FOREWORD

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ABSTRACT

Two concepts of phototropic systems application are presented in this report. These concepts, when considered individually or in combination, make possible the development of improved, directly or indirectly actuated, phototropic, ophthalmic, nuclear flash-protective devices. By the application of a phototropic filter at the focal plane of an optical system, the attenuation of the phototropic response due to distance is minimized. Using a renewable fluid filter, a concept is presented which offers the opportunity to use the more sensitive irreversible phototropic systems while still providing reversible characteristics. The operating characteristics of these concepts are presented along with some derived theoretical relationships.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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THE DYNACELL AND FOCAL PLANE CONCEPTS OF PHOTOTROPIC SYSTEMS APPLICATION TO OPHTHALMIC NUCLEAR FLASH-PROTECTIVE DEVICES

INTRODUCTION

There is a need for a sensitive phototropic nuclear flash ophthalmic protective device possessing the highest possible quantum yield and whose protective response is not attenuated with distance.

The intense electromagnetic radiation emanating from a nuclear flash can produce permanent damage to the retina of the eye, in the form of a thermal lesion. Rapid changes in the illumination level of even lesser energies are capable of producing a visual "dazzle" blindness or flash-blindness which can last for many seconds, but from which there is eventual recovery. Accordingly, to prevent this dazzle blindness, the most sensitive phototropic filter materials must therefore be employed.

It is known that retinal burns resulting from nuclear detonations have occurred to observers located at large distances from the detonation site, so that a system which functions even at greater distances is also desirable.

DYNACELL CONCEPT

By the use of a protective filter constructed as a thin cell and containing the phototropic material as a solution, it is possible to continuously replace or quickly purge out an activated photosensitive system. Such a device could be used with irreversible phototropic systems.

Some of the more sensitive and therefore desirable, currently available photochemical systems which can be considered for use in ophthalmic, nuclear flash-protective devices are the irreversible, phototropic-thermotropic materials. When activated, these materials are neutral in color and are capable of going from an initial transmission of 70 percent down to a value of less than 0.001 percent (optical density = 5). Because of their irreversible characteristic, such systems are normally limited as to their use in optical viewing systems. Once activated, the systems become inoperative for further viewing because of their opacity. The new Polacoat DYNACELL concept of phototropic systems application, by continuous but controlled renewal of the photosensitive element, offers a means of overcoming this detrimental characteristic and permits the use of these more desirable materials.

"Static" cells (i.e., thinly spaced compartments with transparent walls) filled with sealed-in liquid phototropic systems have previously been used to satisfactorily demonstrate the phototropic phenomenon. A dynamic fluid cell, wherein the phototropic liquid would flow continuously through the cell, eliminates the problem of irreversibility. These concepts have been evaluated by fabricating and testing several prototypes at Polacoat. The prototypes successfully demonstrated the renewal concept. The flow rate is sufficiently uniform across the filter that, by a controlled flow rate, a constant gradient density can be maintained. The flow rate can be adjusted to provide a density matched to the intensity of the ambient light.

After activation by exposure to intense incident illumination such as from nuclear flash, the opaque filter cell can then be cleared by purging. The purging action is similar in appearance to the lifting of a black curtain. Throughout this procedure, the filter is in protective operation.

OPERATING CHARACTERISTICS OF THE DYNACELL CONCEPT

On considering the DYNACELL concept, the following advantageous characteristics become apparent:

1) Optical densities of 5 or greater are obtainable using currently available phototropic systems.

2) Initial reaction response speeds of under 30 microseconds are obtainable with currently available phototropic systems.

3) Back reaction (clearing) speeds of 1 second or less to return to the open state (i.e., approximately 65%T) are obtainable with the DYNACELL concept.

4) The most sensitive current one-way phototropic-thermotropic liquid systems (i.e., with quantum yields greater than 1) can be utilized in the DYNACELL concept.

5) Ultraviolet degradation of the phototropic materials due to ambient light does not present a problem, since fresh phototropic liquid is continuously supplied to the DYNACELL.

