple scenarios have been developed, which illustrate possible suitable situations.

The use of a detonating pyrotechnic permits the generation of casing fragments as well as intense light, if the material is enclosed in a metal casing. On the other hand, packing the pyrotechnic into a non-metallic (e.g., cardboard) casing, essentially eliminates any significant fragment hazard. These two modes of operation find separate regimes of possible application.

I. PERIMETER DEFENSE

Given a situation in which a village or a group of men wish to provide a very distinct indication of an attempt at perimeter penetration, by the enemy, and in addition wish to either inflict temporary optical incapacitation alone, permanent optical incapacitation alone, or fragment damage in addition to the optical incapacitation, these pyrotechnic light sources can play a useful role.

Thus, cased in metal and triggered by sensors (or trip wires) within the effective fragment range, they provide direct fragment damage capability with a good possibility of severe permanent optical impairment at such relatively short ranges.

Triggered by sensors deployed outside the effective fragment range, the effects would be primarily temporary optical incapacitation and disorientation with a low probability of fragment damage.

In specific situations, calling for no fragmentation effects, such as one in which friendly personnel may inadvertantly trigger the charge, the sensors can be deployed far enough away to assure only temporary optical incapacitation and fragmentation can be completely eliminated with a cardboard casing for the pyrotechnic.

II. VEHICLE PROTECTION AGAINST KIDNAP ATTEMPT

Given the premise that abductors (e.g., of South American diplomatic representatives) do not wish to kill the hostage during the kidnap attempt, a system for providing even 5 - 10 seconds of optical incapacitation in a 360° field around the car in which the hostage is driving, provides an opportunity for escape, while the abductors are optically disoriented. This system would be more effective at night than in the daytime. The light source could be either pyrotechnic or electric discharge. It could be made safe against accidental discharge causing permanent damage to innocent bystanders.

III. TEMPORARY DISRUPTION OF VEHICLE CONVOY BY CAUSING OPTICAL INCAPACITATION OF LEAD DRIVER

The scenario here is relatively simple in that the lead driver can be optically incapacitated as he's rounding a turn, or caused to block the road by his inability to see it for a sufficient time to cause a wreck.

IV. ESCAPE FROM AN ENCLOSURE WITH NO PERMANENT DAMAGE TO OTHERS

In some situations, where the presence of innocent bystanders, e.g. women and children prevents the use of more damaging techniques, the use of temporary optical incapacitation is of potential interest.

V. PRELIMINARY TO INDIVIDUAL CAPTURE

Where a single individual is to be captured alive, the use of optical incapacitation may provide useful assistance. Thus, a bright light source generated near him by impact functioning of a device fired from a shotgun can provide sufficient temporary optical incapacitation to permit other capture techniques to be employed more reliably.

VI. SUMMARY

While these scenarios do not provide a complete list of potential applications, they should be useful in examining the value of a system which combines the capability for fragmentation damage, severe permanent optical incapacitation and transient optical incapacitation with the choice fairly easy to control.