6) A variable-density sunglass which is controlled by the wearer, utilizing normal environmental radiation for activation, is possible. There is sufficient flexibility of operation that it can be used for either daytime (sunglass) or nighttime (clear) applications.

7) Filtering action for energy in the wavelength range of 200-2000 millimicrons (mμ) is readily provided by the incorporation of fixed filters into the DYNACELL.

8) Increased storage stability is offered as an added feature, since the DYNACELL can readily be adapted to mix the individual components of extremely sensitive, phototropic-thermotropic liquid systems just prior to the entry of the solution into the cells.

9) The number of reversible phototropic responses capable of producing an optical density of 5 without any replacement or maintenance action is limited only by the volume of phototropic material considered feasible from an applications standpoint (e.g., 1000 or more reversals are attainable with 300 cc of currently available materials).

10) Such a system provides continuous protection while being worn.

The major disadvantages of this system appear to be as follows:

1) The replacement of the used phototropic materials with fresh material places some degree of logistic limitations on use. (Current irreversible phototropic liquid systems should be capable of 2 - 2½ hour periods of uninterrupted use in the sunlight with an approximate volume of 300 cc.)

2) Additional equipment over that required by a "static" reversible system is required.

3) The system is not selective as regards an electromagnetic radiation intensity threshold.

FOCAL PLANE CONCEPT

By placing the phototropic materials at the focal plane of an optical system, a protective response to a nuclear detonation can be obtained which is independent of the distance of the observer from the detonation.

The cornea of the human eye functions similarly to an optical lens. It focuses, as an image, the light energy emanating from the source object at a focal plane located in the light sensitive retina. Neglecting atmospheric attenuation, flashblindness and retinal burns are affected by distance in that the image area involved on the retina will become smaller as the distance from the explosion increases. For a person at various distances from the source object, the size of this image changes in proportion to the distance, but the energy received per unit area (i.e., cal/cm^2) at the retinal image remains the same regardless of the distance up to the point where the image resembles a point source. In this manner, the eye behaves similarly to a camera. The film in the camera is located at the camera's focal plane. The density of the image formed on the film (whose exposure is a function of the activating energy per unit area) is the same regardless of the distance from the object until the resolving power of the camera is reached. The image density produced on the film is a function of the light reflected or emanated from the object and only the size of the image changes with distance. Similarly, if one neglects attenuation from the atmosphere, the brightness of the image formed at the retina does not vary with distance until the limit of the optical resolving power of the retina is reached.

When placed in the line of vision, a sensitive self-attenuating phototropic filter has some limitation in its ability to protect the eyes against flashblindness. In this position, the optical density produced by a phototropic filter is in direct proportion to the amount of activating energy received per unit area. This level of energy is in inverse proportion to the square of the distance from the source. When placed at an energy level sufficient to produce a protective optical density, the phototropic system will proportionately reduce the energy level being focused onto the retina. But, at distances from the flash where the activating energy per unit area is insufficient to produce a protective optical density, the lens of the eye can still focus the source object as an image. Although the image is of a reduced size, it will have the same energy level per unit area as an image formed at closer proximity to the detonation. But, as the distance increases, the protective density of a self-activated phototropic filter will be reduced (i.e., neglecting atmospheric attenuation).

By using an optical system which would allow the fireball image to form at a phototropic focal plane, the maximum response would be obtained from the system. The reason for this lies in the increased concentration of activating energy per unit area of the phototropic material. Discounting attenuation, the protective response provided by such an application would not be in proportion to the distance from the activation source. Rather, it would function in proportion to the brilliance of the source.

OPERATING CHARACTERISTICS OF THE FOCAL PLANE CONCEPT

The FOCAL PLANE concept, in combination with the DYNACELL concept affords all of the characteristics of the dynacell in addition to the following advantageous characteristics:

1) A uniform protective phototropic response is provided, regardless of distance.

2) This concept of application provides for the continuous viewing of the field of vision surrounding the activated image.

3) This device also provides for a proportional reduction in the light reflected or emanated from any object appearing in the field of vision.

The major disadvantages of this system appear to be as follows:

1) The field of vision is logically restricted because the system functions as an optical device.

2) The finished device is bulky since it is an optical device.

THEORETICAL CONSIDERATIONS

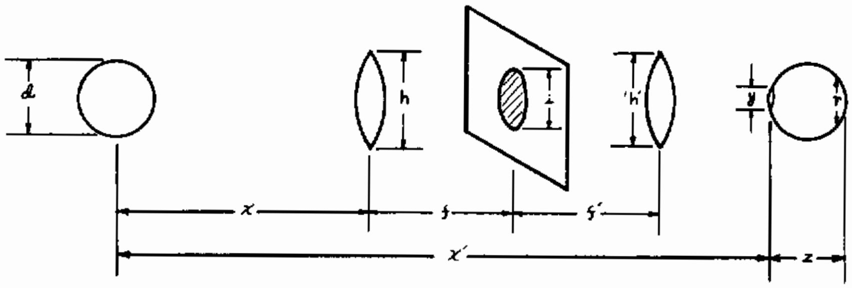

Figure 1. Optical System

Consider the above optical system in which:

d = Diameter of thermal radiation source (fireball) at time t, expressed in centimeters.

x = Distance from detonation to lens, expressed as centimeters.

f = Distance from first lens to a phototropic focal plane, expressed as centimeters.

i = Diameter of image formed at the focal plane, expressed as centimeters.

h = Diameter of first lens, expressed as centimeters.

f' = Distance from focal plane to second lens, expressed as centimeters.

h' = Diameter of second lens, expressed as centimeters.

y = Diameter of pupil, expressed as centimeters.

r = Diameter of image formed on the retina.

z = Distance from cornea to retina, expressed in centimeters.

x' = Distance from detonation to cornea, expressed in centimeters.

The following symbols are used to express various energy and area parameters in the derivation.

E_t = Total thermal radiation emitted by detonation up to time t, expressed as calories.

e_t = Total thermal energy level per unit area received up to time t at the front of the first lens or at the distance x.

A_h = Area of the first lens, expressed as square centimeters.

E_h = Total thermal energy incident to the front of the first lens, expressed as calories.

A_i = Area of image formed at the focal plane, expressed as square centimeters.

e_i = Total thermal energy level per unit area received up to time t incident to the image at the focal plane, expressed as cal/cm^2.

A_d = Area of the thermal radiation source (fireball) at time t, expressed in square centimeters.

e_d = Total thermal energy emitted per unit area of source (fireball) up to time t, expressed as cal/cm^2.

e_{iu} = Activating energy in the wavelength range 310-410 mμ per unit area required to produce an optical density of 4, expressed as cal/cm^2. (This value may be determined experimentally for any given phototropic system.)

U = Decimal percent of the total thermal energy in the activating wavelengths (310-410 mμ) based on black radiator distribution for a color temperature of 6000°K.

e_{iv} = Thermal energy contained in the visible wavelengths (400-700 mμ) per unit area which is incident to the focal plane and equivalent to sufficient activating energy to produce an optical density of 4 at the image, expressed as cal/cm^2.

V = Decimal percent of the total thermal energy in the visible wavelengths (400-700 mμ) based on black body radiator distribution for a color temperature of 6000°K.

e_{ivT} = Total thermal energy per unit area transmitted by the image formed at the phototropic focal plane, while it closes down to an optical density of 4, expressed as cal/cm^2.

T_4 = Decimal percent of incident visible energy transmitted by a specific phototropic filter while closing down to an optical density of 4.

$e_{d'}$ = Apparent total thermal energy emitted per unit area of source (fireball) up to time t after the image has passed through a phototropic focal plane, expressed in cal/cm^2.

e_r = Total thermal energy received by the retina, per unit area, up to time t, after the image has passed through a phototropic focal plane.

In this derivation, it is to be assumed that there will be no attenuation of the thermal radiation due to the atmosphere or the lens materials used.

The thermal energy level per unit area received up to time t at the lens front or at a distance x (e_x), expressed as calories/cm^2 is given by:

$$e_x = \frac{E_t}{4\pi x^2} \qquad (1)$$

The area of the lens (A_h), expressed as cm^2, is given by:

$$A_h = \frac{\pi h^2}{4} \qquad (2)$$

The total amount of thermal energy received by the lens front (E_h), expressed as calories, is given by:

$$E_u = (e_x)(A_h) = \left[\frac{E_t}{4\pi x^2}\right] \cdot \left[\frac{\pi h^2}{4}\right] = \frac{E_t h^2}{16x^2} \qquad (3)$$

Since the total amount of thermal energy received by the lens front (E_u) would then be focused on the focal plane at the image, and since the area of the image (A_i) is given by:

$$A_i = \frac{\pi i^2}{4} \qquad (4)$$

then the formula for determining the total amount of thermal energy per unit area received at the image (e_i), expressed as cal/cm^2, is:

$$e_i = \frac{E_h}{A_i} = \frac{\frac{E_t h^2}{16x^2}}{\frac{\pi i^2}{4}} = \frac{E_t h^2}{4x^2 \pi i^2} \qquad (5)$$

Proportioning the object and image diameters to the object distance and focal length, we obtain:

$$\frac{i}{d} = \frac{f}{x} \qquad (6)$$

Squaring both sides of this equation and solving for i^2, we obtain:

$$i^2 = \frac{f^2 d^2}{x^2} \qquad (7)$$

Substituting the equivalent of i^2 in the formula to obtain the total amount of thermal energy per unit area received at the image (e_i), we obtain:

$$e_i = \frac{E_t h^2}{\frac{4x^2 \pi f^2 d^2}{x^2}} = \frac{E_t h^2}{4\pi f^2 d^2} \qquad (8)$$

Considering that the surface area of the fireball (A_d), expressed as cm^2, is given by:

$$A_d = \pi d^2 \qquad (9)$$

then the total thermal energy emitted per unit area of source (fireball) up to time t (e_d) expressed as cal/cm^2 is given by:

$$e_d = \frac{E_t}{A_d} = \frac{E_t}{\pi d^2} \qquad (10)$$

The relation then, between the total amount of thermal energy emitted per unit area of source and the total amount of thermal energy received per unit area at the image, is given by:

$$\frac{e_i}{e_d} = \frac{\frac{E_t h^2}{4\pi f^2 d^2}}{\frac{E_t}{\pi d^2}} = \frac{h^2}{4f^2} \qquad (11)$$

Thus, when utilizing the focal plane concept, it was theoretically established that the induced phototropic response is proportional to the intensity of the radiant energy of the source (fireball) and the diameter and focal length of the objective lens. On the basis of formula 11, it is now possible to determine the total amount of thermal energy emitted per unit area from the source in order to produce an optical density of 4 at the focal plane.

Experimentally, it has been established that current liquid phototropic-thermotropic systems are capable of producing an optical density of 4 with 0.06 cal/cm^2 of activating ultraviolet energy (310-410 mμ). Assuming the color temperature of the source as being equal to 6000°K (this temperature would contain the highest proportion of energy in the visible wavelengths and, therefore, be the worst condition in application), and assuming that the distribution of the emitted energy follows that of a black body radiator, then the percent of thermal energy emitted from 310-410 mμ is equal to 10.9 percent (i.e., 15.7-4.8, see G. E. Radiation Slide Rule) of the total energy emitted from the source.

Accordingly, the total thermal energy incident to the focal plane which contains sufficient activating energy from a 6000°K source and capable of producing an O.D. of 4 at the image, expressed as cal/cm², is given by:

$$e_i = \frac{e_{iu}}{U} \qquad (12)$$

Substituting the data previously given, we obtain:

$$e_i = \frac{0.06}{0.109} = 0.55 \text{ cal/cm}^2$$

Considering a commercial lens 3.95 cm in diameter and having a focal length of 2.83 cm, it is possible to determine e_d, the total amount of energy emitted per unit area from the source to produce a given O.D. at the focal plane phototropic image (for this case, we will use an O.D. of 4), by using equation 11:

$$e_d = \frac{4e_i f^2}{h^2}$$

$$e_d = \frac{(4)(0.55)(2.83)^2}{(3.95)^2}$$

$$e_d = 1.13 \text{ cal/cm}^2$$

Similar values required to produce O.D.'s of 3, 2, and 1, respectively, at the focal plane are 0.85 cal/cm², 0.57 cal/cm², and 0.28 cal/cm².

At a color temperature of 6000°K, that portion of the total thermal energy in the visible wavelengths (400-700 mμ) is equal to 37.5 percent (51.9-14.4, see G. E. Radiation Slide Rule).

The thermal energy contained in the visible wavelengths (400-700 mμ) per unit area which is incident to the focal plane and equivalent to sufficient activating energy to produce an O.D. of 4 at the image (e_{iv}) is given by:

$$e_{iv} = (e_i)(V) \qquad (13)$$

Substituting the data previously given into the formula, we obtain:

$$e_{iv} = (0.55)(0.375) = 0.206 \text{ cal/cm}^2$$

It has been theoretically and experimentally established that a value of 10 percent or less of the incident thermal energy in the visible wavelengths is transmitted by an irreversible phototropic filter while it is in the process of closing down to an optical density of $4 (T_4)$. Accordingly, the visible energy transmitted by the phototropic image formed at the focal plane (e_{ivT}) is given by:

$$e_{ivT} = (e_{iv})(T_4) \qquad (14)$$

Substituting the data previously given into the formula, we obtain:

$$e_{ivT} = (0.206)(0.10) = 0.021 \text{ cal/cm}^2$$

Utilizing the same type of lens to refocus the image as was used to converge (i.e., 3.95 cm diameter and 2.83 cm focal length), it is now possible to determine the new energy level per unit area in the visible wavelengths emanating from the image source ($e_{d'}$) which will be apparent to the eye. (There is no reduction or magnification brought about by this optical system.) This relationship is given by:

$$\frac{e_{d'}}{e_d} = \frac{e_{ivT}}{e_i}$$

Solving for $e_{d'}$, we obtain:

$$e_{d'} = \frac{(e_{ivT})(e_d)}{(e_i)} \qquad (15)$$

Substituting the data previously given into this formula, we obtain:

$$e_{d'} = \frac{(0.021)(1.13)}{(0.55)}$$

$$e_{d'} = 0.043 \text{ cal/cm}^2$$

Since the eye behaves like a simple convex lens, the relationship of formula 11 could be used to obtain the amount of thermal energy received per unit area at the retinal image (e_r) when a current irreversible, phototropic-thermotropic liquid system is placed in the focal plane.

Thus,

$$\frac{e_r}{e_{d'}} = \frac{y^2}{4z^2}$$

and solving for e_r, we obtain:

$$e_r = \frac{(y^2)(e_{d'})}{4z^2} \qquad (16)$$

Since an average pupil diameter (y) of 0.45 cm can be used along with an average focal distance to the retina (z) of 1.5 cm, e_r can readily be computed using these and other data previously given. Thus,

$$e_r = \frac{(0.45)^2(0.043)}{4(1.5)^2}$$

$$e_r = 0.00096 \text{ cal/cm}^2$$

This value, obtained under the conditions stated, is much lower than the value of 1.0 cal/cm^2 as given by Ham et al. (see ref. 1) which caused a retinal burn on a rabbit's eye.

CONCLUSIONS

The FOCAL PLANE and DYNACELL concepts of phototropic systems application afford a means of obtaining proportionate phototropic protection regardless of the distance from the source. They also afford a means of utilizing the more sensitive, one-way, phototropic-thermotropic materials. Up to this time, these systems had limitations as to their use because of their irreversible character. The DYNACELL concept allows for the use of these sensitive materials and also offers the advantages of a reversible phototropic system.

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